Appendix 13 – Water Reports

Hydrology and Bauxite Mining on the Darling Plateau

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Abstract

A review was undertaken of the interaction between bauxite mining, its restoration, and the hydrology of the Darling Plateau. Alcoa's mining operation is predominately within the water supply catchments of Perth, giving rise to three hydrological issues: turbidity, stream yields, and stream salinity. Turbidity management is effected through attention to detail in day-to-day operations. Due to the high rates of evapotranspiration, yields from Jarrah forest catchments are low by normal standards, varying from 25% of rainfall in the highest rainfall area to less than 1% of rainfall in the lowest; this has been further exacerbated by the below-average rainfall since 1975. These low yields have resulted in increased interest in stream yields from mined and restored mine areas and how these may be maintained compared with unmined forest. Under current rainfall regimes, it is unlikely that there will be a significant salinity response due to Alcoa's mining, but it is inadvisable to discount the salinity issue in the lower rainfall zone, and research will need to consider the possibility of further climate change.

Key words: catchment yield, hydrological processes, mine restoration, surface mining, water supply, Western Australia.

Introduction

The Darling Plateau of the southwest of Western Australia is of great importance to the city of Perth because it supplies up to 50% of the city's reticulated water (Bari & Ruprecht 2003); the six main water supply catchments are shown in Figure 1. Water supply is considered to be the priority land use of the northern Jarrah forest of the Darling Plateau (Bartle & Slessar 1989); however, catchment yields of the Darling Plateau are low by normal standards due to the high rates of evapotranspiration by its forest cover (Schofield et al. 1989; Ruprecht & Stoneman 1993), and these low yields have been further exacerbated by the below-average rainfall since 1975 (Table 1; Water Corporation 2005). As well, there are stream salinity concerns in the eastern, lower rainfall section of the Darling Plateau (Stokes et al. 1980).

For the mining operations of Alcoa World Alumina Australia (Alcoa) within the western, higher rainfall section of the Darling Plateau (>1,100 mm/annum average rainfall), there are agreed limits under the working arrangements with state government that define acceptable standards for turbid run-off. Although there are no such limits for the maintenance of stream yields, it is desirable that stream yields should remain comparable with those for unmined forest.

In response to the frequency of dryland salinity following agricultural clearing, for the eastern, lower rainfall section of the Darling Plateau (<1,100 mm/annum average rainfall), there are conditions relating to salinity effects (Bartle & Slessar 1989). In particular, Alcoa of Australia Ltd. (1978) committed as part of the revised 1978 Environmental Review and Management Programme for the Wagerup Alumina Project that "mining will not take place in the eastern, lower rainfall portion of Alcoa's lease until research shows that mining operations can be conducted without significantly increasing the salinity of the water resources."

The Darling Plateau

The Darling Plateau was formed by a marginal upwarping of the Yilgarn Block, a relatively stable shield area which forms a major part of the Great Plateau of Western Australia (Schofield & Bartle 1984). The Darling Plateau is characterized by sharply incised drainage lines forming dense drainage networks in the western, higher rainfall section, with these transitioning to open, flat-floored valleys in the eastern, lower rainfall section (Churchward & Dimmock 1989). The primary bedrock of the Darling Plateau is granitic with this divided by the intrusion of numerous sheet-like doleritic dykes that vary in thickness from a few millimeters to tens of meters. Deep in situ weathering has produced a soil profile with a typical depth range of 10–40 m (average about 25 m; Kew et al. 2007).

The Darling Plateau is naturally fully forested. The dominant overstorey species on the middle and upper slopes are Jarrah (*Eucalyptus marginata*) and Marri

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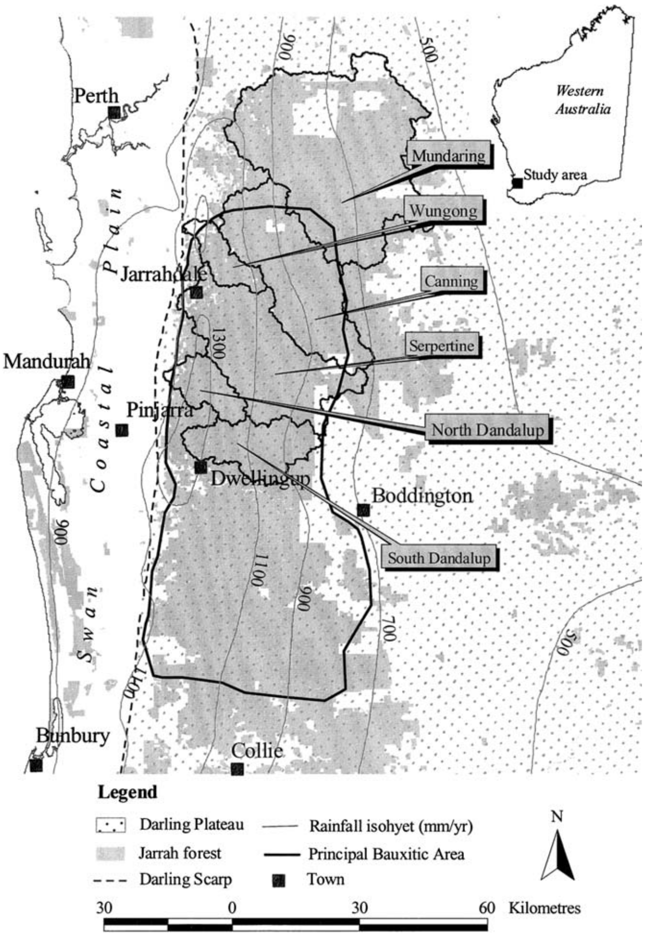

Figure 1. Locality plan for the Darling Plateau with rainfall isohyets, water supply catchment boundaries, and the principal bauxitic area. After Bartle and Slessar (1989).

(*Corymbia calophylla*) with Bullich (*E. megacarpa*) and Yarri (*E. patens*) on the lower slopes (Havel 1975; Koch & Samsa 2007). The forest of the Darling Plateau is naturally variable in density and composition with this variation increased further by logging and *Phytophthora* die-back (caused by *Phytophthora cinnamomi*); the result is a forest with highly variable age and composition (Abbott 1984; Abbott et al. 1993; Colquhoun & Kerp 2007).

Table 1. Average rainfalls for Jarrahdale and reservoir inflows for Perth.

	Water Years (May to April)		
	1911–1974	*1975–1996*	*1997–2003*
Average rainfall Jarrahdale (mm/yr)	1,251	1,073	985
Average Perth reservoir inflow (GL/yr)	338	177	121

From Water Corporation (2005).

The climate of the Darling Plateau is Mediterranean, characterized by hot dry summers and cool wet winters with most rainfall occurring between May and October (Gentilli 1989; Gardner & Bell 2007). This seasonality in rainfall creates a similar pattern in streamflows. Streamflow hydrographs tend to be more damped than might be expected, primarily because the soil profile is deep and highly pervious near the surface (Sharma et al. 1987) resulting in streamflow generation being dominated by interflow and groundwater discharge, with direct surface run-off a lesser fraction of total flow (Schofield et al. 1989). Williamson et al. (1987) found that for the Salmon catchment on the Darling Plateau, direct surface run-off accounted for only 3–4% of streamflow with the balance made up of interflow and groundwater discharge. As well, Turner et al. (1987) estimated that during four rainfall events in 1985 on the Salmon catchment, 60–95% of the streamflow originated from shallow groundwater. They also showed that the residence time of this water within the aquifer system was short, in the range 20–50 days, thereby indicating its transient nature. Kinal (1986) studied the development of transient aquifers and shallow throughflow for two sites on the Darling Plateau. He found that perching developed in the mottled zone above the pallid clay for both sites, and perching also developed on the duricrust of the site with the more continuous duricrust.

Streamflow and Salinity

Streamflows across the Darling Plateau are strongly correlated with rainfall, varying from 25% of rainfall in the highest rainfall area to less than 1% of rainfall in the

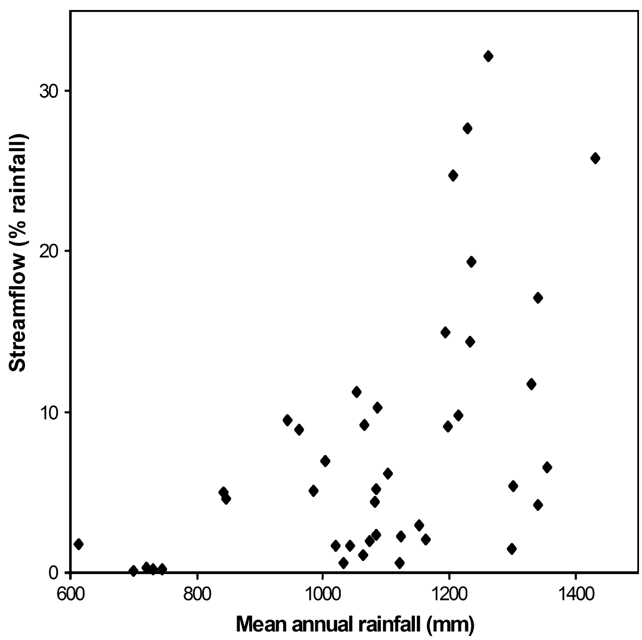

Figure 2. Comparison of rainfall versus streamflow for Jarrah forested catchments. From Schofield et al. (1989).

lowest (Fig. 2; Schofield et al. 1989; Croton & Bari 2001; Bari & Ruprecht 2003). Streamflows of the Darling Plateau are also strongly affected by the density of forest cover, including canopy loss due to *Phytophthora* die-back (Fig. 3; Schofield et al. 1989), and by clearing for agriculture: following 50% clearing for agriculture, the streamflow of a Jarrah forest catchment increased eight times (Croton 2004*a*).

The soil salt storages on the Darling Plateau are related to rainfall with soil salinities relatively low in the high-rainfall zone but increasing rapidly with decreasing annual average rainfall (Stokes et al. 1980; Johnston 1981; Slessar et al. 1983; Tsykin & Slessar 1985). Tsykin and Slessar's data for 327 boreholes confirmed that on the Darling Plateau, there is a low–soil salt content zone extending east from the Darling Scarp to the 1,100 mm/annum rainfall isohyet; the average soil salt content for this zone was 4 kg/m^2. Salt content was found to increase in a near-exponential manner with distance inland reaching 20 kg/m^2 by the 750–1,100 mm/annum average rainfall zone. There are also north–south trends in soil salt storages within the principal bauxitic area of the 900–1,100 mm/yr rainfall zone (Fig. 1), with the lowest storages being in the north (Croton 1991*b*). Similar trends were found in groundwater salinities (Croton 1991*a*). In the northern section of the principal bauxitic area, groundwater salinities were essentially the same in west and east of the 1,100 mm/annum rainfall isohyet, 438 and 447 mg/L, respectively; whereas in the southern section of the principal bauxitic area, they were very different, 191 and 837 mg/L, respectively.

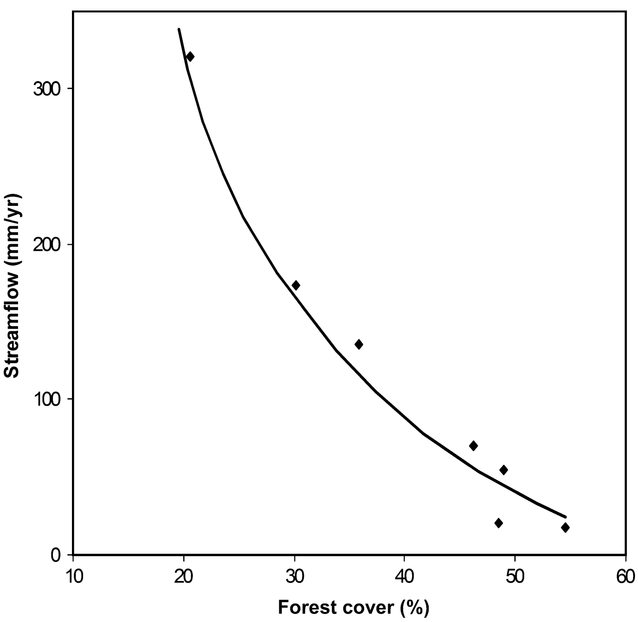

Figure 3. Comparison of forest cover versus streamflow for seven higher rainfall zone catchments. From Schofield et al. (1989).

Bauxite Mining in the Higher Rainfall Zone

Alcoa's mining operations are mainly in the higher rainfall zone to the west of the 1,100 mm/annum rainfall isohyet. Two hydrological issues relate to bauxite mining in the higher rainfall zone; the prevention of turbid discharge to streams and streamflow volumes.

For the control of turbid discharges, a system of sediment traps is used to process water from active mine areas prior to its release; whereas for restored mine areas, a containment pond with a size equal to the ones in 20-year rainfall event is worked into the minepit landscape at time of restoration (Croton & Tierney 1985). When these measures are combined with the nonerosive and self-armoring nature of the pisolitic surface soils found on the bauxitic areas of the Darling Plateau and the low-rainfall intensities of the Darling Plateau (one in 100 year, 1-hour event of 45 mm/hr—Institution of Engineers, Australia 1987), erosion and turbidity reduce in significance and are managed through attention to detail at the operational level. Stream turbidity is monitored via a continuous sampling network placed on tributaries flowing from the mine envelope. Reporting limits have been agreed with the Water Corporation. Any event exceeding 25 Nephelometric Turbidity Units for two hours or more is reported as an environmental incident and the event is investigated and appropriate corrective actions are implemented. For the whole of Alcoa's operations on the Darling Plateau, there were just four reportable events for the period 2003–2006, inclusive.

Paired catchment studies and modeling have identified two phases of the streamflow response to mining: there were increases in stream yields due to temporary removal of vegetation during the mining phase and stream yields in the near term following rehabilitation progressively decreased (Fig. 4; Croton 2004*b*; Croton et al. 2005). For the three catchments studied by Croton (2004*b*) and Croton et al. (2005), the increases were about 4 ml/yr for each hectare of mine area and persisted for about 5 years following restoration.

The primary analysis method of Croton (2004*b*) and Croton et al. (2005) was modeling rather than paired (treated and control) catchment studies; nevertheless, strong emphasis is always placed on analysis of observed data. The two catchments probably best representing observed responses are Warren and Bennetts (Fig. 5).

Similar streamflow responses to mining and restoration were observed in all other experimental catchments in the high-rainfall section of the Darling Plateau (Table 2): all catchments displayed consistent behavior—an increase in flow during mining and restoration followed by a decline in the near-term, postrevegetation period.

Bauxite Mining in the Lower Rainfall Zone

Historically, clearing for agriculture in the southwest of Western Australia has resulted in dryland salinity: the

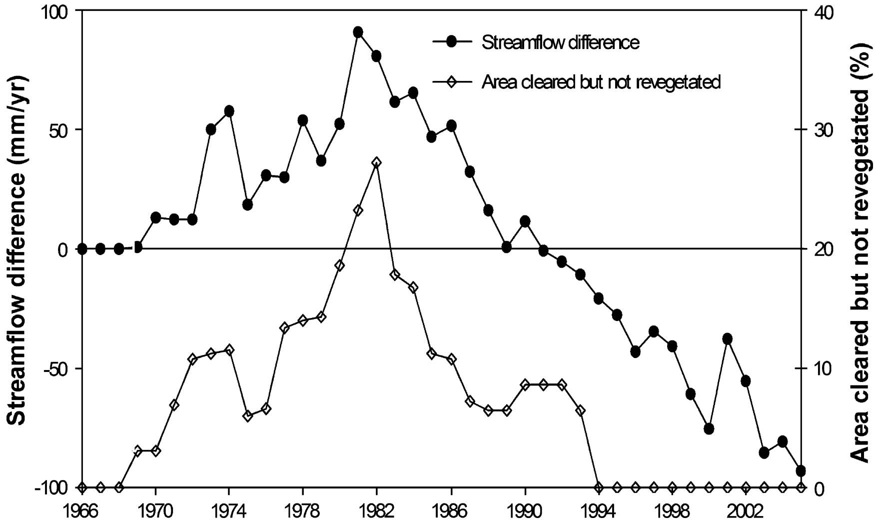

Figure 4. Difference between mined and unmined streamflows for More Seldom Seen catchment. Area cleared but not revegetated is plotted for comparison. After Croton et al. (2005).

discharge of saline groundwater to streams due to increased recharge from the removal of deep-rooted, perennial vegetation (Mayer et al. 2005). This agricultural response has led to salinity concerns regarding Alcoa's mining in the lower rainfall zone and the commitment by Alcoa of Australia Ltd. (1978). The 1,100 mm/annum rainfall isohyet (Fig. 1) presently demarcates the eastern edge of the area in which Alcoa is permitted to undertake normal mining operations.

It has been established that "resolution of the Alcoa commitment related to the lower rainfall zone mining would be best addressed by a dual process of predicting the impacts of mining by computer simulation and confirming if necessary by an experimental mining operation within the lower rainfall zone" (Mauger et al. 1998). To meet the specific needs of modeling a distributed operation-like Darling Plateau bauxite mining, the WEC-C computer model (Croton & Barry 2001) has been developed and extensively applied to Darling Plateau hydrology and to issues associated with human impact on catchment hydrology (Bari & Croton 2000, 2002; Croton & Bari 2001; Beverly & Croton 2002; Croton 2004*a*). Experimental mining was deemed necessary and is now underway within a group of catchments immediately to the east of the 1,100 mm isohyet (Cameron Experimental Mining Exercise [CEME]). The CEME commenced operations in 2004 and last restoration should be completed in 2011.

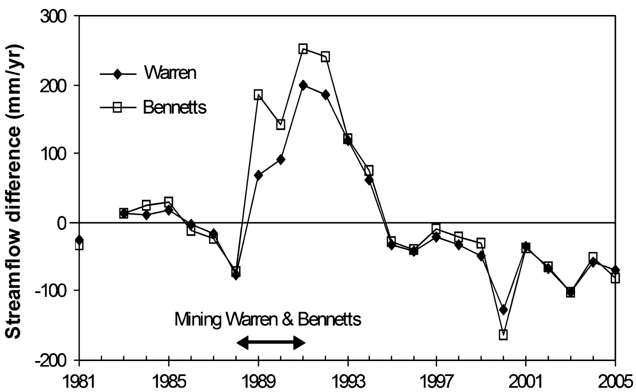

Figure 5. Flow differences between Warren and Bennetts catchments and Vardi Road control catchment.

Mauger et al. (1998) reported, using modeling, how the CEME would be likely to affect the salinity of the inflows to Serpentine Reservoir, a drinking water supply for the city of Perth. The high-rainfall case for the modeling of the CEME had a peak inflow salinity difference between the mined and the unmined states of 7.6 mg/L. For the average rainfall case, the peak inflow-salinity difference between the mined and the unmined states was 1.8–2.4 mg/L; and for the low-rainfall case, typical of present rainfall conditions, it was only 0.1 mg/L. These compare with the average salinity for Serpentine Reservoir of 195 mg/L (Mauger et al. 1998).

Under the current protracted below-average rainfall, groundwater levels have decreased. For a mid-slope piezometer in a control catchment to the east of the CEME, the depth to groundwater has been steadily increasing from 1975 to present and is now at 23 meters compared with 12 meters in 1975 (Fig. 6).

Discussion

Higher Rainfall Zone

The observed stream yield reductions for the Darling Plateau are a significant issue. However, there is a complex interaction between forest growth, disease effects,

Table 2. Observed responses in streamflow due to mining for all experimental catchments in the higher rainfall zone on the Darling Plateau (analysis by the control catchment method).

			Peak Increase		Decline 2001–2005	
Catchment Name	*Catchment Area (ha)*	*Area Mined (%)*	*(mm/yr)*	*(% Flow)*	*(mm/yr)*	*(% Flow)*
More Seldom Seen	327	62	247	136	40	38
Seldom Seen	706	34	230	113	4	5
Del Park	131	32	98	49	31	29
Warren	86	40	200	81	66	58
Bennetts	82	48	252	78	67	54
Lewis	201	51	163	135	—	—

reforestation, climatic variations, and stream yield (Ruprecht & Stoneman 1993). Croton (2004*b*) and Croton et al. (2005) found that the reductions in yield due to mine restoration were of a similar order to the reductions due to natural growth in the unmined forest. The combined effect of forest growth and mine restoration was less than the effect from reduced rainfall. Thus, mine restoration effects can be masked by these other factors and difficult to estimate accurately.

The effects of mine restoration on catchment yields have not generally been reported in the literature probably because mining and restoration are normally a small area relative to the size of monitored catchments. However, there are many studies that show increased stream yields when forests are cleared and decreased stream yields when reforestation occurs, both in tropical and in temperate forest (Hibbert 1967; Gilmour 1977; Trimble & Weirich 1987; Waterloo 1994). In a moist eucalypt forest, streamflows were increased for six years following logging and regeneration (Cornish 1993). In a number of catchments in the United States, yield increases persisted for 10 years following logging but could be maintained if herbicides were used to control regrowth (Hornbeck et al. 1993). Eucalypts in particular show a stronger effect in reducing stream yields than pines or deciduous hardwoods (Sahin & Hall 1996; Scott & Smith 1997; Farley et al. 2005).

The longer-term effects of afforestation, restoration, thinning, and logging on stream yields are less understood. Other researchers have reported early declines in streamflows following revegetation after logging but a return to pre-treatment stream yields over time. The mountain ash forests of Victoria, where the major water supply catchments of the city of Melbourne are located, have been studied extensively. Langford (1976) and Kuczera (1987) both related catchment water yield to forest stand age, and Kuczera (1985) developed an idealized curve between the two based on the results of eight study catchments. For the mountain ash forest, there is less streamflow when the forest is young, and this is strongly related to an initial peak in tree canopy density following fire. The canopy density then declines over the next 100 years, and streamflow returns to prefire levels. In the mountain ash forest, this process is driven by the well-developed self-thinning behavior: initial stocking densities in the order of 100,000 individuals/ha reduce to in the order of 100 individuals/ha by year 100. Old-growth Jarrah forest has similar low tree densities (<100 stems/ha); however, unlike mountain ash, once Jarrah reaches the pole stage, there is little self-thinning (Stoneman et al. 1989). For Alcoa's mine restoration to follow a similar hydrological behavior to the mountain ash, it is likely that management intervention will be required.

Bartle and Slessar (1989) discussed the potential for decreased yields and considered thinning may be necessary if the revegetation continues its early vigorous growth. Grant (2006) using state-and-transition successional modeling considered that "more than half of the rehabilitated area is regarded as being above the desired trajectory because of high tree density." Recent thinning of mine revegetation in a Jarrah forest catchment significantly increased streamflows—130% in the second year following treatment, but streamflow reduced to pre-treatment levels four years after treatment. The return to pre-treatment flows appeared to relate to growth of a vigorous understorey rather than a recovery of overstorey density; hence, the rapidity of the response. The short-lived nature of the streamflow responses for mine revegetation thinning differ from those observed for Jarrah forest thinning to similar stand densities: it was found that it took 12–15 years following thinning of the Jarrah forest for yields to return to pre-treatment levels (Ruprecht & Stoneman 1993). However, the treatments described by Ruprecht and Stoneman tended to be more complex than the once-off operations performed on the mine restoration. It appears that management of Alcoa's mine restoration for water yield may not be simple and is likely to require multiple steps. As an initial measure in 2001, Alcoa reduced the target establishment densities of both trees and leguminous shrubs for restored areas.

The present uncertainty in terms of appropriate management practices has led to the implementation of a comprehensive research program into the hydrological processes of the Darling Plateau, how they are affected by bauxite mining and mine restoration, and how mine restoration may be managed to ensure stream yield effects are minimized. This research includes catchment-scale management trials.

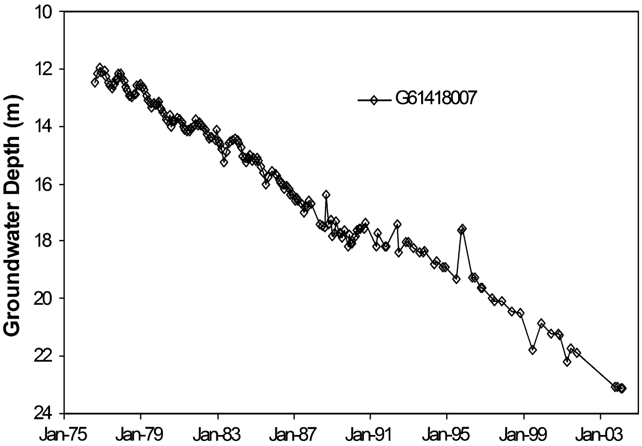

Figure 6. Depth to groundwater for a long-term, mid-slope piezometer in the Tunnel Road control catchment to the east of the CEME.

Lower Rainfall Zone

Providing rainfalls remain at historically low levels, it is unlikely that there will be a significant salinity response due to Alcoa mining in the lower rainfall zone. This is because the current protracted below-average rainfall period has depressed groundwater levels. Given that the primary cause of dryland salinity effects is the discharge of saline groundwater, such a strong decline in groundwater levels means that the expected groundwater rise of 2–6 m beneath the mined areas due to the temporary removal of the vegetation will be too small to generate a groundwater discharge. This is in contrast to early predictions which assumed that groundwater would freely discharge due to increased recharge on the mine areas. For instance, Peck (1976) and Schofield (1988) predicted through modeling, based on observed groundwater rises and streamflow responses due to permanent agricultural clearing, that bauxite mining would increase stream salinities by 35–380 mg/L in the lower rainfall section. Later predictions by Mauger et al. (1998) were 0.1–7.6 mg/L depending on rainfall scenario, though these were for CEME mining alone.

Although the continuance of below-average rainfall due to possible climate change would effectively prevent a mining-related stream salinity response, it is inadvisable for Alcoa to base its long-term mining strategy on climatic assumptions. Predictions of mining-related effects need to be based on detailed scenario modeling in combination with empirical data emanating from the CEME. Such contingency has been thought likely since the late 1980s (Bartle & Slessar 1989).

Conclusions

The present, below-average rainfall period is causing a change in emphasis in the hydrological issues relating to current mining from a primary focus on preventing turbid discharge to that of maintaining stream yields. However, managing mine restoration to ensure a hydrological outcome requires a detailed understanding of Darling Plateau hydrology and its interaction with mining. To this end, a hydrological research program is being undertaken.

Under current rainfall regimes, it is unlikely that there will be a significant salinity response due to Alcoa's bauxite mining in the lower rainfall zone where soil salinities and salt storages are higher than for present operations. Thus, Alcoa will be able to meet its salinity-related commitments as long as below-average rainfalls continue. It is, though, inadvisable to discount the salinity issue and instead research will need to rely more heavily on modeling that considers a range of climate scenarios.

Implications for Practice

- Climate change, and factors such as reduced rainfall, can significantly affect the hydrological issues facing a mining operation during its life.
- Empirical catchment trials take decades to implement and are at the mercy of climate variables such as rainfall that can significantly affect their usefulness.
- Early hydrological responses to mine restoration may not be indicative of long-term outcomes, and an understanding of systems is required before extrapolations can be made with confidence.
- The longevity of hydrological responses to treatments such as thinning is highly dependent on the total vegetation community response.

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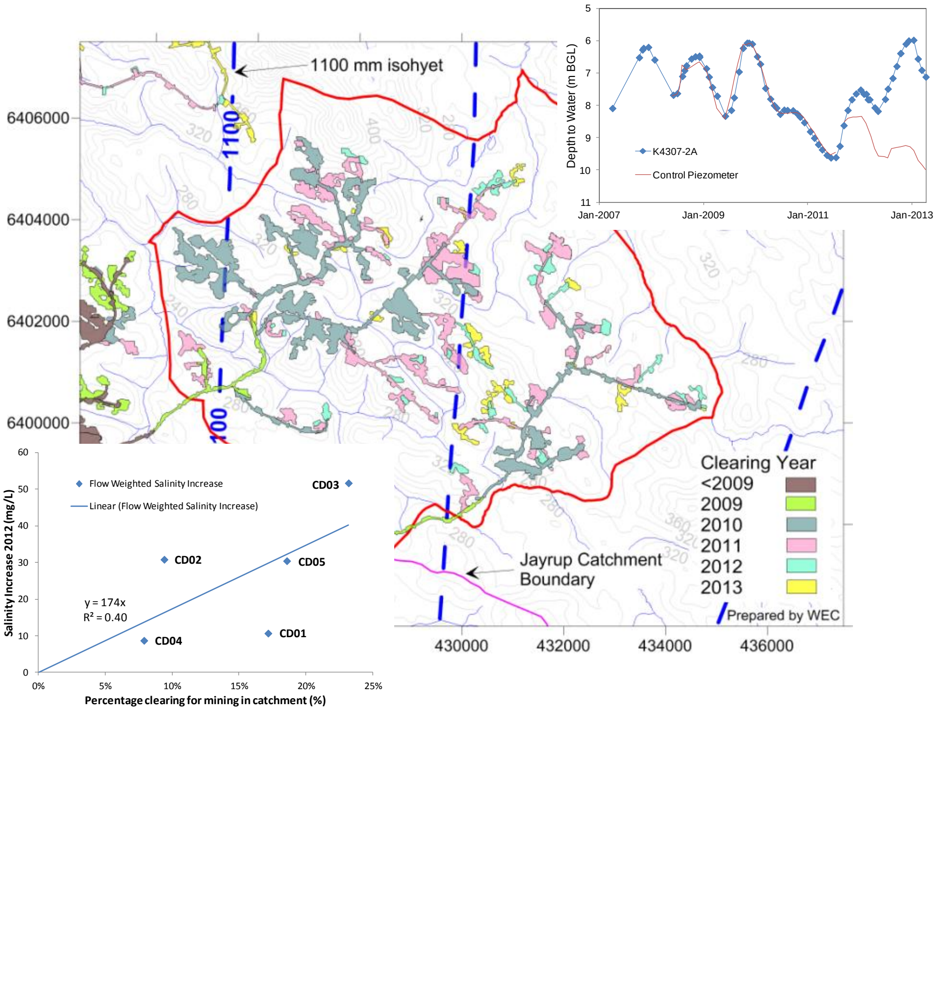
REPORT

TO

BAUXITE HYDROLOGY COMMITTEE

HYDROLOGICAL RESPONSE OF THE O'NEIL TO McCOY MINING AREA



J.T. Croton, G.T. Dalton, K.A. Green and J.A. Dalton

Water & Environmental Consultants

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CONTENTS

EXECUTIVE SUMMARY

A study was undertaken to assess the hydrological responses associated with mining the O'Neil-to-McCoy mine area in the Intermediate Rainfall Zone (900 to 1,100 mm/annum, IRZ). The O'Neil to McCoy area was a logical extension of the present operations within the McCoy mining area. Initial salinity-risk assessments for O'Neil to McCoy have already been produced, and tabled at Bauxite Hydrology Committee (BHC) meetings (Croton & Dalton 2008, Croton, *et al*. 2008, Croton & Dalton 2010 and Croton & Dalton 2011). The BHC recommended to the MMPLG that O'Neil-to-McCoy mining should proceed, providing additional items of research and monitoring that were described in Croton & Dalton (2008) be undertaken by Alcoa.

First mining of O'Neil-to-McCoy commenced in 2010 with first clearing in 2009. The historically low rainfall of 2010 caused a decline in groundwater levels and a strong dampening of hydrological behaviour in the O'Neil to McCoy area. In 2011 the BHC decided that a full review of the hydrological responses be held over until after the hydrological system had recovered. With above average rainfall in 2011 and close to average in 2012, this recovery is now at least partly complete. The present report is the requested detailed review and includes a full assessment of the groundwater and stream salinity responses to the mining in the O'Neil-to-McCoy area, as well as recommendations for future monitoring.

Starting with groundwater, Figure I shows the nine responsive piezometers in the O'Neil-to-McCoy mine area. All nine of these piezometers have responded by essentially returning to pre-treatment levels while the control piezometers have languished at deeper levels.

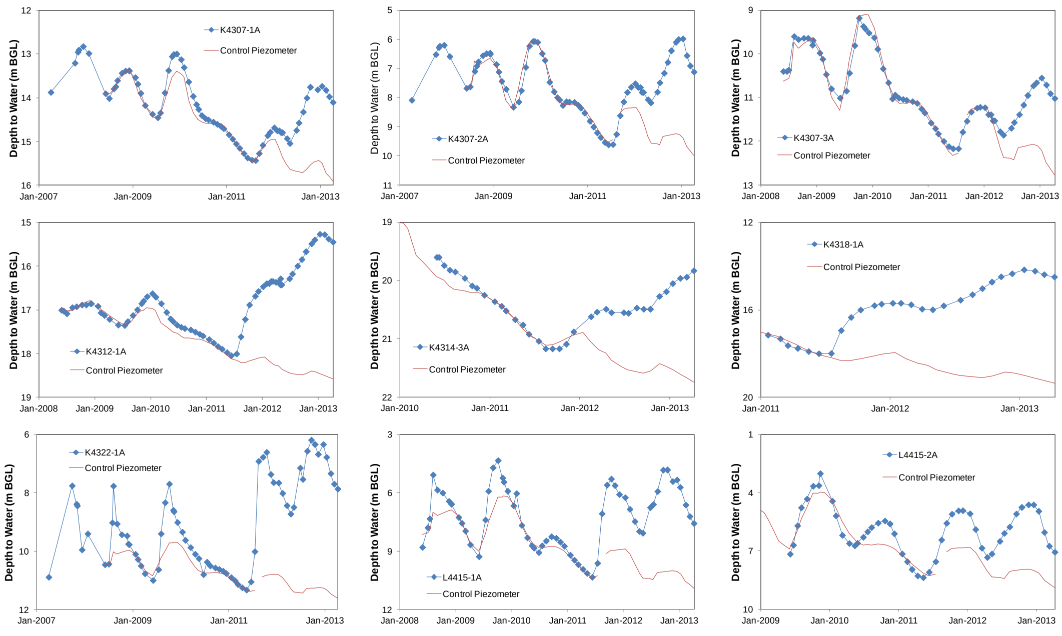

Figure I: Piezometer hydrographs for the nine responsive piezometers in the O'Neil-to-McCoy mine area.

As there are a number of sections of the valley-floor in the O'Neil-to-McCoy mine area where the groundwater is at or near to the soil surface, groundwater contributes to streamflow. The rises shown in Figure I have therefore provided groundwater to streamflow over and above that expected under full forest conditions; resulting in what appears to be a mining-related stream-salinity signature. Using the manually-collected stream-salinity sample data, Figure II shows the salinity responses for the six treated stream-sites compared to the untreated control site. Figure III is a plot of the estimated flow-weighted stream-salinity increase for 2012, obtained by plotting the data for the five continuous-logger sites against the percentage area of clearing for mining in their catchment.

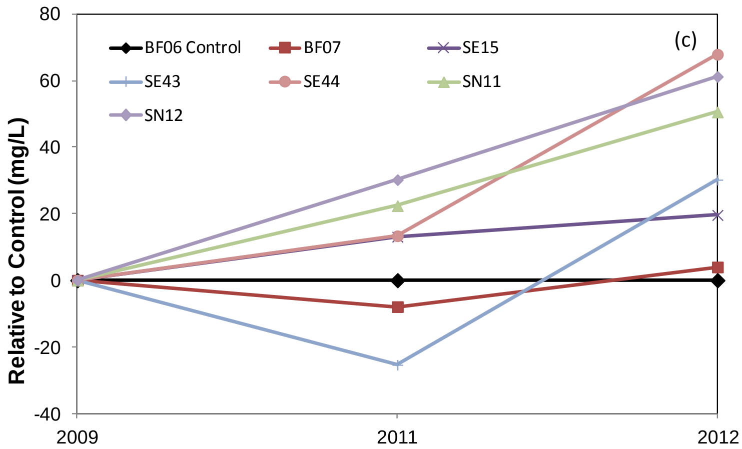

Figure II: October 2009, 2011 and 2012 stream salinity values for those manual stream-salinity sampling points of the O'Neil-to-McCoy mine area that have October data for all three years.

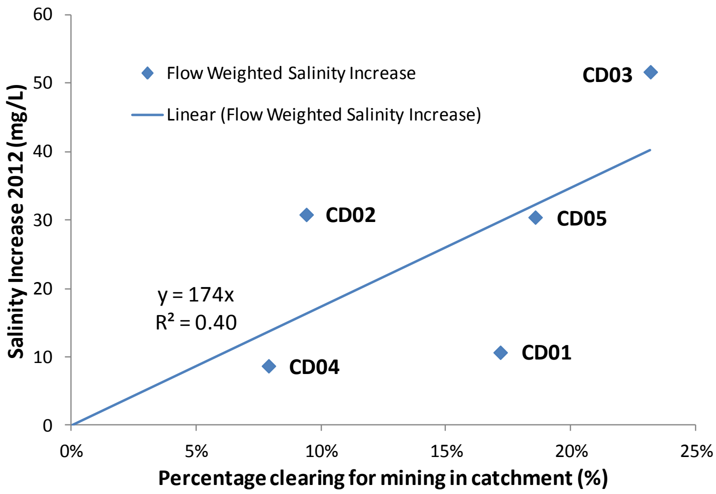

Figure III: Estimated flow-weighted stream-salinity increase for 2012 for the continuous-logger sites, plotted against the percentage area of clearing for mining up to the beginning of 2012.

The data for the O'Neil-to-McCoy mine area was combined with the estimated stream-inflow and water-storage volume for 2012 for the Serpentine Reservoir, to create estimates of the effect of mining of the O'Neil-to-McCoy area on the salinities of the reservoir; these are shown in Table I. The stream-inflow salinity was estimated to increase by 3.0 mg/L due to mining effects, and the pond salinity was estimated to increase by 0.44 mg/L. Neither of these responses were unexpected and are on the low side of what was predicted by Croton & Dalton (2010), and accepted by the BHC when making their recommendation to the MMPLG that O'Neil-to-McCoy mining should proceed. As well, due to the continued below-average rainfalls during the mining period of the O'Neil-to-McCoy area, the saltloads that have actually occurred are an order of magnitude less than those predicted by Croton & Dalton (2010). The estimated mining-related saltload increase in 2012 due to actual O'Neil-to-McCoy mining was 15.3 tonnes, compared to 361 and 419 tonnes for the two scenario-predictions by Croton & Dalton (2010). Given that the salinity of the overall water-supply system is driven by the saltload calculations, that is total salt vs. total water in the system, then what matters to the overall water-supply system is the saltload of the stream-inflow to Serpentine Reservoir rather than the salinity of the stream-inflow.

Table I: Mining related stream-inflow and reservoir-lake saltload calculations for 2012 for the Serpentine Reservoir and mining of the O'Neil-to-McCoy area.

Item	**Flow and Volume** (ML)	**Saltload** (kg)	**Salinity** (mg/L)
Total reservoir inflow	5,047		
Change in reservoir inflow		15,268	3.0
Reservoir pond volume Dec 2012	34,366		
Change in reservoir pond salinity		15,268	0.44

Recommendations were also made as to what monitoring should be continued for the O'Neil-to-McCoy mine area. These recommendations are strongly affected by the present climate, and its likelihood of continuing. It is proposed that if the present below-average rainfalls continue then the hydrological monitoring of the O'Neil-to-McCoy mine area can be maintained at a much lower level than if rainfall patterns change.

A climate change that would trigger consideration of a change in monitoring was defined as at least 1,300 mm/yr rainfall for the Big Brook rain-gauge. Such a rainfall would provide a large water-excess and would significantly replenish soil-water storages and boost streamflow. If rains continue at or below average levels, then they are expected at best to maintain the hydrological status quo.

It is proposed that the monitoring programme outlined in Table II be maintained at least until the end of 2015, unless a rainfall year of 1,300 mm/yr or more occurs, in which case a follow-up review should be undertaken.

Table II Proposed monitoring programme for the O'Neil-to-McCoy mine area.

Item	No. of sites	Monitoring frequency
Continuous stream salinity loggers	5	15 minute logging interval plus manual check-sampling during winter.
DoW gauging stations	2	Big Brook as treated and Gordon as control. Gordon may have too little flow from 2013 to be useful.
Manual stream salinity monitoring	6 primary sites and 30 secondary	Once per year in October.
Groundwater levels	23	Six weekly manual water-level readings, which is nine times year.
Groundwater water-quality	none	Considered that sufficient data has already been collected.

1. INTRODUCTION

Alcoa of Australia (Alcoa) operates the Huntly and Willowdale mines in the northern jarrah forest on the Darling Plateau. Due to the known issues associated with salinity and agricultural clearing in the south-west of W.A., as part of the revised 1978 Environmental Review and Management Program (ERMP) for the Wagerup Alumina Project, Alcoa made the commitment that "*mining will not take place in the eastern, lower rainfall portion of Alcoa's lease until research shows that operations can be conducted without significantly increasing the salinity of water resources*".

As part of the latest Wagerup approval, this commitment has been changed to now read: *"Bauxite mining will not take place in the eastern, lower rainfall portion of Alcoa's lease, until research shows that mining can be conducted without significantly increasing the salinity of the water resources with exception of the Trial Mining Project in the intermediate rainfall zone which commenced in 2005 to test modelling predictions and mining and rehabilitation methods developed from the 25 years of research to date. This trial was approved by the Mining and Management Programme Liaison Group. Results from the trial mining and continuing hydrology research and modelling will form the basis for future approval by the Mining and Management Programme Liaison Group of Alcoa's plans for mining in the intermediate rainfall zone. These plans will be presented in Alcoa's annual Mining and Management Programme submission at an appropriate date."*

In line with these changes, Alcoa no longer considers an application for general access to the Intermediate Rainfall Zone (900 to 1,100 mm/annum, IRZ) appropriate. Alcoa prefers now to apply for access in a staged approach by including strategically determined sections of the IRZ as part of the annual five-year mine-plans, using the existing approval process with the Mining and Management Programme Liaison Group (MMPLG). The first area of interest is a section of the IRZ within the Serpentine Reservoir catchment, known by the mining area name "O'Neil to McCoy" (Figure 1).

It can be seen from Figure 1 that O'Neil to McCoy is a logical extension of the present operations within the McCoy mining area; this present mining includes the IRZ mining in the Cameron Experimental Mining Exercise (CEME) in the Jayrup and associated catchments (Croton, *et al.* 2011). Initial salinity-risk assessments for O'Neil to McCoy have already been produced, and tabled at Bauxite Hydrology Committee (BHC) meetings (Croton & Dalton 2008, Croton, *et al*. 2008, Croton & Dalton 2010 and Croton & Dalton 2011). The BHC recommended to the MMPLG that O'Neil-to-McCoy mining should proceed, providing additional items of research and monitoring that were described in Croton & Dalton (2008) be undertaken by Alcoa. First mining of O'Neil-to-McCoy commenced in 2010 with first clearing in 2009.

The historically low rainfall of 2010 caused a decline in groundwater levels and a strong dampening of hydrological behaviour in the O'Neil to McCoy area. In 2011 the BHC agreed with the proposal by Croton & Dalton (2011) that a full review of the hydrological responses be held over until after the hydrological system had recovered. With above average rainfall in 2011 and close to average in 2012, this recovery is now at least partly complete. The present report is the requested detailed review and includes a full assessment of the groundwater, streamflow and stream salinity responses to the mining in the O'Neil-to-McCoy area, as well as recommendations for future monitoring.

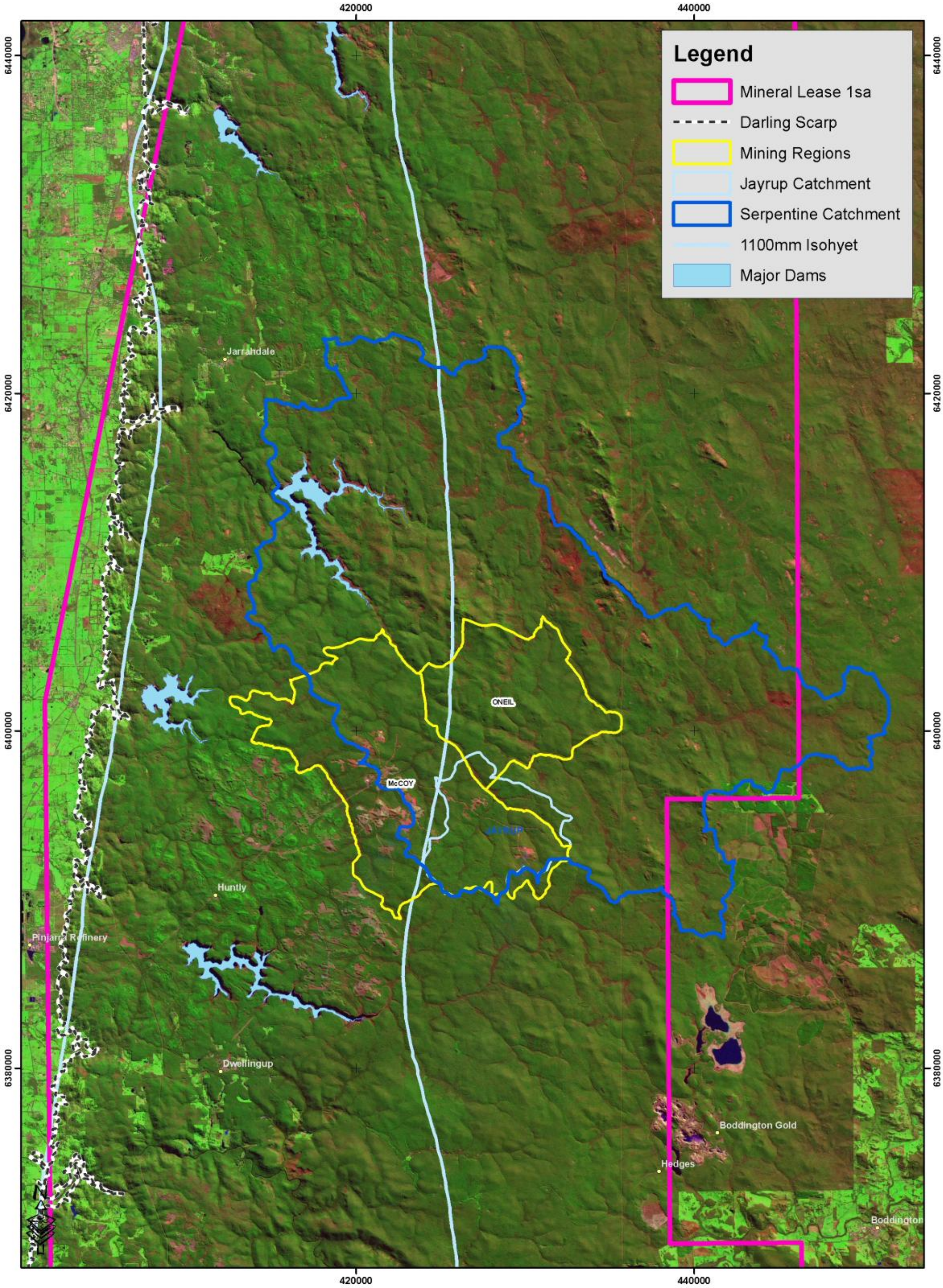

Figure 1: Location of the O'Neil-to-McCoy mine area plotted over the major features of the Darling Plateau. See author's note 1 regarding 1,100 mm isohyet.

Author's note 1: The pre-1978 rainfall isohyets by Hayes & Garnaut (1981) are used throughout this report to estimate rainfalls, as they are the most widely accepted and were used in previous studies.

2. O'NEIL TO McCOY BACKGROUND

2.1 Hydrological Setting

Using data previously collected by Alcoa, Croton & Dalton (2010) provided a detailed review of the soil salt-storages, groundwater salinities and stream salinities of the Darling Plateau and compared them with data collected in the O'Neil-to-McCoy mine area. They concluded that for its rainfall regime, the soil salt-storages, groundwater salinities and stream salinities of the O'Neil-to-McCoy mine area can all be considered typical (Figure 2).

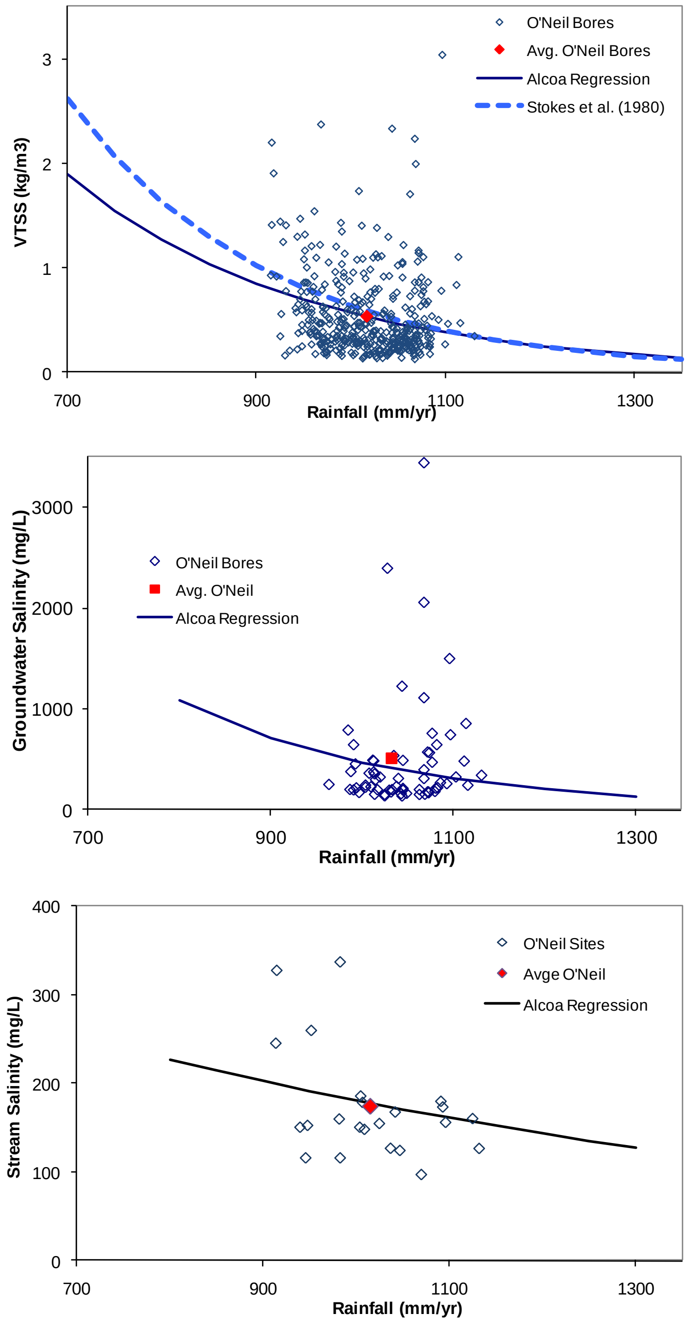

Figure 2: : Soil salt-storage (VTSS), groundwater salinity and stream salinity for the O'Neil-to-McCoy mine area. Also plotted are regression curves for the Alcoa data, and for soil salt-storage the regression by Stokes *et al.* (1980) is included as well.

Croton & Dalton (2010) also noted that for stream salinities there has been a definite decline with time, probably associated with the present below-average rainfall period (Figure 3).

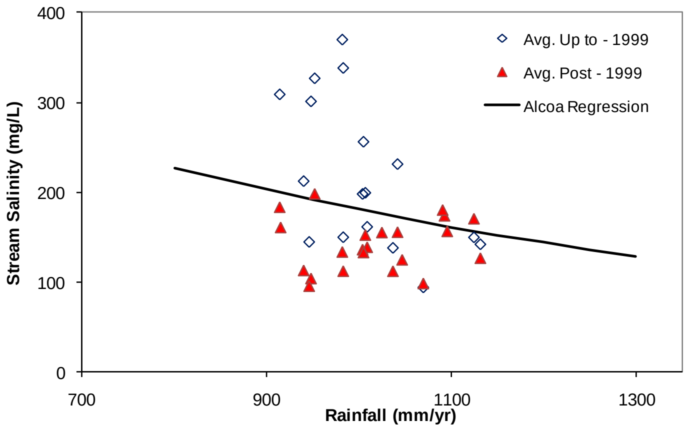

Figure 3: Average stream-salinity for the monitoring points in the O'Neil-to-McCoy mine area, divided into the two periods of upto-1999 and post-1999. The regression curve from Figure 2 has also been plotted.

The depth to groundwater is a significant factor in the O'Neil-to-McCoy mine area hydrology, particularly in stream areas downslope of mine areas. Croton & Dalton (2010) used the available minimum depth-to-water data for 2009 to produce an estimated depth-to-water map for that year (Figure 4).

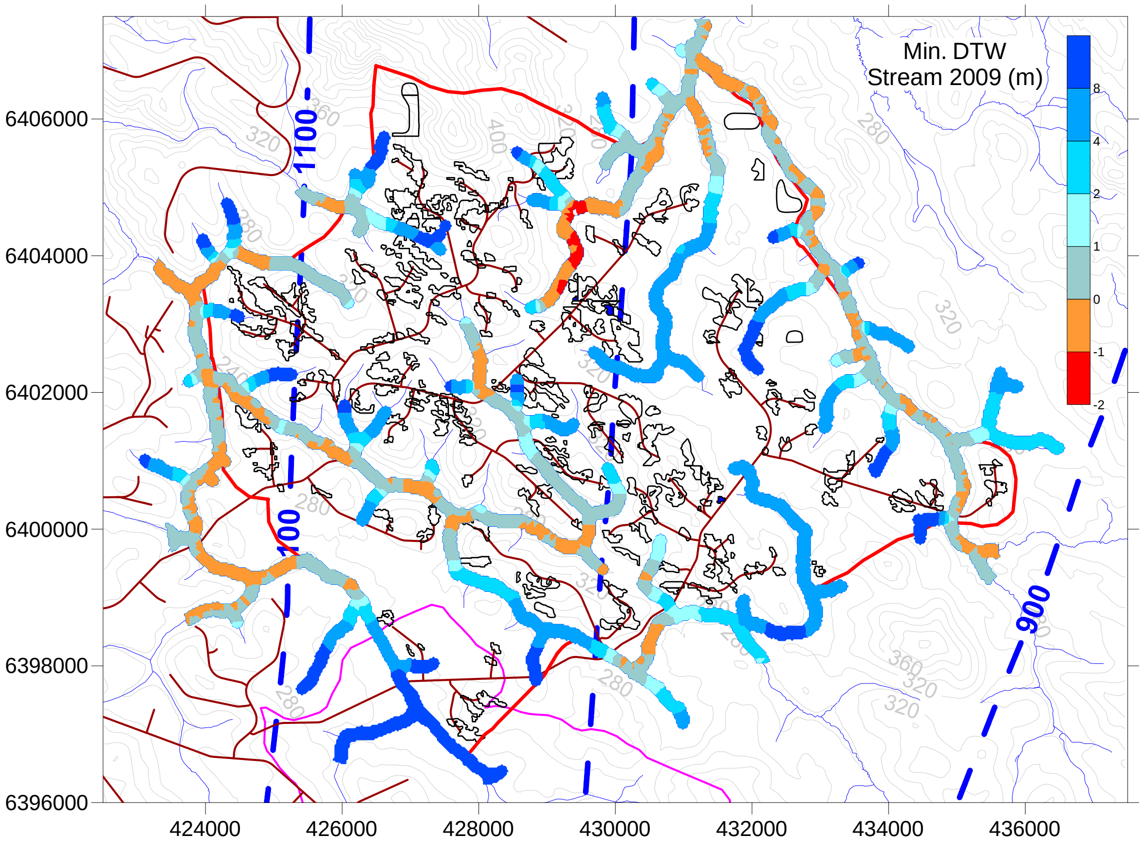

Figure 4: Estimated minimum DTW in 2009 for streamlines in the O'Neil-to-McCoy mine area.

A key conclusion from Figure 4 is that for a considerable fraction of the stream system in the O'Neil-to-McCoy mine area the peak groundwater level in 2009 was at or near the soil surface. Given the present below-average rainfall conditions, it can be assumed that historical groundwater-levels would have been higher and the historical contact between groundwater and the soil surface in the streamzone would have been more extensive. This proximity of the groundwater to the soil surface implies groundwater contributions to streamflow across significant sections of the O'Neil-to-McCoy mine area stream-system; borne out by the stream salinities in Figures 2 and 3 being 100 mg/L and above. When the groundwater system is fully disconnected from streamflow generation, e.g. the Gordon catchment in the Cameron catchment group, stream salinities remain below 100 mg/L (Croton, *et al.* 2011).

The removal of the vegetation cover to allow mining to proceed in the O'Neil-to-McCoy area will cause an increase in groundwater discharge compared to the unmined situation, resulting in some increase in stream salinity compared to unmined levels. The estimates of likely mining effects made by Croton & Dalton 2008, Croton, *et al*. 2008 and Croton & Dalton 2010 were all based on this premise and placed emphasis on putting these effects into hydrological perspective. Past recommendations by the BHC that mining in the O'Neil-to-McCoy area should proceed were based on the committee's consideration that these effects are likely to be acceptable.

In defining the hydrological setting for the O'Neil-to-McCoy mine area, an important component is understanding the differences between this area and the Cameron experimental catchments directly to the south of the O'Neil-to-McCoy mine area (Figure 1). Croton, *et al.* (2011) found that there was almost complete absence of any observable response to mining in the streamflow and stream-salinity records for the Cameron experimental catchments. This lack of stream response in the Cameron experimental catchments was considered by Croton, *et al.* to be directly due to groundwater being at depth in the streamzones of all the catchments prior to the study commencement, and at no time during the study did mining cause it to rise near to the surface. This situation is very different to that for the O'Neil-to-McCoy mine area.

2.2 O'Neil to McCoy Mineplan

Figure 5 shows by clearing year the O'Neil-to-McCoy area and the mine areas that are within and adjacent to it. First clearing within the O'Neil-to-McCoy mine area was in 2009, with all complete by mid-2013. In Figure 6 the mine areas have been divided into two: those cleared, mined and rehabilitated; and those cleared but still within the mining process and not yet rehabilitated.

Figure 7 is a false-colour Landsat 8 image for 31st May 2013 using the bands near-infrared, green and blue. The presently cleared or recently rehabilitated areas with little vegetation cover show as light brown, forest as a dark green, and mine rehabilitation two or more years old as bright green. The O'Neil-to-McCoy mine area is presently at a minima in terms of vegetation cover on mine areas; no areas yet have the bright green of new foliage as seen in the bottom left-hand corner of Figure 7.

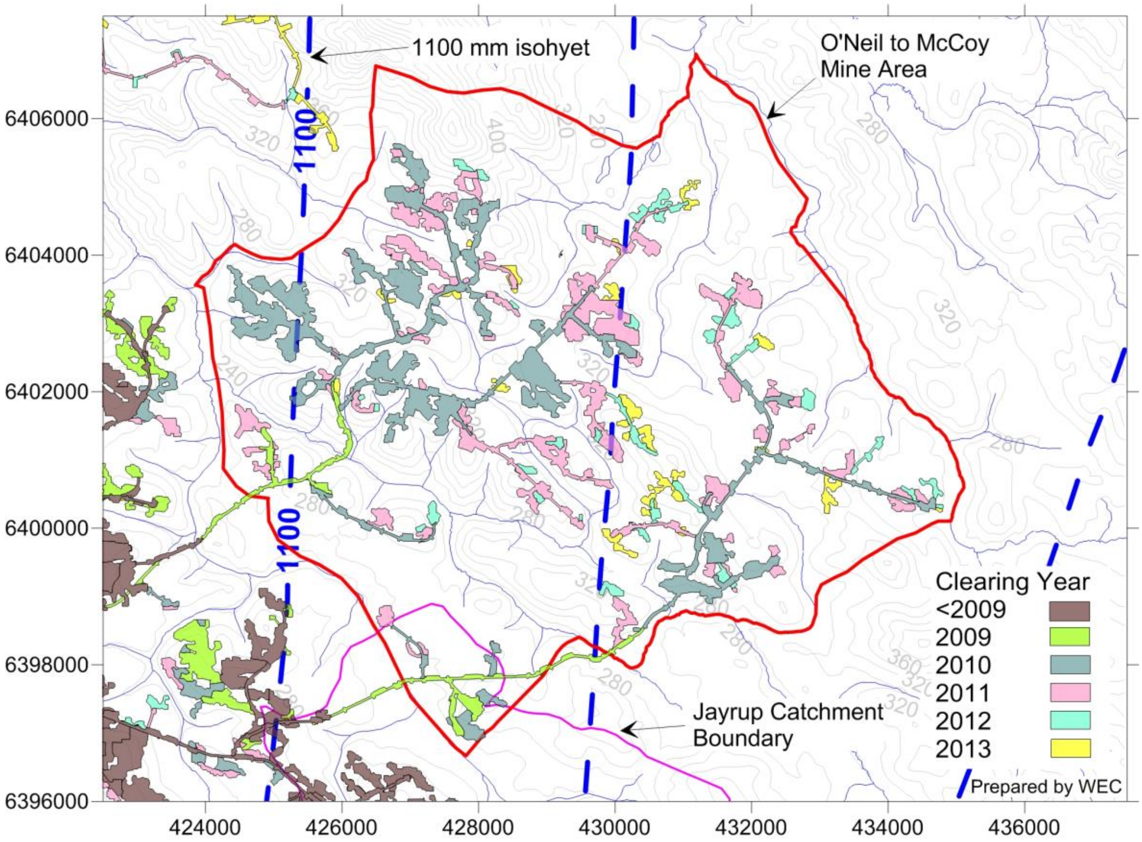

Figure 5: Clearing by year for the O'Neil-to-McCoy mine area.

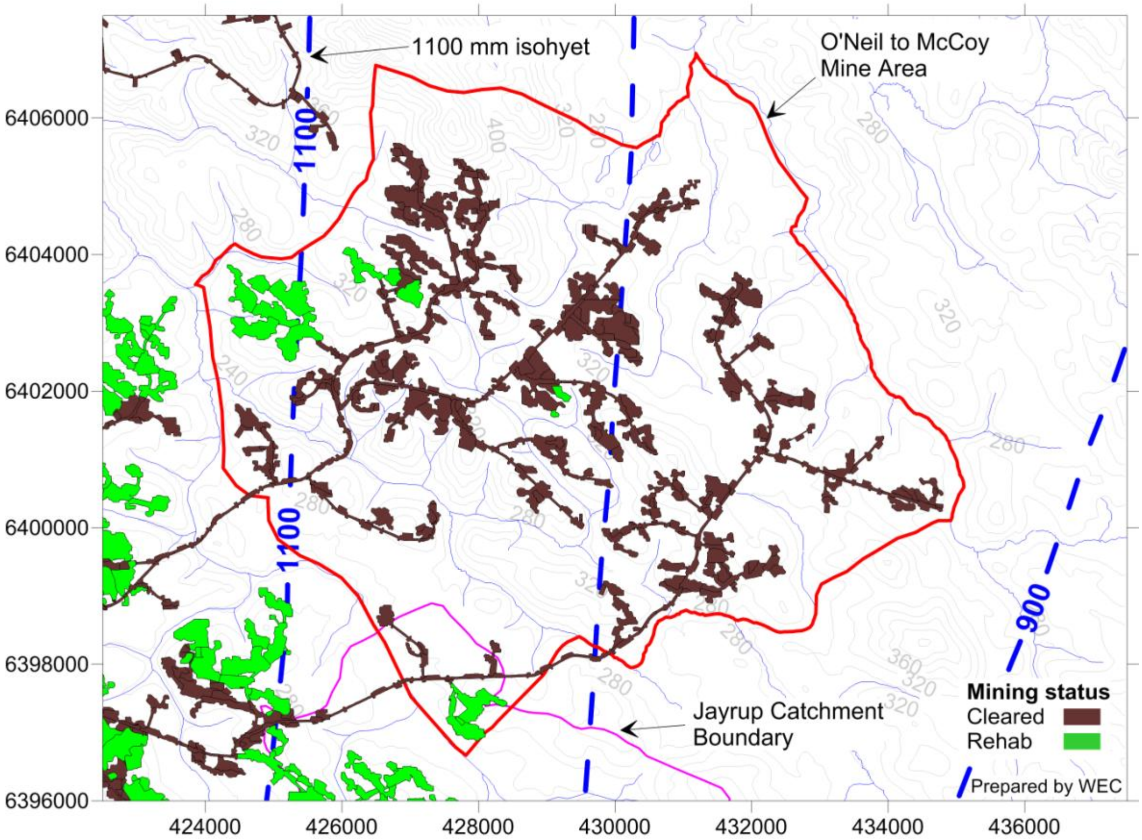

Figure 6: Clearing and post-mining rehabilitation areas for the O'Neil-to-McCoy mine area.

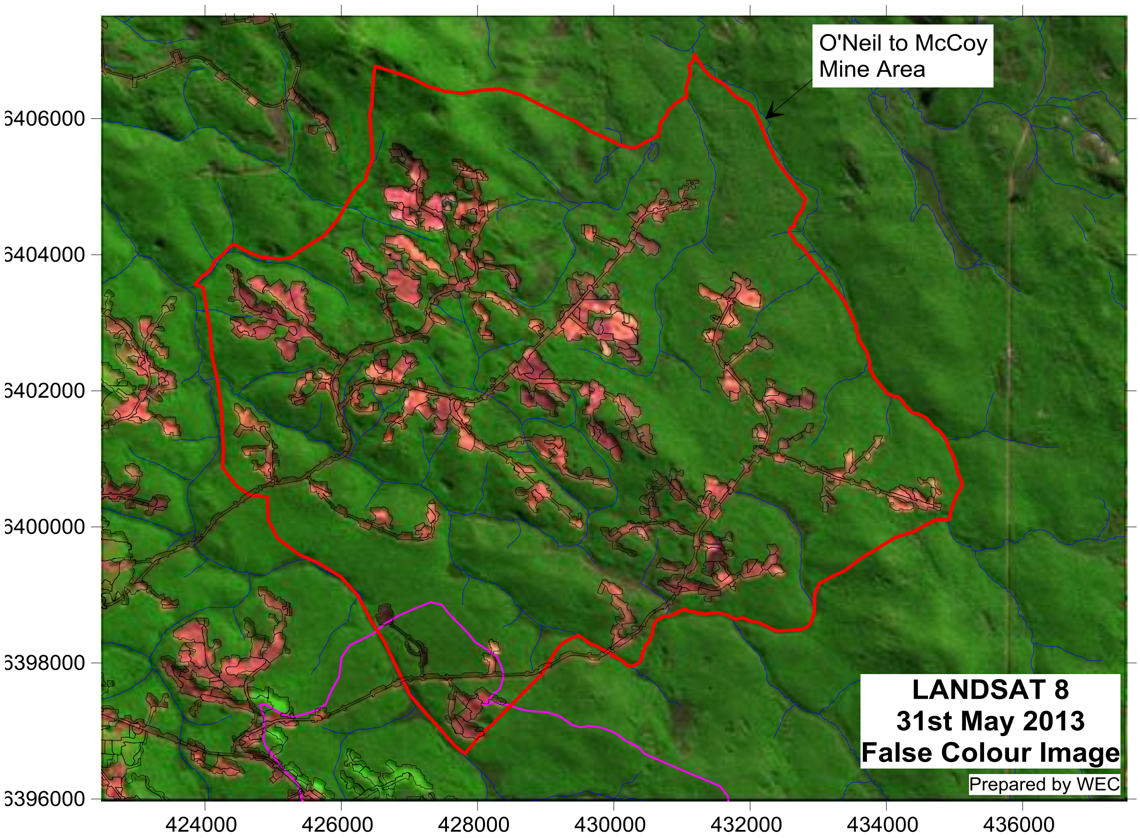

Figure 7: Clearing outlines for the O'Neil-to-McCoy mine area plotted over a false colour Landsat 8 image for 31st May 2013.

2.3 Climatic Setting

Before embarking on a review of the monitoring results per se, it is best to first review the historical rainfalls and to understand the trends they contain, particularly those associated with the recent below-average rainfall period. Figure 8 shows the annual-rainfalls (see author's note 2) for the Big Brook pluviometer for the period 1889 to present. These are synthetic annual rainfalls obtained from the SILO Data Drill system (http://www.longpaddock.qld.gov.au/silo/, see author's note 3).

It can be seen there have been four distinct periods of rainfall behaviour for the Big Brook site. Firstly, there was a period of below-average rainfall which persisted up to the dry year of 1914. This was followed by a period of average and above average rainfall from 1915 till 1974. The year 1975 marks the beginning of a below-average period where, while the mean for this period is below the record average, there are still frequent moderate-rainfall years which rise above the mean. The fourth, and last, period is from 2001 to date where only one year (2003) rose above the long-term mean, with the rest below it. There are only eight years with a rainfall below 800 mm/yr in the complete 124 years of record; three of these occur from 2001 on, including the historically-low year of 2010.

Author's note 2: This report uses the standard calendar year, 1st January to 31st December, for annual reporting of data. A water year of 1st May to 30th April is often used in south-west W.A., but this is not considered advisable here as it fails to consider the effects of summer rainfall on the antecedent conditions of a catchment and its effect on streamflow in the coming winter.

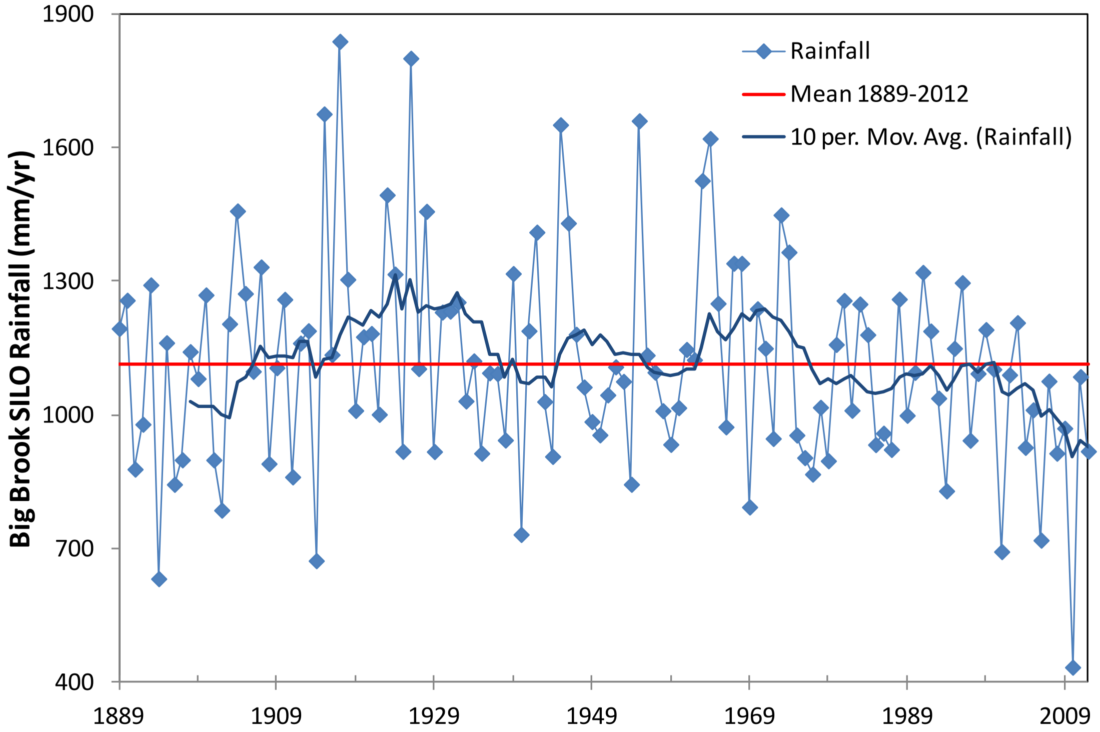

Figure 8: Synthetic annual rainfalls from 1889 for the Big Brook pluviometer obtained using the SILO Data Drill system, see author's note 3.

A close inspection of Figure 8 reveals two components to the rainfall behaviour of the recent period compared to the balance of the dataset. Firstly, as already said, there is the over-representation of low rainfall years, there are three years with a rainfall below 800 mm/yr in the 12 years since 2001. Secondly, there is the general absence of high-rainfall years with this trend extending back to 1975; there has been only one year with a rainfall above 1,300 mm/yr since 1975 (1,321 mm in 1991, or once in 37 years), while there are some 20 years above 1,300 mm/yr in the balance of the record (once every 4.5 years). Given the non-linearity of hydrological processes on the Darling Plateau due to its dominance by evapo-transpiration, with the high-rainfall years producing proportionally much more groundwater recharge and streamflow, it is likely that the general lack of high-rainfall years since 1975 is a greater driver of the presently observed hydrological decline than is the increase in the number of below-average rainfall years.

In the following review of the hydrological responses in the O'Neil-to-McCoy area to mining, it appears that the recent below-average rainfall period is acting as a dampener on the observed responses, and the hydrological behaviour is much more subdued than would be expected if we were studying a treatment during a wetter period.

Author's note 3: There a number of significant differences between the annual rainfalls for Big Brook from the SILO Data Drill system (http://www.longpaddock.qld.gov.au/silo/) and those previously developed for long time-series by using observed data, e.g. those for the Cameron West catchment by Croton *et al*. (2011). However, for the purposes of Figure 6, the SILO Data Drill data has been deemed sufficient.

3. O'NEIL TO McCOY GROUNDWATER DATA

3.1 Groundwater Level Data

Figure 9 shows the location of the 96 deep piezometers that have been established in the O'Neil-to-McCoy mine area. Appendix A provides hydrograph plots for all available water-level data for these piezometers.

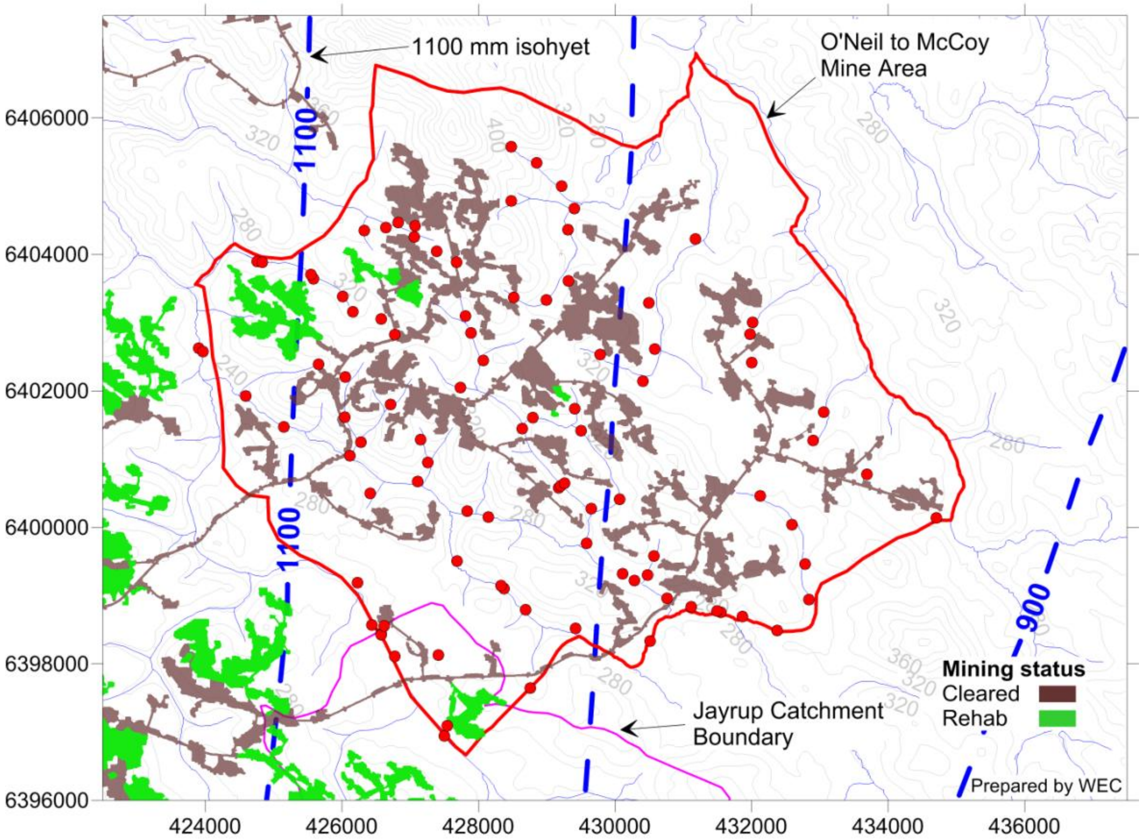

Figure 9: Location of the 96 deep groundwater piezometers in the O'Neil-to-McCoy mine area.

To make the groundwater-level data easier to interpret, we have divided the data into annual minimum depth-to-water classes of <1.0 m, 1 to 2 m, 2 to 4 m and >4 m. The map for 2009 is shown in Figure 10. Like the estimated depth-to-water map shown in Figure 4, it can be seen that a number of valley-floor piezometers had a groundwater depth of <1.0 m in 2009. However, the historically-low rainfall of 2010 had a marked effect, with groundwater declines (increasing depth-to-water) for every piezometer in the O'Neil-to-McCoy mine area regardless of its position or association with activities such as clearing for mining. Figure 11 shows the minimum depth-to-water for 2010 plotted in the same manner as in Figure 10. There are only seven piezometers in 2010 with groundwater within a metre of the surface, whereas there were 24 in 2009. There was some recovery in 2011 (Figure 12), when there were 11 piezometers with groundwater within a metre of the surface, and nine in 2012 (Figure 13).

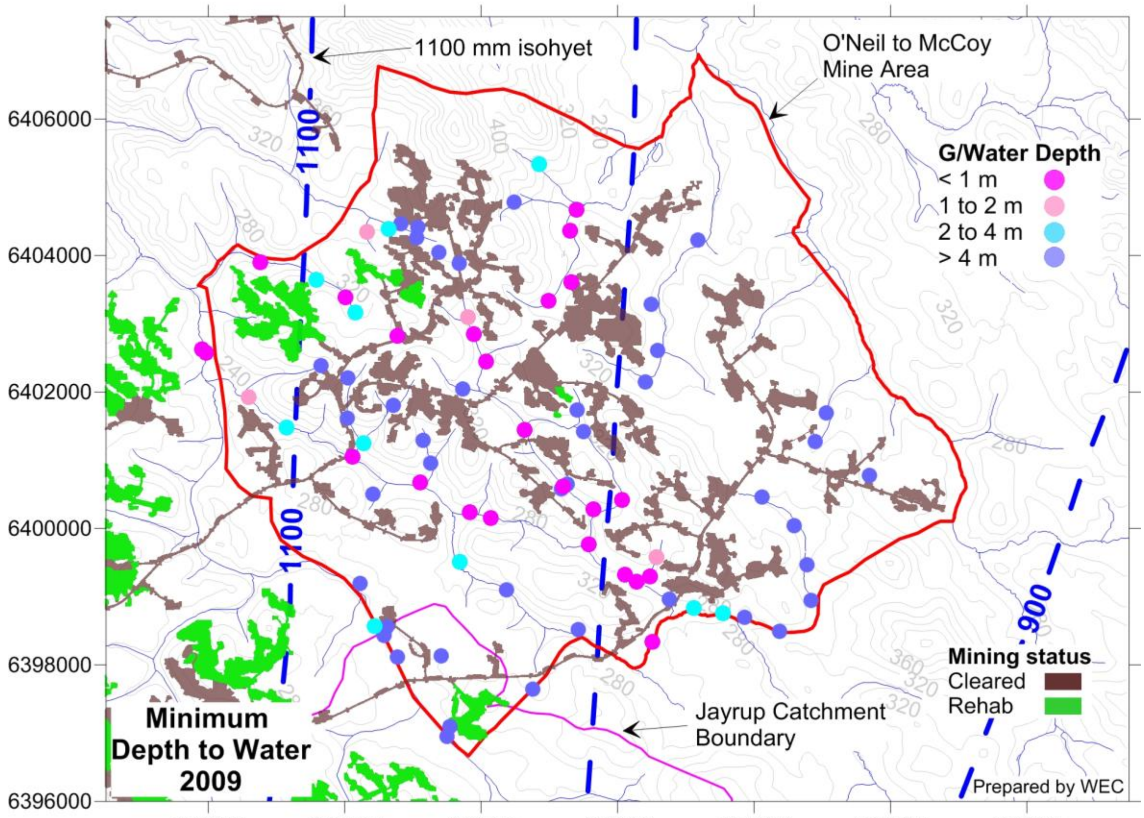

Figure 10: Minimum depth-to-water for 2009 for the groundwater piezometers in the O'Neil-to-McCoy mine area.

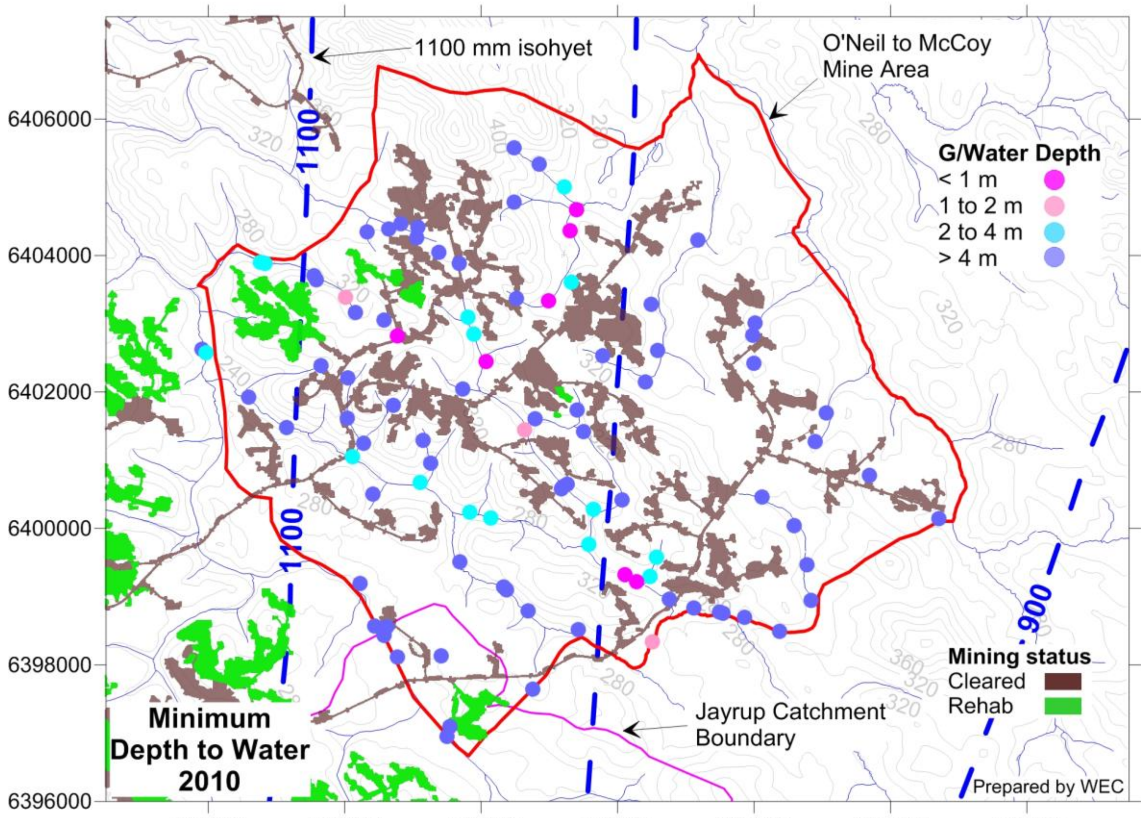

Figure 11: Minimum depth-to-water for 2010 for the groundwater piezometers in the O'Neil-to-McCoy mine area.

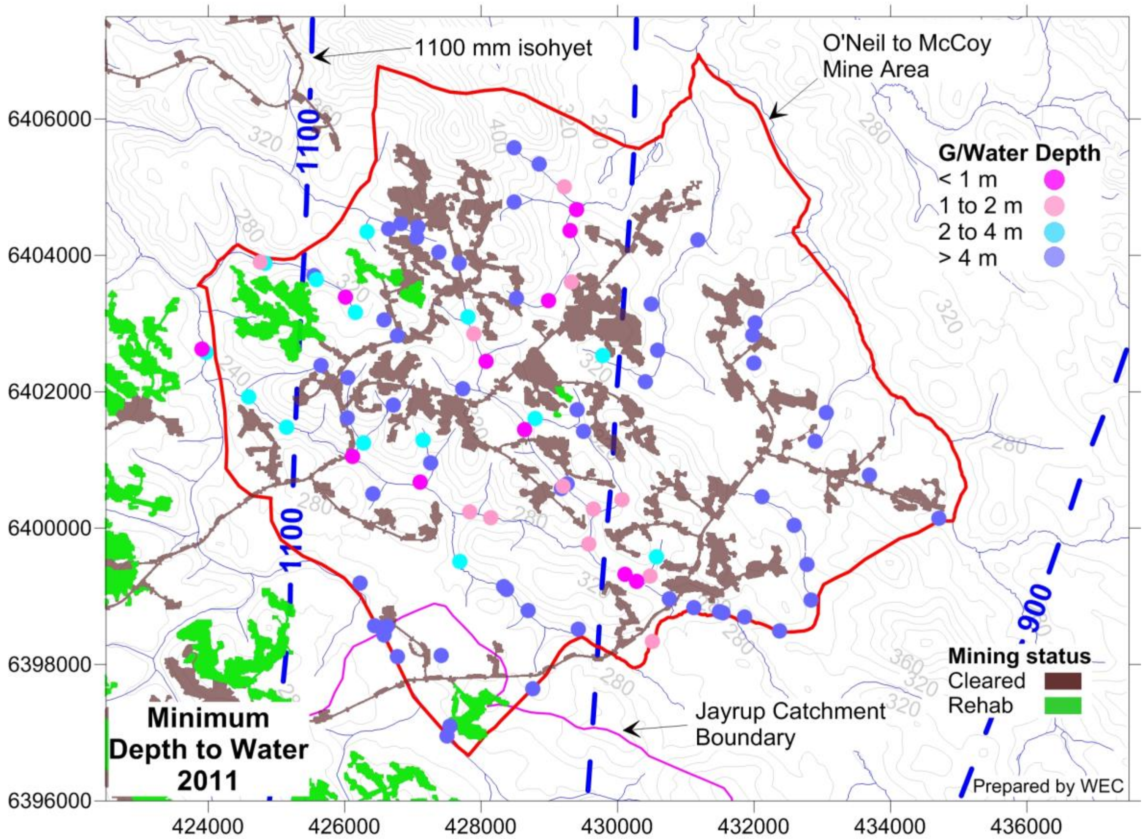

Figure 12: Minimum depth-to-water for 2011 for the groundwater piezometers in the O'Neil-to-McCoy mine area.

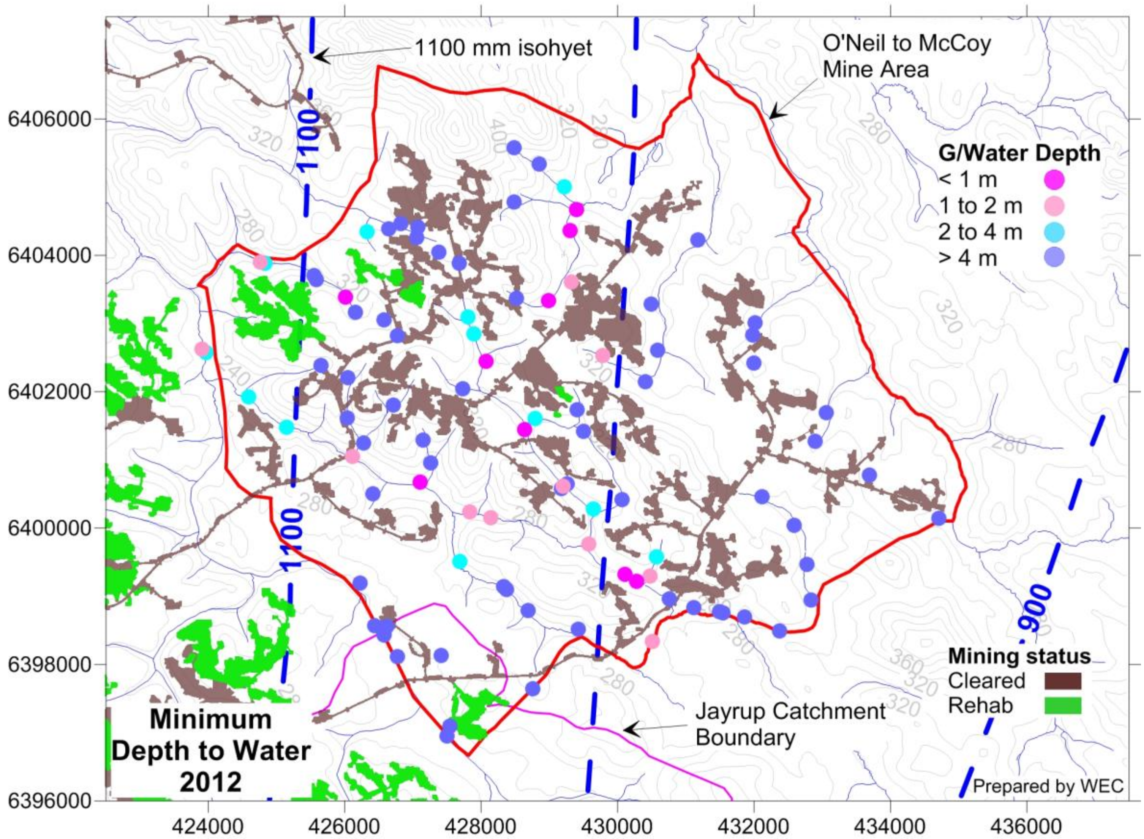

Figure 13: Minimum depth-to-water for 2012 for the groundwater piezometers in the O'Neil-to-McCoy mine area.

The most useful plots when interpreting the responses to mining are those where the difference in level is compared between years. It was seen in Figure 5 that only a small area within the O'Neil-to-McCoy mine area was cleared in 2009 and so 2009 can for all practical purposes be taken as the last pre-treatment year.

Figure 14 is a plot of the change in minimum depth-to-water from 2009 to 2011 for the groundwater piezometers in the O'Neil-to-McCoy mine area. As mentioned already, the historically-low rainfall of 2010 caused every piezometer in the O'Neil-to-McCoy mine area to decline in 2010, so this year isn't being used in the comparisons. It can be seen that between 2009 and 2011 only two piezometers have risen in level, K4312-1A and K4322-1A, with all others essentially equivalent between years in level or declining.

Figure 15 is a plot of the change in minimum depth-to-water from 2009 to 2012 for the groundwater piezometers in the O'Neil-to-McCoy mine area. While there are differences between Figures 14 and 15, these are not large and there are only three piezometers with significant rises between 2009 and 2012: K4312-1A and K4322-1A as per Figure 14, plus K4419-3A in the south of the O'Neil-to-McCoy mine area. However, K4419-3A has a doubtful hydrograph shape and has been dropped from the following analysis.

Figure 16 shows a difference plot between 2011 and 2012. While the majority of the piezometer water-levels are still essentially equivalent or declining, nine piezometers in this plot have risen in 2012 to be 0.25 m or more above the 2011 level; all these rising piezometers are closely associated with mining. The groundwater hydrographs for these nine piezometers are shown in Figure 17, and their rises compared to control piezometers are tabulated in Table 1.

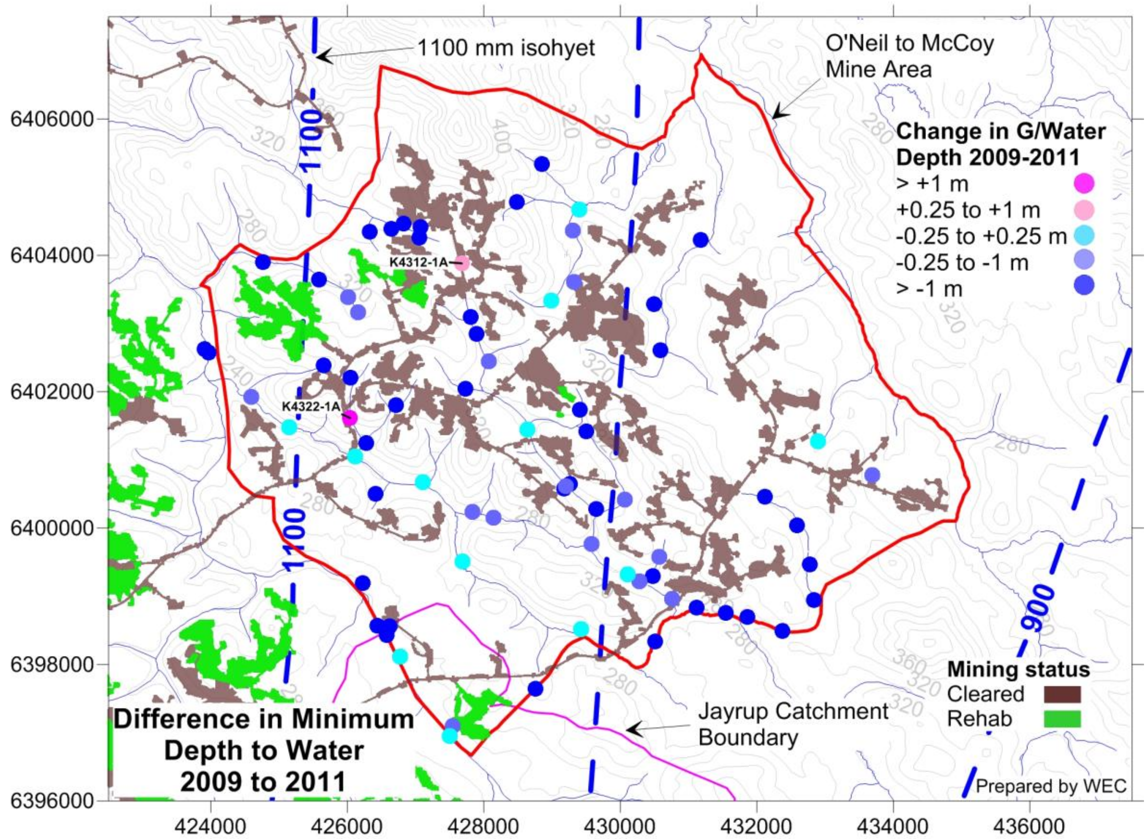

Figure 14: Change in minimum depth-to-water from 2009 to 2011 for the groundwater piezometers in the O'Neil-to-McCoy mine area.

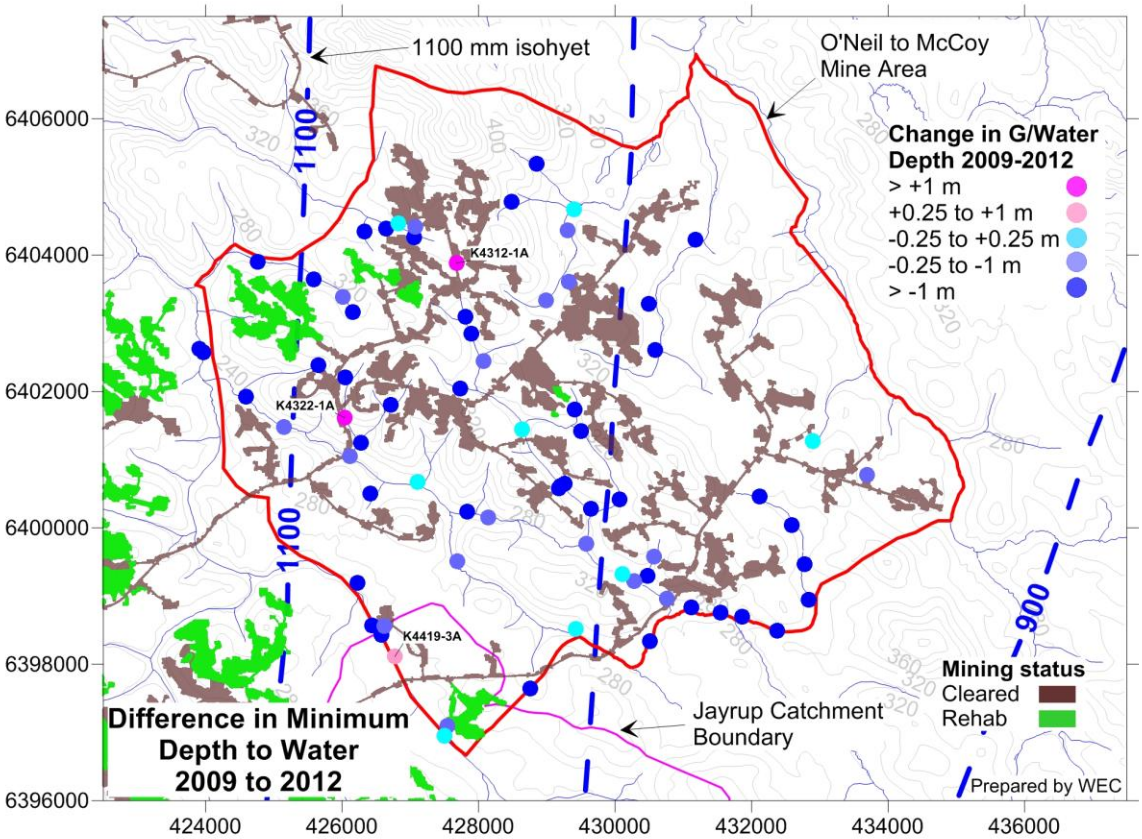

Figure 15: Change in minimum depth-to-water from 2009 to 2012 for the groundwater piezometers in the O'Neil-to-McCoy mine area.

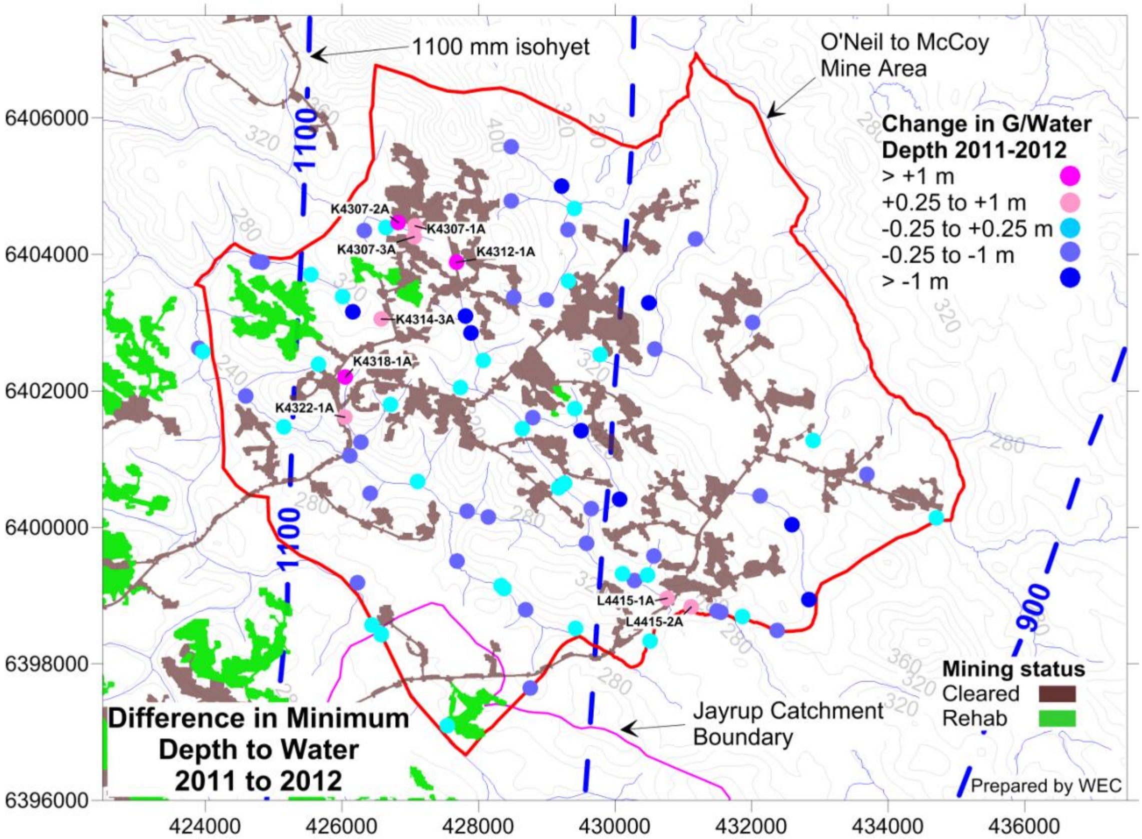

Figure 16: Change in minimum depth-to-water from 2011 to 2012 for the groundwater piezometers in the O'Neil-to-McCoy mine area.

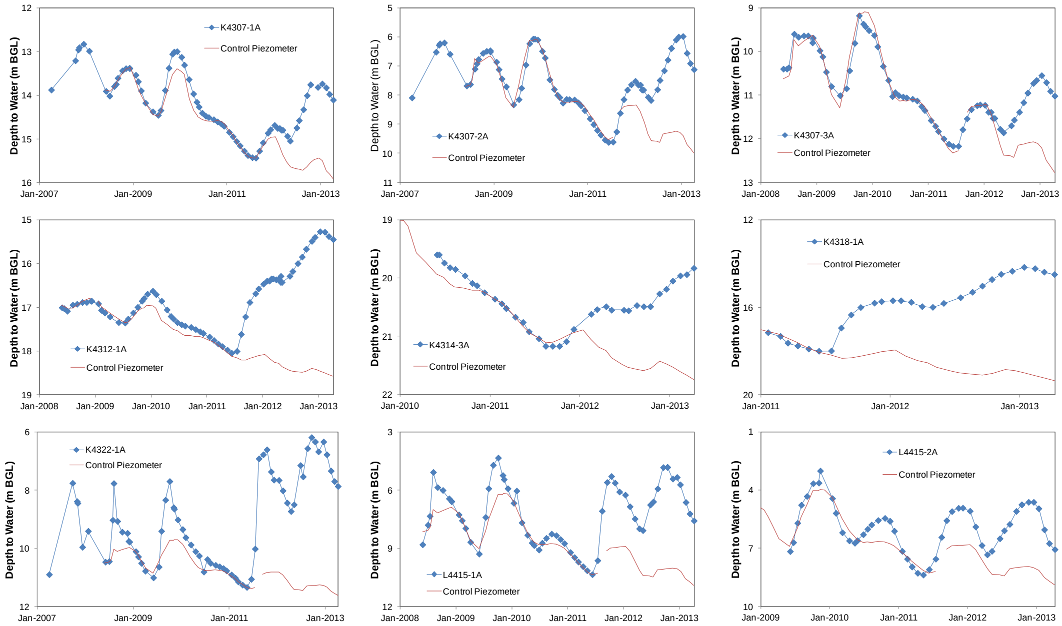

Figure 17: Piezometer hydrographs for the nine responsive piezometers labelled in Figure 16.

Table 1: Groundwater rises for the nine responsive piezometers labelled in Figure 16 compared to control piezometers.

Piezometer	**Easting** (m GDA94)	**Northing** (m GDA94)	**Rise Relative to Control** (m)
K4307-1A	427071	6404417	1.8
K4307-2A	426823	6404469	3.4
K4307-3A	427058	6404259	1.5
K4312-1A	427676	6403882	3.2
K4314-3A	426576	6403052	1.6
K4318-1A	426050	6402205	4.8
K4322-1A	426040	6401615	4.0
L4415-1A	430763	6398962	5.4
L4415-2A	431115	6398834	3.2

It can be seen from Figure 17 and Table 1 that significant rises have occurred relative to the control piezometers. The largest rise was 5.4 m for L4415-2A which is directly downslope of a crescent-shaped area of mining. It can be seen from Figure 17 that the historically-low rainfall of 2010 caused there to be little or no hydrograph peak in 2010, and this in turn makes the rises due to mining essentially a restoration of the levels in 2009 rather than a rising to higher levels.

3.2 Groundwater Salinity Data

It was shown in the previous section via Figures 10 to 13 that the yearly peak groundwater-level in the valley-floors of the O'Neil-to-McCoy mine area was at or near the surface for a number of streams over this period. This implies that groundwater would have interacted with streamflow generation during this period and would also be having an effect on stream salinity. Such a process was expected, and was discussed at length by Croton & Dalton (2010). A key component of the modelling by Croton & Dalton (2010) was an assumed salinity for the discharging groundwater that was contributing to streamflow. They produced a map of groundwater salinity for the O'Neil-to-McCoy mine area from the groundwater salinity data collected in November 2009 (Figure 18). To assess whether the groundwater salinity has been varying due to the mining process, follow-up groundwater salinity collection programmes have been undertaken each year; Figure 19 shows the latest for November 2012, and Figure 20 shows the difference between 2009 and 2012. It can be seen that there is consistency between the two datasets, with only one piezometer, K4408-2A, having a significant increase in salinity (223 mg/L in 2009 to 638 mg/L in 2012). Interestingly, this piezometer is distant from any mining, so the variation almost certainly relates to some factor other than mining.

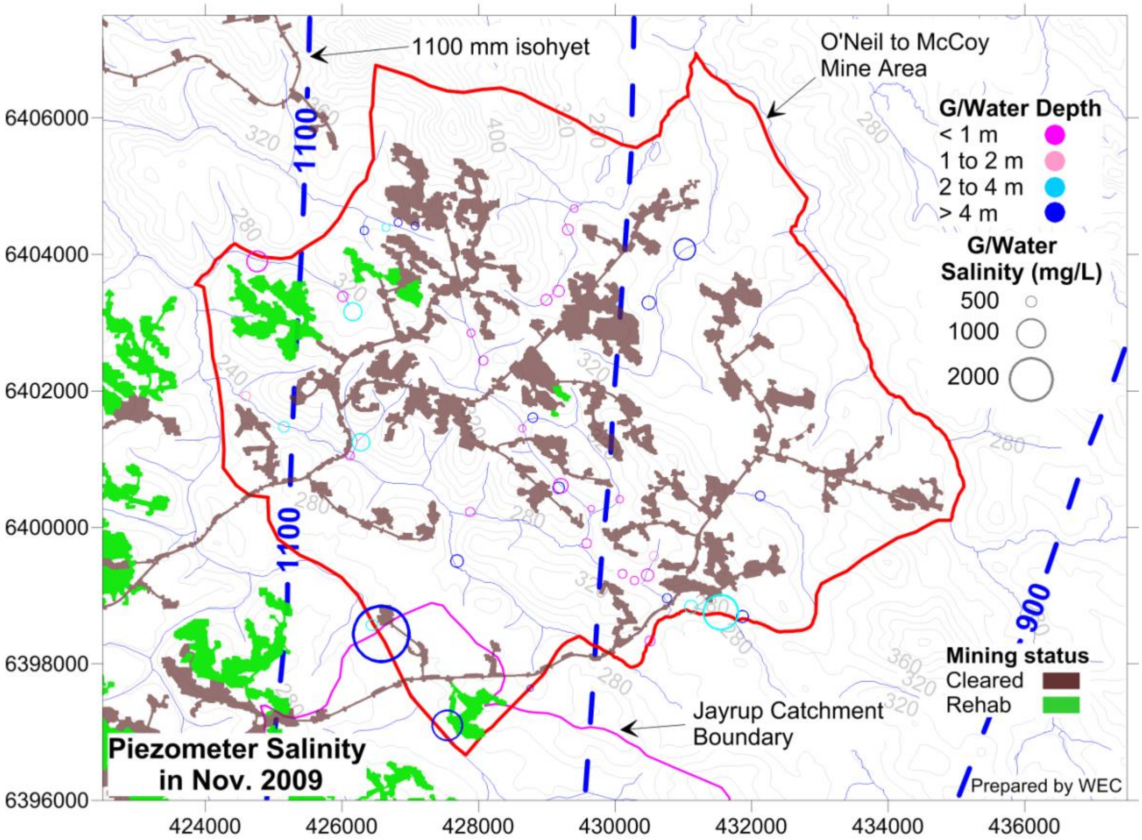

Figure 18: Piezometer groundwater salinities from the pump-sampling programme in November 2009.

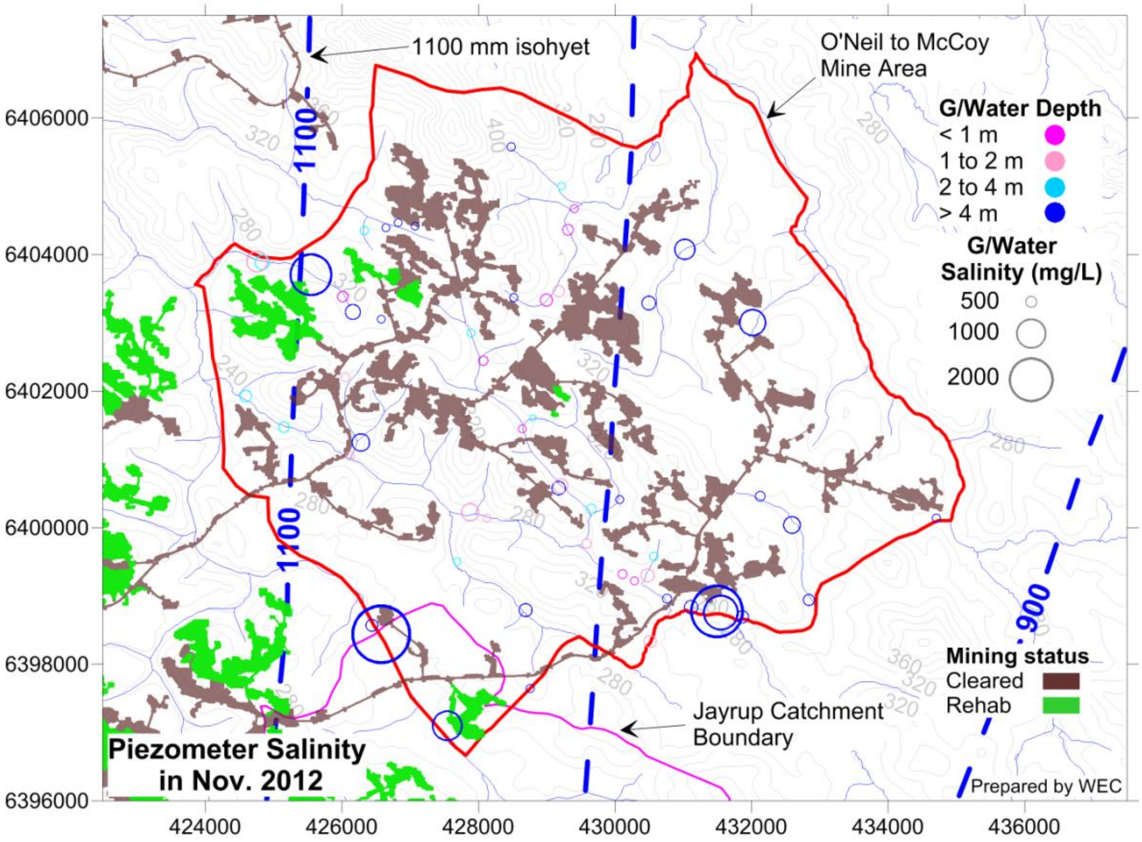

Figure 19: Piezometer groundwater salinities from the pump-sampling programme in November 2012.

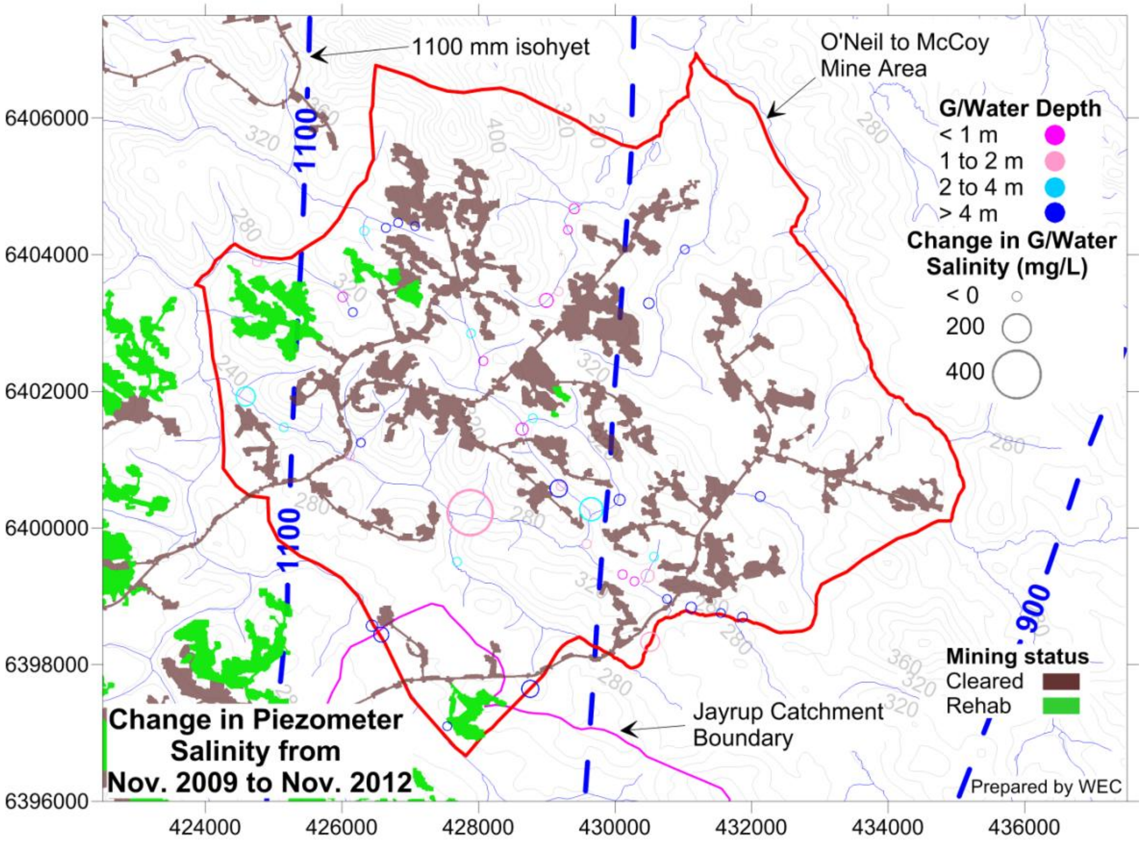

Figure 20: Change in piezometer groundwater salinities from November 2009 to November 2012.

4. O'NEIL TO McCOY STREAM DATA

The stream salinity monitoring for O'Neil-to-McCoy mine area can be divided into three parts. Firstly, there is a manual sampling network that covers the area and is intended to track any local changes (Figure 21). Secondly, there is a continuous-logger network consisting of five sites, CD01 to CD05, at which stream-salinity loggers have been deployed by Alcoa. Most of the mining in the O'Neil-to-McCoy area is contained within the catchments of these loggers. Croton & Dalton (2008) developed these manual-sampling and logger networks, and the BHC recommended to the MMPLG that O'Neil-to-McCoy mining should proceed providing this monitoring was undertaken by Alcoa.

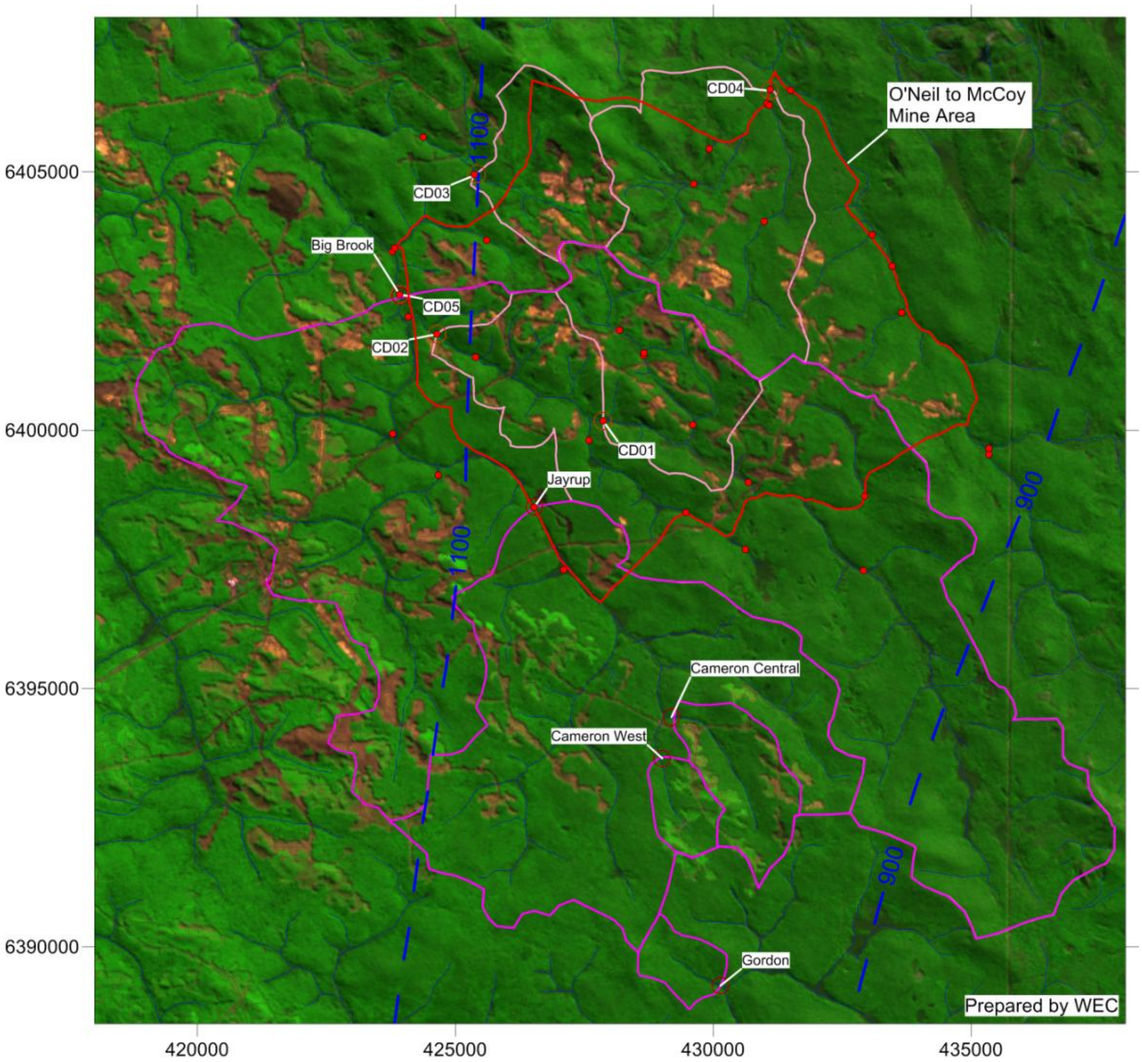

Figure 21: Manual stream-salinity sampling points, and continuous-logger stream-salinity monitoring points and their catchments, for the O'Neil-to-McCoy mine area. Also shown are the DoW monitoring sites and catchments associated with the Cameron Experimental Mining Exercise (CEME).

The third component to the monitoring system is the gauging stations operated by the Department of Water (DoW); this is both the long-term station of Big Brook and the catchments which are part of the Cameron Experimental Mining Exercise (CEME) (Croton, *et al.* 2011). The CEME stations are the treated catchments of Cameron West, Cameron Central and Jayrup and the control catchment of Gordon (Figure 21). It should be noted that continuous-logger site CD05 is located at the Big Brook gauging-station to allow direct comparison between the Alcoa and DoW monitoring. Big Brook is also important in that it contains not just the CEME, but also the majority of the O'Neil-to-McCoy mine area and a significant proportion of the mining directly to the west.

In the following sections the manual sampling will be analysed first, followed by the continuous-logger, and then the DoW gauging stations. Comparisons will then be made between all the data types. Key dates in the analysis are: first significant clearing for mining in the Big Brook catchment was 2003; first clearing for mining in Jayrup was 2004; first clearing for mining in the O'Neil-to-McCoy area was 2009, with significant clearing from 2010.

4.1 Manual Stream-Salinity Data

There are 36 stream monitoring sites in and around the O'Neil-to-McCoy mine area and all the available data for them has been tabulated in Appendix B. To show the relativity between the sample values for 2009, 2011 and 2012, Figure 22 is a proportional plot of the October values for each of these years. October has been used as it tends to be the month in which flow is still expected to occur, but is after the winter streamflow peaks and is therefore indicative of the salinity of the interflow/baseflow component of streamflow. It can be seen that stream salinity has increased year by year for all sites which have at least two readings, this is for both sites that have and don't have mining in their catchments. There is also a degree of complication in Figure 22 in that some sites weren't visited in 2009, hence they lack a value for this year even though there was probably flow at them for that year. As well, the lower rainfall in 2012 compared to the other two years, and the resultant reduction in flows, has meant that a number of sites lack a salinity value for that year. This lack also has a geographical component in that the first and second-order catchments on the eastern side of the O'Neil-to-McCoy mine area are generally lacking a 2012 value while the first and second-order catchments on the western side generally have one. This is probably associated with two factors, the east-west trend of rainfall with higher rainfall on the western side, and the level of topographic incision with the eastern section being much flatter than the west.

There are seven sites in Figure 22 which are directly associated with the O'Neil-to-McCoy mine area and have October data for all three years; these have been labelled in Figure 22 and are plotted as a time-series in Figure 23(a). Of these points, BF06 was established as a control; and Figure 23(b) is a plot with the October salinity values for each year for the other sites plotted as a percentage of the BF06 October value for that year. The 2011 value for SE43 has plotted below BF06, all other values in Figure 23(b) have plotted above BF06. The averages for the non-control values are 107% in 2011 and 124% in 2012. Figure 23(c) is a plot, with the salinity values as differences for a year compared to the control value for that year; these are an estimate of salinity change due to mining. The averages for the non-control values are 8 mg/L in 2011 and 39 mg/L in 2012. All the plots in Figure 23 show a geographical component, with the values for the westerly sampling points being higher than those for the easterly ones.

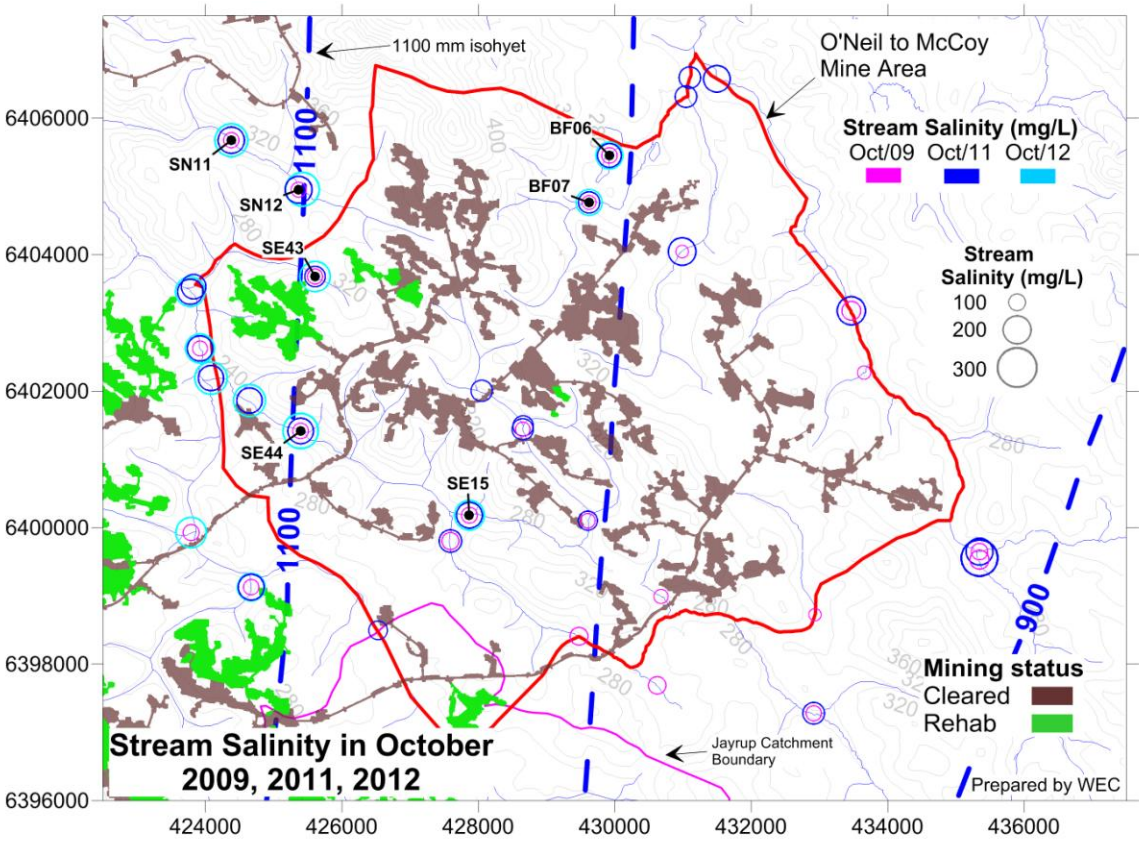

Figure 22: October 2009, 2011 and 2012 stream-salinity values for the manual stream-salinity sampling-points for the O'Neil-to-McCoy mine area.

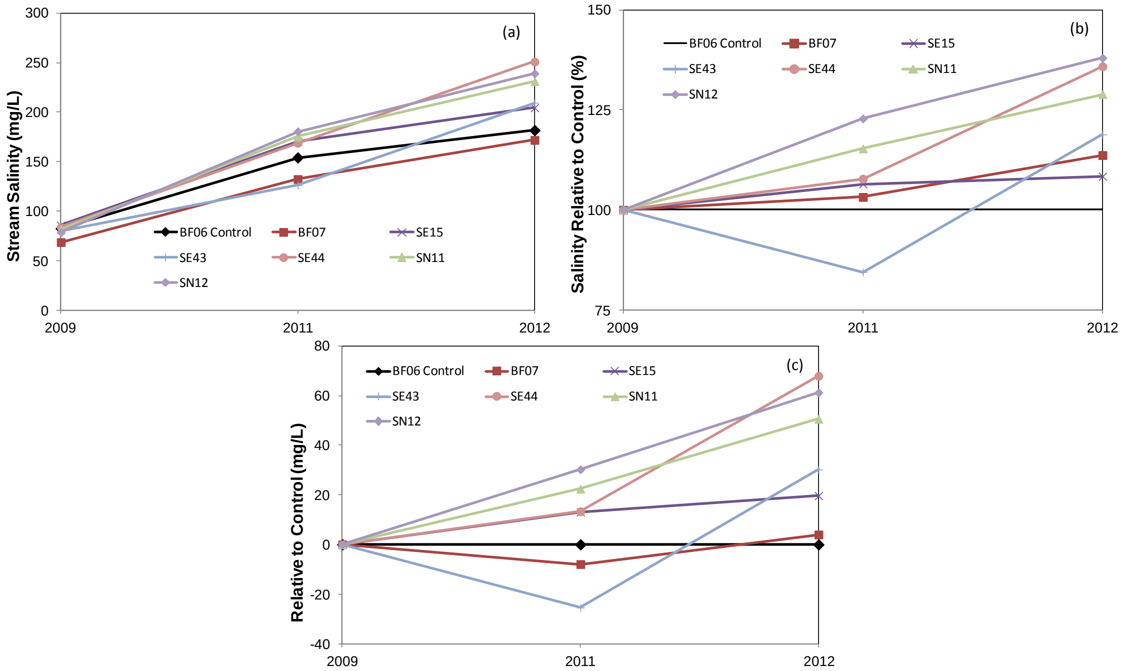

Figure 23: October 2009, 2011 and 2012 stream-salinity values for the manual stream-salinity sampling-points for the O'Neil-to-McCoy mine area that have October data for all three years.

4.2 Continuous-Logger Stream-Salinity Data

Five continuous-logger stream-salinity sites were established by Alcoa in 2009, their locations are shown on Figure 21. The sites were run-of-stream, where the logger was placed on the stream-bed on an anchor block and was open to the passing flow. There was full data-recovery for these loggers in 2009 and 2011; for 2010, any flows that did occur at the sites were generally insufficient to inundate the loggers and no real data was available for this year. For 2012 there was complete failure of all five loggers and no useful logger-data was collected at any of the sites. There was however manual check-samples still being collected at the sites in 2012, and these are plotted in Figure 24 along with the continuous data for 2009 and 2011. Various options were considered for creating a synthetic record for 2012, including using the Big Brook salinity trace and morphing it to fit the manual check-samples. However, while this of course can be done for CD05 as it is located at the Big Brook gauging-station, realistic traces could not be developed for the other four sites and the only useful 2012 data for these remains the manual check-samples.

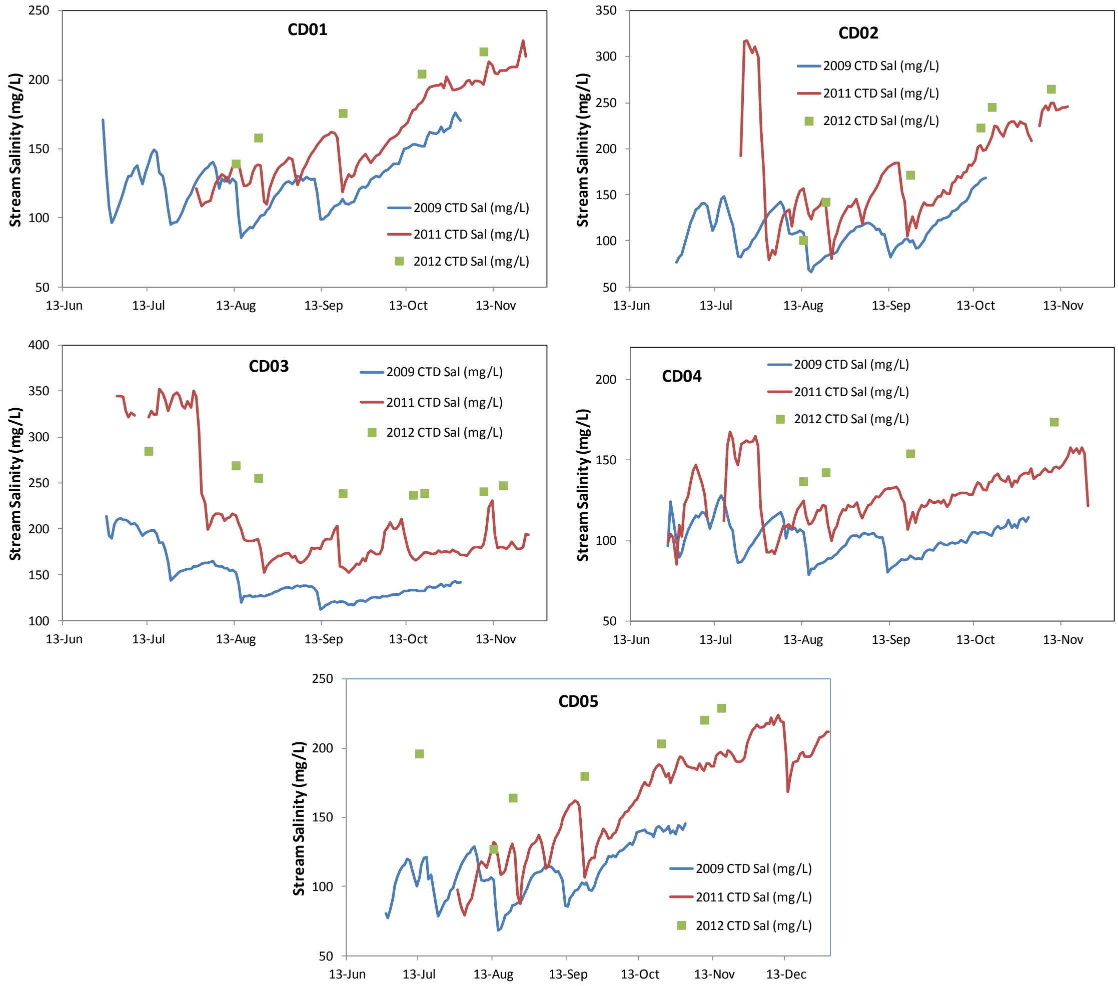

Figure 24: Stream salinity traces for the stream-salinity logger sites in the O'Neil-to-McCoy mine area.

As was seen for the manual stream-salinity sampling points discussed in the previous section, there has been a steady rise in stream salinities for successive years for the stream-salinity logger sites. Again the question is, how much of this is related to mining responses, and how much relates to climatic factors, particularly the historically-low rainfall of 2010. Figure 25 is a plot of the differences in average salinity between the two years 2012 and 2009 for the five stream-salinity logger sites plotted against the percentage area of clearing for mining up to the beginning of 2012. The catchment areas for CD02 and CD05 have been adjusted by the deletion of that 27.3 km^2 of the catchments that is flowing from the forest tributary to the east This lower rainfall area (isohyet average of 900 mm/annum) has markedly lower streamflow than the O'Neil-to-McCoy mine area; it was not possible to obtain a salinity sample from this catchment stream in 2012, implying it had little to no flow in that year.

As streamflows are not being measured at any site other than CD05, where the Big Brook gauging station is located, it isn't possible to calculate flow-weighted salinities and those in Figure 25 are simple averages. Despite this limitation and that associated with the lack of continuous data for 2012, it appears likely from Figure 25 that there is some relationship between the area cleared for mining and the salinity difference. The intercept of 39 mg/L is an estimate of the natural increase independent of clearing for mining.

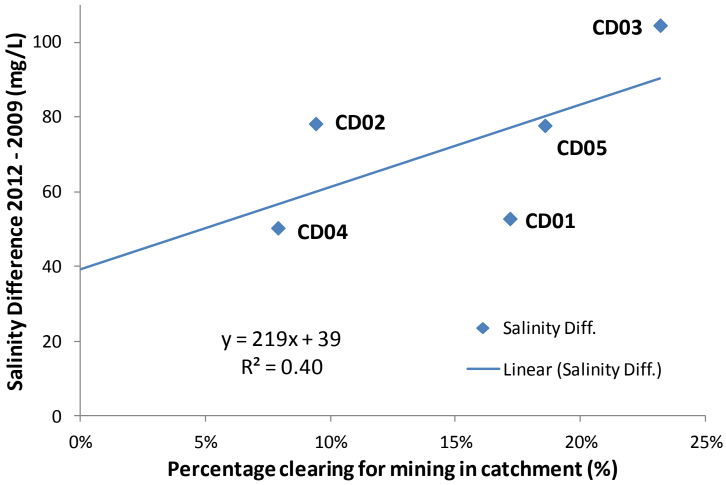

Figure 25: Salinity difference between 2012 and 2009 for continuous-logger sites plotted against the percentage area of clearing for mining up to the beginning of 2012.

4.3 DoW Data

4.3.1 Gordon

Gordon is the control catchment that was established as part of the CEME. It is a small catchment of only 2.1 km^2, but was established at the time as no larger alternatives presented themselves. Figure 26(a) is a plot of the annual rainfall vs. streamflow relation for Gordon with the data divided into two groups, that up to and including 2002 and that from 2003 on. This division is chosen because it matches with the first significant clearing in the Big Brook catchment (Figure 21). Two things are readily apparent from Figure 26(a). Firstly, the relationship between rainfall and streamflow isn't strong with low R^2 values and a wide scatter in the points. Secondly, 2011 and 2012 have both plotted well below all the other years; it appears that the historically-low rainfall of 2010 has "dried" the catchment to such a level that streamflow hasn't recovered during either of these years. Figure 26(b) is a plot of rainfall vs. stream salinity for Gordon catchment. While 2011 has plotted slightly above mid-level in this graph, 2012 has plotted at the top. Figure 27(a) is a plot of annual streamflow vs.

stream salinity for Gordon; again 2011 has plotted fairly consistently with the other years while 2012 has plotted at the top.

Figure 27(b) is a plot of streamflow vs. flowdays for Gordon, flowdays are defined as days with an average flow of 0.2 L/sec or more (17 m^3/day). For 2011 there is a respectable number of flowdays at 59 days, but for 2012 there are only six flowdays. The total flow for 2012 was only 0.17 mm/yr or 357 m^3/yr (0.357 ML/yr), as well the saltload for 2012 totalled only 35 kg/yr. Such small flow volumes and saltloads for 2012 make it a year for which Gordon can't be confidently used as a control for the other catchments. There was 793 ML/yr of flow for Big Brook (5.3 mm/yr) and the saltload was 110 tonnes/yr; these are 2,200 and 3,100 times as much as Gordon.

Interestingly however, if Gordon is accepted for the moment as a salinity control and is processed as an unweighted or simple average in the same way as for the continuous-logger sites in Figure 25, the increase in average salinity between 2009 and 2012 is 19 mg/L (108 – 89). While this is half the Figure 25 intercept of 39 mg/L (zero area of clearing for mining), it would still be considered confirmation of the regression in Figure 25, though it does imply that the natural increase may be overestimated in Figure 25. However, as already discussed, Gordon 2012 data is questionable and alone isn't sufficient grounds to revise the preceding analysis.

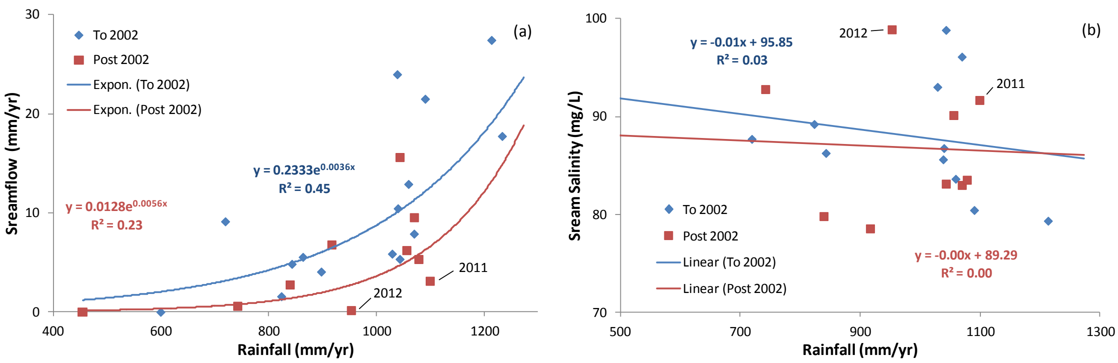

Figure 26: Gordon annual rainfall vs. streamflow and rainfall vs. stream-salinity divided into two periods, up to 2002 and post 2002.

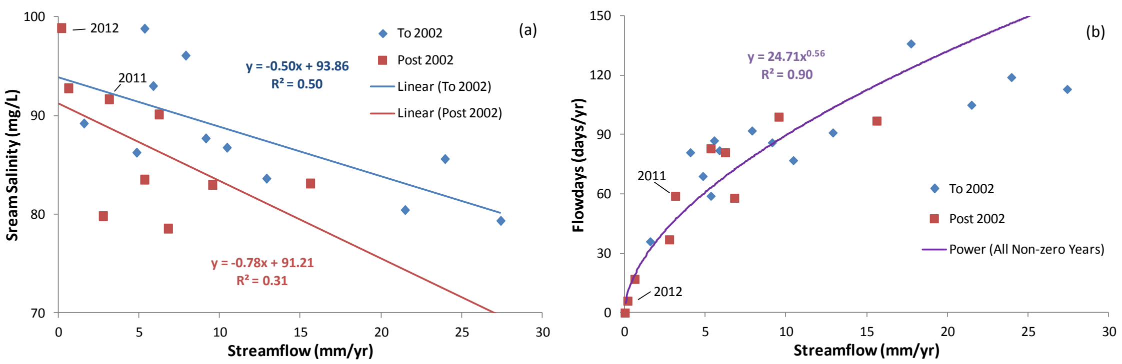

Figure 27: Gordon annual streamflow vs. stream-salinity and streamflow vs. flow-days divided into two periods, up to 2002 and post 2002.

Figure 28 is a plot of the daily salinities for Gordon for the years 2009, 2011 and 2012. With the exception of the shorter flow durations, this graph is similar in form to those given in Figure 24 for the stream-salinity logger sites in the O'Neil-to-McCoy mine area.

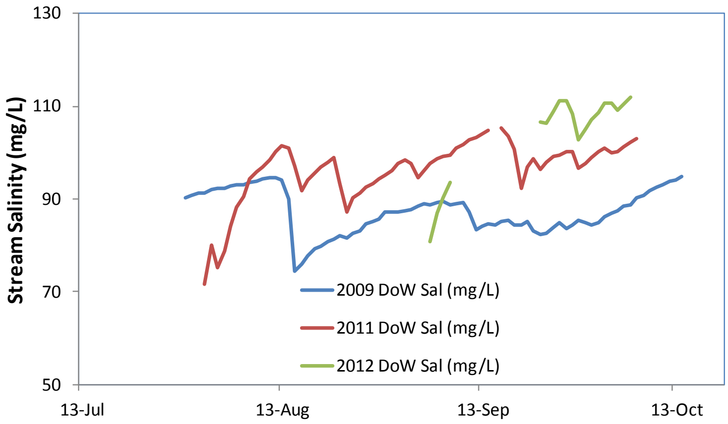

Figure 28: Gordon daily stream salinities for 2009, 2011 and 2012.

4.3.2 Jayrup

Jayrup is the medium-scale treated catchment within the CEME and has an area of 45.5 km^2, the first-order treated catchments of Cameron West and Central are sub-catchments of it (Figure 21). Figure 29(a) is a plot of the annual rainfall vs. streamflow relation for Jayrup with the data divided into two groups, that up to and including 2002 and that from 2003 on. This division is chosen as it matches with the first significant clearing in the Big Brook catchment (Figure 21). Two things are readily apparent from Figure 29(a). Firstly, unlike Gordon, the relationship between rainfall and streamflow is strong with high R^2 values, 0.94 and 0.85. Secondly, like Gordon, 2011 and 2012 have both plotted well below all the other years, but unlike Gordon, there is still significant flow in 2012. Figure 29(b) is a plot of rainfall vs. stream salinity for Jayrup catchment; unlike Gordon, both 2011 and 2012 have plotted mid-level in this graph. Figure 30(a) is a plot of annual streamflow vs. stream salinity for Jayrup; again 2011 and 2012 have plotted fairly consistently with the other years. However, before reading too much into these differences in salinity behaviour between Jayrup and Gordon, the freshness and small range of the salinity readings needs to be noted; the range of annual average-salinities for Jayrup is 71 mg/L to 83 mg/L (12 mg/L) and for Gordon is 79 mg/L to 99 mg/L (20 mg/L). Neither range is large, and small errors in measurement, including sensor drift, could be driving some of the observed variation between catchments. Figure 30(b) is a plot of streamflow vs. flowdays for Jayrup, flowdays are defined as days with an average flow of 0.5 L/sec or more (43 m^3/day). For 2011 there are 93 flowdays and for 2012 there are 63 flowdays. The 2012 flowdays' value for Jayrup is markedly different to the six days for Gordon.

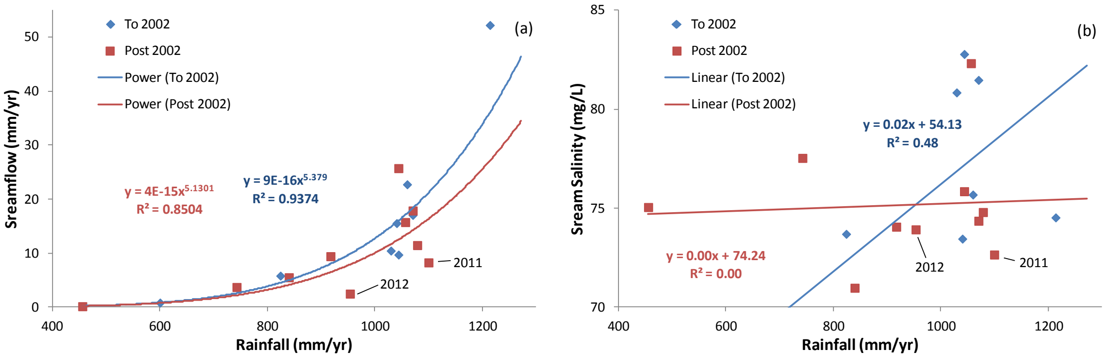

Figure 29: Jayrup annual rainfall vs. streamflow and rainfall vs. stream-salinity divided into two periods, up to 2002 and post 2002.

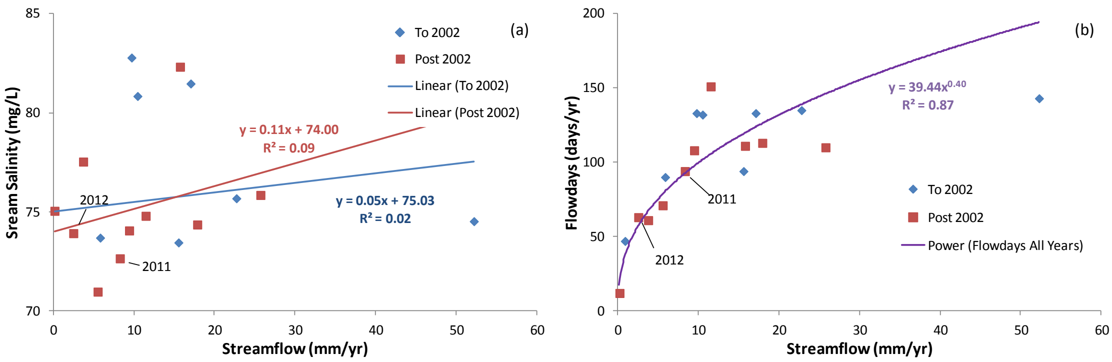

Figure 30: Jayrup annual streamflow vs. stream-salinity and streamflow vs. flow-days divided into two periods, up to 2002 and post 2002.

Figure 31 is a plot of the daily salinities for Jayrup for the years 2009, 2011 and 2012. This graph has a much higher activity level than that for Gordon in Figure 28; this is consistent with the larger flows and apparently greater hydrological activity level of Jayrup compared to Gordon.

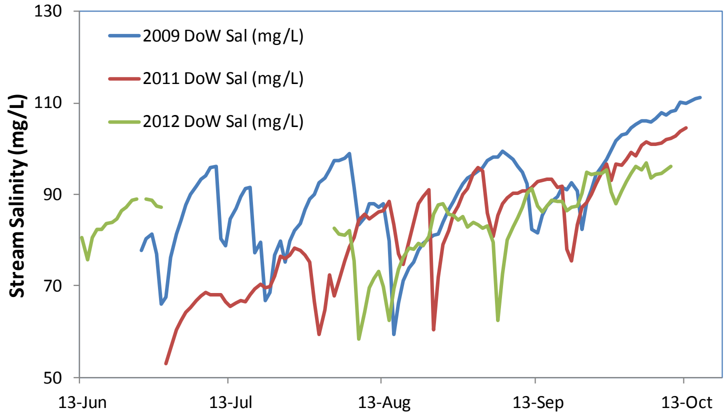

Figure 31: Jayrup daily stream salinities for 2009, 2011 and 2012.

4.3.3 Big Brook

The Big Brook catchment includes the CEME, the majority of the O'Neil-to-McCoy mine area, and a significant proportion of the mining directly to the west of these areas (Figure 21); its catchment area is 149 km^2. Figure 32(a) is a plot of the annual rainfall vs. streamflow relation for Big Brook with the data divided into two groups, that up to and including 2002 and that from 2003 on. This division is chosen as it matches with the first significant clearing in the Big Brook catchment (Figure 21). In terms of the strength of the annual rainfall vs. streamflow relation, Big Brook with R^2 values of 0.69 and 0.50 falls midway between Gordon and Jayrup. However, 2011 for Big Brook, while still plotting below the regression, is clustered with the other years rather than in an isolated pairing with 2012. 2012 has plotted below all the other years, but there is still significant flow in 2012.

Figure 32(b) is a plot of rainfall vs. stream salinity for the Big Brook catchment, this graph is introducing a new behaviour that wasn't observed for either Gordon or Jayrup. 2011 has plotted in the general grouping while 2012 has plotted well above. Also, while it is plotting in-line with two of the upto-2002 years (1998 and 2001), it is well above all the post-2002 values.

Figure 33(a) is a plot of annual streamflow vs. stream salinity for Big Brook; 2011 has plotted with the other post-2002 years while 2012 has plotted at the top of the graph and like Figure 32(b) has associated itself with the upto-2002 years of 1998 and 2001. Given the range of annual salinity values for Big Brook, 93 mg/L to 138 mg/L (45 mg/L), these variations appears to be a genuine catchment response. Figure 33(b) is a plot of streamflow vs. flowdays for Big Brook, flowdays are defined as days with an average flow of 0.5 L/sec or more (43 m^3/day). For 2011 there are 121 flowdays and for 2012 there are 129 flowdays; this exceeding of flowdays for 2011 by those in 2012 is the first such occurrence, both Gordon and Jayrup had markedly less flowdays in 2012 than 2011.

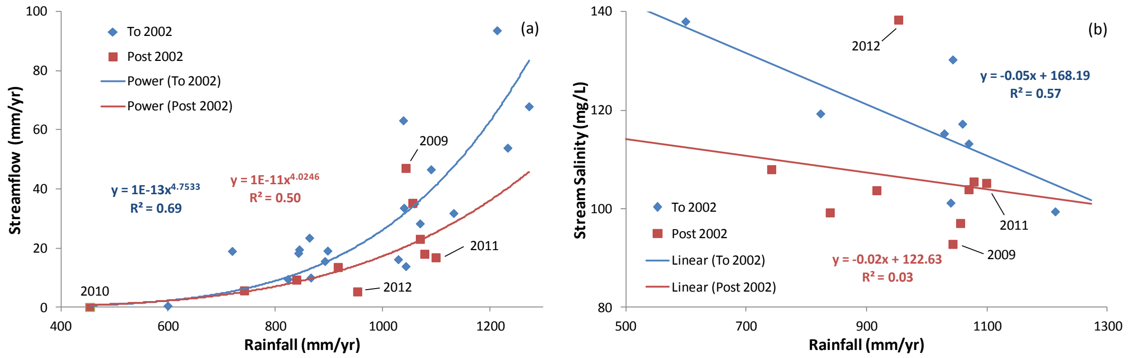

Figure 32: Big Brook annual rainfall vs. streamflow and rainfall vs. stream-salinity divided into two periods, up to 2002 and post 2002.

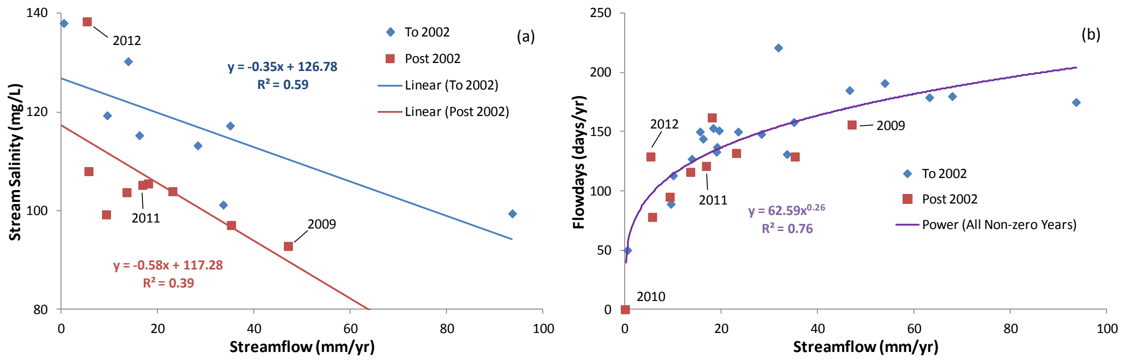

Figure 33: Big Brook annual streamflow vs. stream-salinity and streamflow vs. flow-days divided into two periods, up to 2002 and post 2002.

Figure 34 is a plot of the daily salinities for Big Brook for the years 2009, 2011 and 2012. This graph is interesting in that it displays a much higher range of variation in salinity in the early period of 2012 than it does for 2009 and 2011. Peak to trough ranges are around 40 to 80 mg/L in 2012 while they were 40 mg/L or less in 2009 and 2011. Jayrup has similar ranges for all years of about 20 mg/L; and Gordon has so little flow in 2012 that a range can't really be defined for that year, with ranges of 10 to 20 mg/L in the other years. This increased range of salinities for Big Brook in 2012 probably indicates a mining-related response with the higher salinities being associated with increased groundwater discharge.

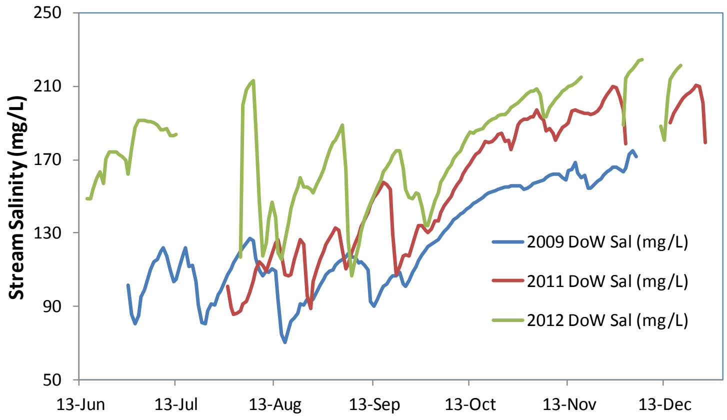

Figure 34: Big Brook daily stream-salinities for 2009, 2011 and 2012.

5. ESTIMATION OF MINING RELATED RESPONSES

5.1 Stream Response for the O'Neil-to-McCoy Mine Area

Figure 25 in Section 4.2 was the salinity difference between 2012 and 2009 for continuous-logger sites plotted against the percentage area of clearing for mining up to the beginning of 2012. A linear relationship was passed through the five data points on this graph and the intercept, or zero-mining salinity-increase, was obtained. If Figure 25 is plotted with the intercept set to zero, then we have an estimate of the increase in stream salinity in 2012 for these five sites due to mining. However, such a plot would be based on a simple average rather than a flow-weighted average for the stream salinity. The only continuous-logger site at which flow was measured was CD05 (Big Brook). For the DoW data for Big Brook for 2012, the simple-average stream-salinity is 174 mg/L while the flow-weighted average is 138 mg/L, which gives a factor of 79% as the adjustment between simple average and flow-weighted average for 2012 stream salinities. Applying this same factor to the continuous-logger sites produces Figure 35 as the flow-weighted increases in stream salinity in 2012 due to mining.

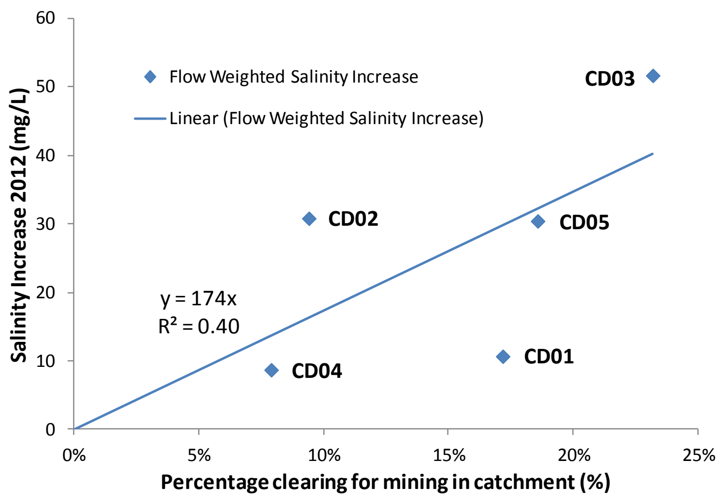

Figure 35: Estimated flow-weighted stream-salinity increase for 2012 for the continuous-logger sites plotted against the percentage area of clearing for mining up to the beginning of 2012.

Further, if the streamflow per unit area for Big Brook (mm/yr) is assumed to be the streamflow per unit area for the other continuous-logger sites (mm/yr), an estimate of stream saltload increase can be developed using the catchment areas for the logger sites in combination with the estimated flow-weighted stream-salinity increase for 2012 from Figure 35. These equate to the estimates given in Table 1. It needs to be noted that as CD05 is at the Big Brook gauging station, then the saltload increase for this site includes more than just that emanating from the O'Neil-to-McCoy mine area; Big Brook will be considered further in the next sub-section.

Table 1: Estimated mining-related stream-saltload increases for 2012 for the continuous-logger sites. Note that for CD02 an adjusted catchment area without the forest tributary to the east is being used (34.3 km^2).

Logger Site	**Stream Salinity Increase 2012** (mg/L)	**Catchment Area** (km^2)	**Stream Saltload Increase 2012** (tonnes)
CD01	11	9.7	0.85
CD02	31	61.6 (34.3)	8.67
CD03	52	6.8	2.86
CD04	9	17.8	1.27
CD05	30	149.4	30.4

5.2 Stream Response for Big Brook to Mining

In the previous sub-section an estimate was made for the stream-salinity and saltload increases due to mining for the continuous-logger site CD05, this site is also the Big Brook gauging station. Now using DoW data only, an estimate will be made of the change in stream salinity due to mining for Big Brook. If simple differences in flow-weighted stream salinity between 2009 and 2012 are calculated for the three DoW catchments we get: a 16 mg/L increase for Gordon, a 2 mg/L reduction for Jayrup, and a 45 mg/L increase for Big Brook. Further, if Gordon is accepted as control, despite its limitations in terms of lack of flow in 2012, then the increase for Big Brook due to mining in 2012 would be the overall increase for Big Brook (45 mg/L) minus the increase for Gordon (16 mg/L) which is 29 mg/L, or essentially the same as the increase of 30 mg/L that was obtained in the previous section using the five continuous-logger sites to develop a relation between percentage clearing for mining and increase in stream salinity.

Obtaining the same increase in stream salinity in 2012 due to mining for Big Brook using two independent methods implies that this estimate is probably realistic. Qualitative support for this also comes from Figures 32(b) and 33(a); in both of these figures the year 2012 is plotting separate to all other post-2002 years and it appears to be about 30 mg/L higher than would be expected if climate was the only variable.

5.3 Response of Inflows to the Serpentine Reservior

The Water Corporation produces a monthly estimate of stream inflows into the Serpentine Reservoir and these were used with the data above to create an estimate of the effect of mining the O'Neil-to-McCoy area on stream-inflow salinities to Serpentine Reservoir. The first step in this process is to determine the saltloads for the areas of mining at O'Neil to McCoy; most of the mine areas are contained within continuous-logger sites CD02, CD03 and CD04, though there are some areas on the eastern and western sides which aren't. Table 2 lists the estimated saltload increases for 2012 due to mining, including the calculated increase for Big Brook in total and that part of Big Brook which is outside of the O'Neil-to-McCoy mine area. These have been combined in Table 3 with the stream-inflow flow-rate estimate for 2012 and the estimated reservoir-pond volume on 31st Dec 2012, to calculate the changes in inflow salinity and reservoir-pond salinity due to both mining of O'Neil-to-McCoy area and mining of the balance of the Big Brook catchment.

Table 2: Estimated mining-related stream-saltload increases for 2012 for the continuous-logger site catchments and the other misc. areas of the O'Neil-to-McCoy area. Also included are the mining-related saltloads for Big Brook.

Catchment	**Stream Saltload Increase for 2012** (tonnes)
CD02	8.67
CD03	2.86
CD04	1.27
Western side extra mine areas	1.52
Eastern side extra mine areas	0.95
Total for O'Neil-to-McCoy	**15.3**
Total for Big Brook	30.4
Big Brook Outside of O'Neil-to-McCoy	**21.6**

Table 3: Mining-related stream-inflow and reservoir-pond saltload calculations for 2012 for the Serpentine Reservoir.

Item	**Flow and Volume** (ML)	**Saltload** (kg)	**Salinity** (mg/L)
Total reservoir inflow	5,047		
Change in reservoir inflow due to O'Neil-to-McCoy mining		15,268	3.0
Change in reservoir inflow due to Big Brook mining outside of O'Neil-to-McCoy		21,557	4.3
Reservoir-pond volume Dec 2012	34,366		
Change in reservoir-pond salinity due to O'Neil-to-McCoy mining		15,268	0.44
Change in reservoir-pond salinity due to Big Brook mining outside of O'Neil-to-McCoy		21,557	0.63

5.4 Comparison with Croton & Dalton (2010) Predictions

Croton & Dalton (2010) estimated the likely effects of mining the O'Neil-to-McCoy area on the salinity of the Serpentine Reservoir, and the BHC recommended to the MMPLG that O'Neil-to-McCoy mining should proceed based on these estimates. Their worst-case scenario estimated the change in stream-inflow salinity for the Serpentine

Reservoir for 2012 was 4.9 mg/L for mining of the O'Neil-to-McCoy area; this was based on assuming that the historical rainfall for 1997 to 2007 inclusive fell for the period 2009 to 2019 and that 2012 was represented by the historical year 2000. They also produced a best-case scenario based on the historical rainfalls for 1970 to 1980 and obtained a 2.6mg/L increase in 2012 based on the rainfall for 1973 being used to simulate that year. The present estimated value of 3.0 mg/L (Table 3) falls between these two estimates and is at the lower end of their range.

What differs markedly between the calculations of Croton & Dalton (2010) and what has actually occurred in the period 2009 to 2012 is the very low actual stream-inflow rates to Serpentine Reservoir (see author's note 4). Table 4 lists the actual inflows and the predictive scenarios used by Croton & Dalton (2010). While the actual and the scenario flows for 2009 fall within a similar range, the historically-low rainfall of 2010 caused the actual inflows in that year to be an order of magnitude less than the two scenarios. As well, the drawing down of catchment soil-water storages by the low rainfall of 2010 has caused a knock-on effect so that the inflow in 2011 is less than the inflow in 2009 (18.7 GL/yr compared to 30.9 GL/yr), even though the rainfall in 2011 was greater than in 2009. There is a similar occurrence for 2012: the actual 2012 inflow was 5.0 GL/yr while the rainfall of 2012 was greater than in 2008 when the inflow was 15.2 GL/yr, a threefold difference.

Table 4: Actual stream-inflows for Serpentine Reservoir and those assumed by Croton & Dalton (2010).

Year	**Actual Stream-inflows** (GL/yr)	**Worst Case Stream-inflows** (GL/yr)	**Best Case Stream-inflows** (GL/yr)
2009	30.9	22.7	88.5
2010	3.0	24.7	59.3
2011	18.7	25.5	45.8
2012	5.0	41.1	101.3
Total	**57.6**	**114.0**	**294.9**

The net result of all of the above is that while the predictions of stream-inflow salinity changes made by Croton & Dalton (2010) are similar to what has occurred in reality, the large reductions in actual stream-inflow rates has meant that the saltload increases predicted by them are significantly greater than what actually occurred. Given that the salinity of the overall water-supply system is driven by the saltload calculations, that is total salt vs. total water in the system, then it is the saltload of the stream-inflow to Serpentine Reservoir rather than the salinity of the stream-inflow which matters to the overall water-supply. For saltloads, the estimated mining-related saltload increase in 2012 due to actual O'Neil-to-McCoy mining was 15.3 tonnes compared to 361 and 419 tonnes for the two scenario predictions by Croton & Dalton (2010).

Author's note 4: The actual inflows are those estimated by the Water Corporation using a water-balance model of the Serpentine Reservoir. These have been provided to the study by Charles Jeevaraj of the Water Corporation.

6. FUTURE MONITORING RECOMMENDATIONS

The following is a listing of our recommendations as to what monitoring should be continued for the O'Neil-to-McCoy mine area. The monitoring recommendations have been strongly affected by the present climate, and the realisation that the recent past is probably the most likely scenario for the near future. Even this *modus operandi* can lead to overestimates of the true position: Croton & Dalton (2010) assumed that the period 1997 to 2007 was a reasonable worst-case scenario for what would happen from 2009 on; history has disproved this. As discussed in Section 2.3, the present rainfall period is both an increase in the number of low-rainfall years and essentially an absence of high-rainfall years. There have been three years of rainfall below 800 mm/yr in the 12 years since 2001 and only one year of rainfall above 1,300 mm/yr since 1975. If these trends continue then hydrological monitoring of the O'Neil-to-McCoy mine area can be maintained at a much lower level than if rainfall patterns change to a higher state.

Perhaps unexpectedly, the definition of a change that would trigger an increase in monitoring isn't associated with the relative mix of below-average and average rainfall years. With the present level of soil-water storages, an average-rainfall year seems to do little more than maintain the below-average status quo. This was well demonstrated by the recent stream-inflows to Serpentine Reservoir where the above-average year of 2011 followed by the slightly below-average year of 2012 still resulted in well below average stream-inflows to the reservoir.

Instead, the trigger for a possible upward revision of the monitoring would be the occurrence of a rainfall year that was well above average. A suggested threshold for this is at least 1,300 mm/yr for the Big Brook rain-gauge. As discussed in Section 2.3, there has been only one year with a rainfall above 1,300 mm/yr since 1975 (1,321 mm in 1991, or once in 37 years), while there are some 20 years above 1,300 mm/yr in the balance of the record (once every 4.5 years). From a simple water-balance calculation using all the available rainfall and streamflow record for Big Brook, it appears that evapo-transpiration and other misc. losses account for something like 950 mm/yr. Therefore a rainfall of 1,300 mm/yr provides an excess of about 350 mm/yr to be available for soil-water replenishment and streamflow, while a rainfall of 1,000 mm/yr provides only 50 mm/yr, or one seventh, and 950 mm/yr just maintains the soil-water status quo with nothing available for streamflow.

It is proposed that the monitoring programme suggested below be maintained at least until the end of 2015, unless a rainfall year of 1,300 mm/yr or more occurs. The proposed programme has been divided into five segments.

6.1 Continuous-Logger Sites

The present five continuous-logger sites CD01 to 05 were not logged in 2012 due to failure of all five loggers; they were operated successfully from 2009 to 2011. As sites CD01 to 04 cover the majority of the stream outflows from the O'Neil-to-McCoy mine area, it is proposed that these loggers be reinstated (Figure 21). CD05 was placed at the Big Brook gauging-station to allow comparison of the logger data with the DoW station record. Given all the issues with the continuous-loggers, this comparison site should be maintained.

6.2 DoW Stream-Gauges

The two DoW stream gauges of direct interest are Big Brook and Gordon. It is recommended that both still be considered part of the O'Neil-to-McCoy mine area monitoring-programme, though it is likely that Gordon will have so little flow from 2013 on that it can no longer be considered a useful streamflow control.

6.3 Manual Stream-Salinity Sites

There are 36 stream monitoring sites in and around the O'Neil-to-McCoy mine area, many of which have at least some data going back to the early 1990s. In the past there has been an intention to collect regular samples during winter at these sites, though without flow information it is somewhat difficult to place a useful interpretation on this data. One targeted use has been to take the results for the later part of winter, e.g. the October sample, and compare the values between years (e.g. Figure 22). October has been used as it tends to be the month in which flow is still expected to occur, but is after the winter streamflow peaks and is therefore indicative of the salinity of the interflow/baseflow component of streamflow.

It is considered justifiable to continue the October manual-sampling of stream salinity to identify year-to-year changes, but without a definite use for manual sampling in the other parts of the year, sampling outside of October can't really be justified. Also with the October sampling, it is recommended that emphasis be placed on six of the seven sites where values for 2009, 2011 and 2012 have already been obtained, with the other 30 sites being of secondary priority. The seventh site, SN11, was dropped from the primary list as the upstream SN12 site makes it redundant. BF06 has the highest priority of the six primary sites as it is acting as the untreated control. The details for the six primary sites are given in Table 5.

Table 5: Manual stream-salinity sampling-points that are in the primary list.

Site	Easting	Northing
BF06	429920	6405452
BF07	429624	6404763
SE15	427865	6400181
SE43	425606	6403679
SE44	425394	6401416
SN12	425365	6404953

6.4 Groundwater Level Monitoring

There are 96 piezometers on the present monitoring list (see Appendix A). These were strategically placed to be either controls or downslope of mining areas. However, with the present dampened hydrological responses, many of these have little to no response; while others do have a response but that local response is also seen in another, more suitable, piezometer. It was decided that the list could be rationalised to 23 piezometers of which four are controls and 19 are associated with mining. This listing is given in Table 6 and is plotted in Figure 36. Regarding monitoring frequency, presently piezometers have their water-levels manually read on a monthly basis. Due to the dampened responses, it is considered reasonable to reduce the frequency to six weekly, nine times per year.

Table 6: The 23 piezmeters recommended for continued water-level monitoring.

Site	Easting	Northing	Control	Site	Easting	Northing	Control
K4228-1A	428482	6405580	Yes	L4309-2A	428993	6403333	
K4307-1A	427071	6404417		L4309-3A	429318	6403611	
K4307-2A	426823	6404469		L4318-1A	429782	6402532	
K4307-3A	427058	6404259		L4325-1A	428641	6401447	
K4312-1A	427676	6403882		L4410-2A	430111	6399320	
K4314-1A	426010	6403385		L4415-1A	430763	6398962	
K4314-3A	426576	6403052		L4415-2A	431115	6398834	
K4318-1A	426050	6402205		L4419-1A	430515	6398336	
K4320-1A	428070	6402448		M4407-1A	434707	6400139	
K4322-1A	426040	6401615		M4413-1A	432836	6398942	Yes
K4410-1A	426225	6399189	Yes	M4417-1A	432375	6398492	Yes
L4301-1A	429403	6404669					

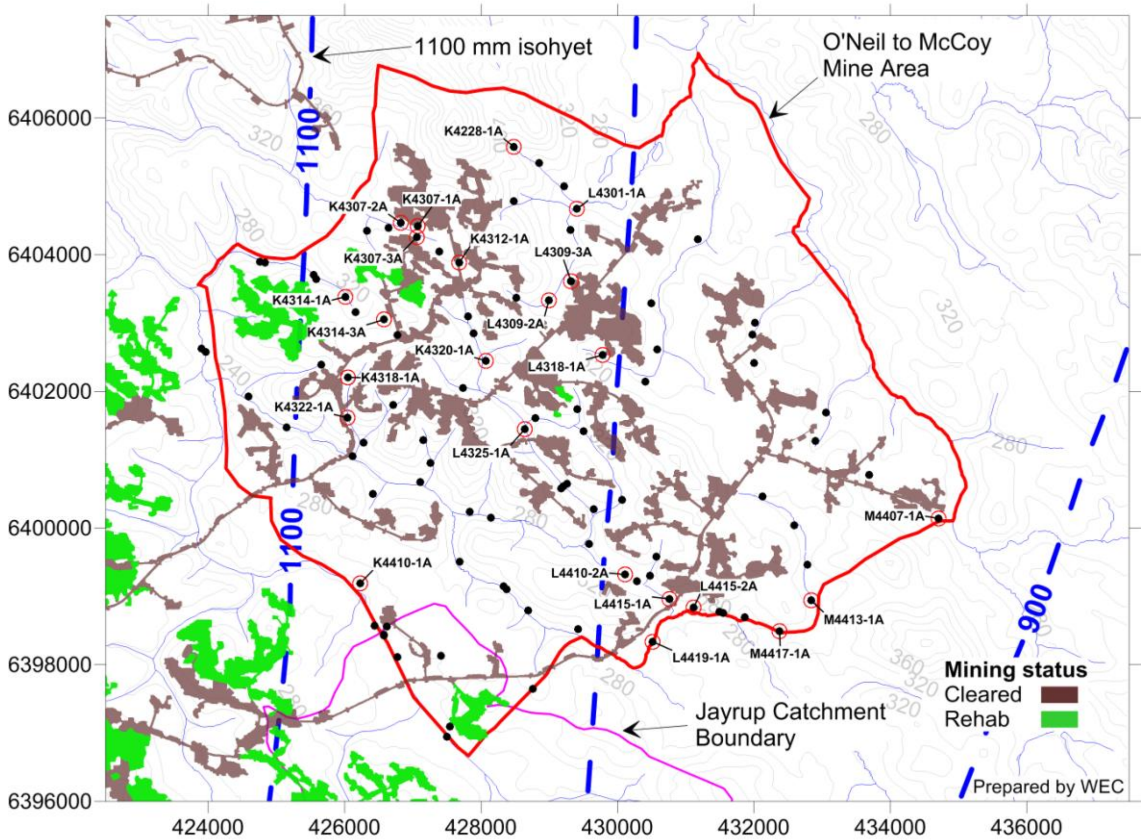

Figure 36: The 23 piezmeters recommended for continued water-level monitoring

6.5 Groundwater Water-Quality Sampling

Groundwater water-quality sampling has been undertaken in previous years to establish a base dataset and to also allow assessment of changes with time. The reality is that while there are some within-year and year-to-year variations in groundwater salinity, these aren't of a significant level. Further, it needs to be asked for what the groundwater water-quality data is to be used. In a baseline study it can be used to make pre-operational estimates of possible treatment effects, such as in Croton & Dalton 2008, Croton, *et al*. 2008 and Croton & Dalton 2010. However, the O'Neil-to-McCoy mining exercise is mature and reaching the end of its operational phase, so baseline studies are no longer required. Instead the emphasis for monitoring is on tracking treatment-responses and ensuring they do not exceed previously predicted levels; and in the case of O'Neil-to-McCoy this is primarily by monitoring groundwater levels, streamflows and stream salinities. It is therefore recommended that sampling groundwater-salinities be discontinued for the O'Neil-to-McCoy mine area.

7. CONCLUSION

The study successfully defined the hydrological responses associated with mining the O'Neil-to-McCoy area. There were significant groundwater level rises in parts of the area, with the nine most responsive piezometers having rises between 1.5 and 5.4 m compared to equivalent controls. As the groundwater in a significant proportion of the valley-floors of the O'Neil-to-McCoy mine area was at or close to the soil surface, such rises also seemed to influence streamflows and stream salinities. A relation between percentage-area of mining and stream-salinity was developed and estimates were made of the additional stream-inflow salinity for the Serpentine Reservoir due to mining of the O'Neil-to-McCoy area. The stream-inflow salinity was estimated to increase by 3.0 mg/L due to mining effects and the pond salinity was estimated to increase by 0.44 mg/L. Neither of these responses were unexpected and are on the lower side of what was predicted by Croton & Dalton (2010), and accepted by the BHC when making their recommendation to the MMPLG that O'Neil-to-McCoy mining should proceed.

Due to the continued below-average rainfalls during the mining period for the O'Neil-to-McCoy area, the saltloads that have actually occurred are an order of magnitude less than those predicted by Croton & Dalton (2010). The estimated mining-related saltload increase in 2012 due to actual O'Neil-to-McCoy mining was 15.3 tonnes compared to 361 and 419 tonnes for the two scenario predictions by Croton & Dalton (2010). Given that the salinity of the overall water-supply system is driven by the saltload calculations, that is total salt vs. total water in the system, then it is the saltload of the stream-inflow to Serpentine Reservoir rather than the salinity of the stream-inflow which matters to the overall water-supply system.

Recommendations were also made as to what monitoring should be continued for the O'Neil-to-McCoy mine area. These recommendations were strongly affected by the present climate, and its likelihood of continuing. If the present below-average rainfalls continue, then it is proposed hydrological monitoring of the O'Neil-to-McCoy mine area can be maintained at a much lower level than if a change in the rainfall patterns were to occur. The definition of a climate change that would trigger consideration of an increase in monitoring was suggested to be at least 1,300 mm/yr rainfall for the Big Brook rain-gauge. This is because such a rainfall would provide a large water-excess and would significantly replenish soil-water storages and boost streamflow. If rainfalls continue at average levels or below, then they are expected to do little more than maintain the hydrological status quo.

8. REFERENCES

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APPENDIX A – Observed Groundwater Data for the O'Neil-to-McCoy Mine Area

Figure A1 shows the locations of the 96 deep piezometers in the O'Neil-to-McCoy mine area. Figure A2 shows the piezometer hydrographs for all available data. Table A1 is a listing of the piezometers including a flag as to whether they have been water-quality sampled by pumping. Table A2 is a listing of water quality data since 2007 for the O'Neil-to-McCoy mine-area piezometers.

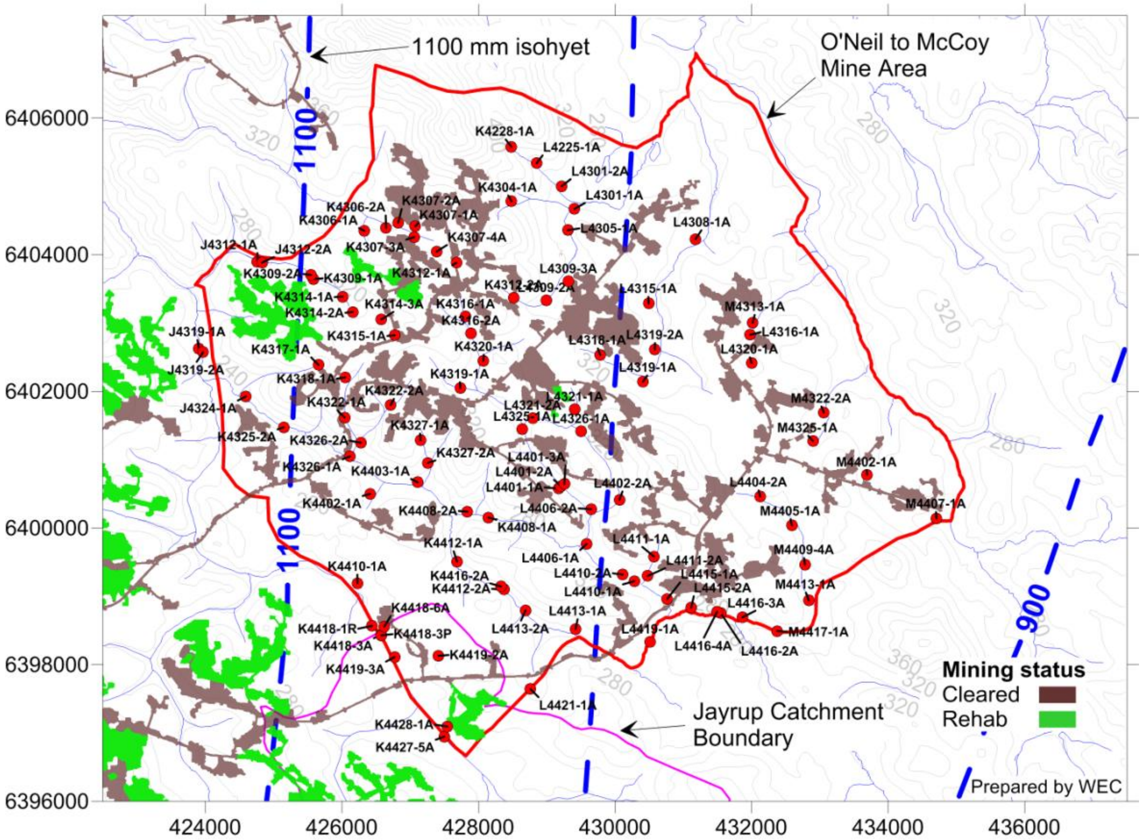

Figure A1: Location of the 96 deep groundwater piezometers in the O'Neil-to-McCoy mine area.

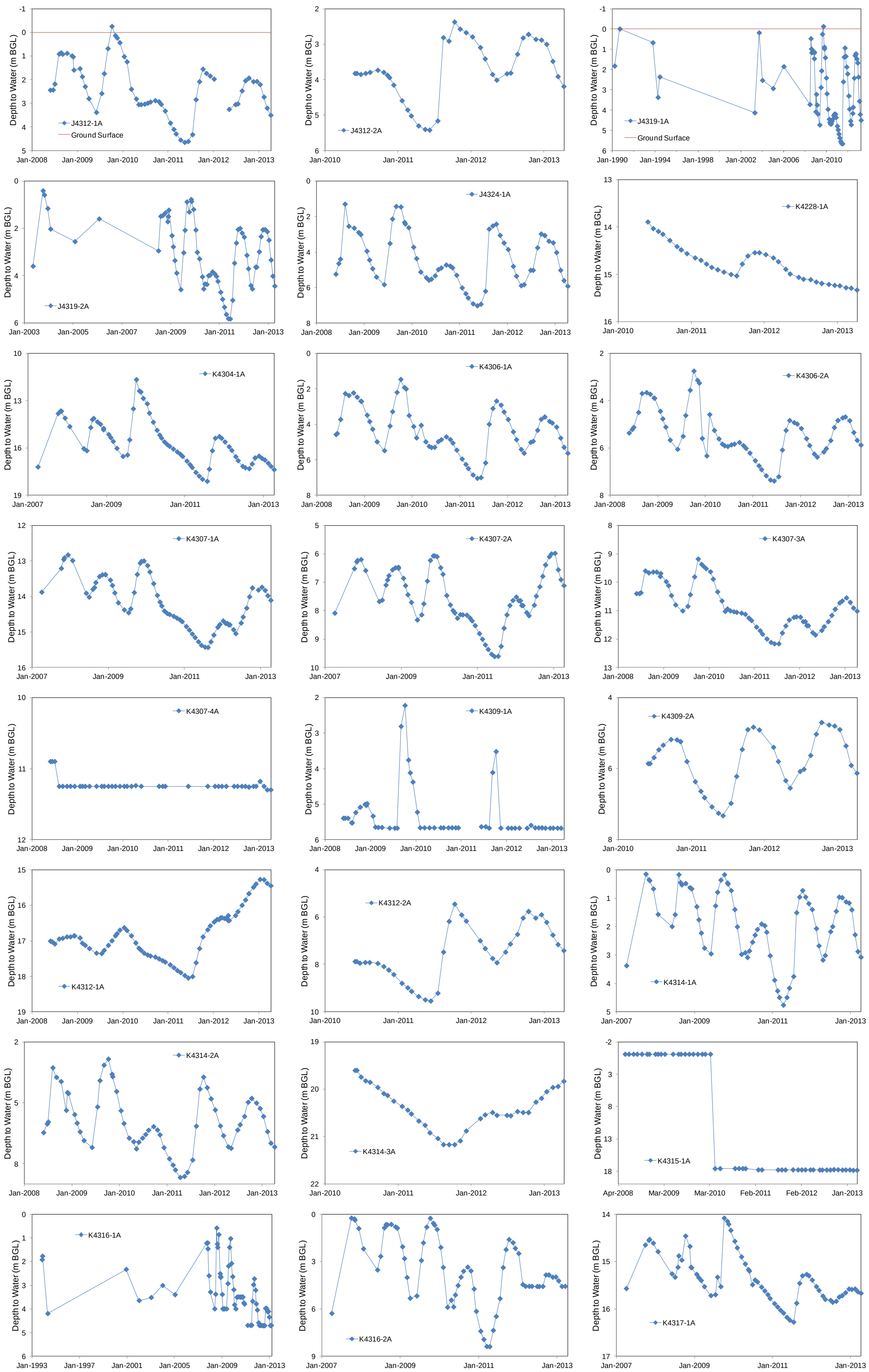

Figure A2 continued

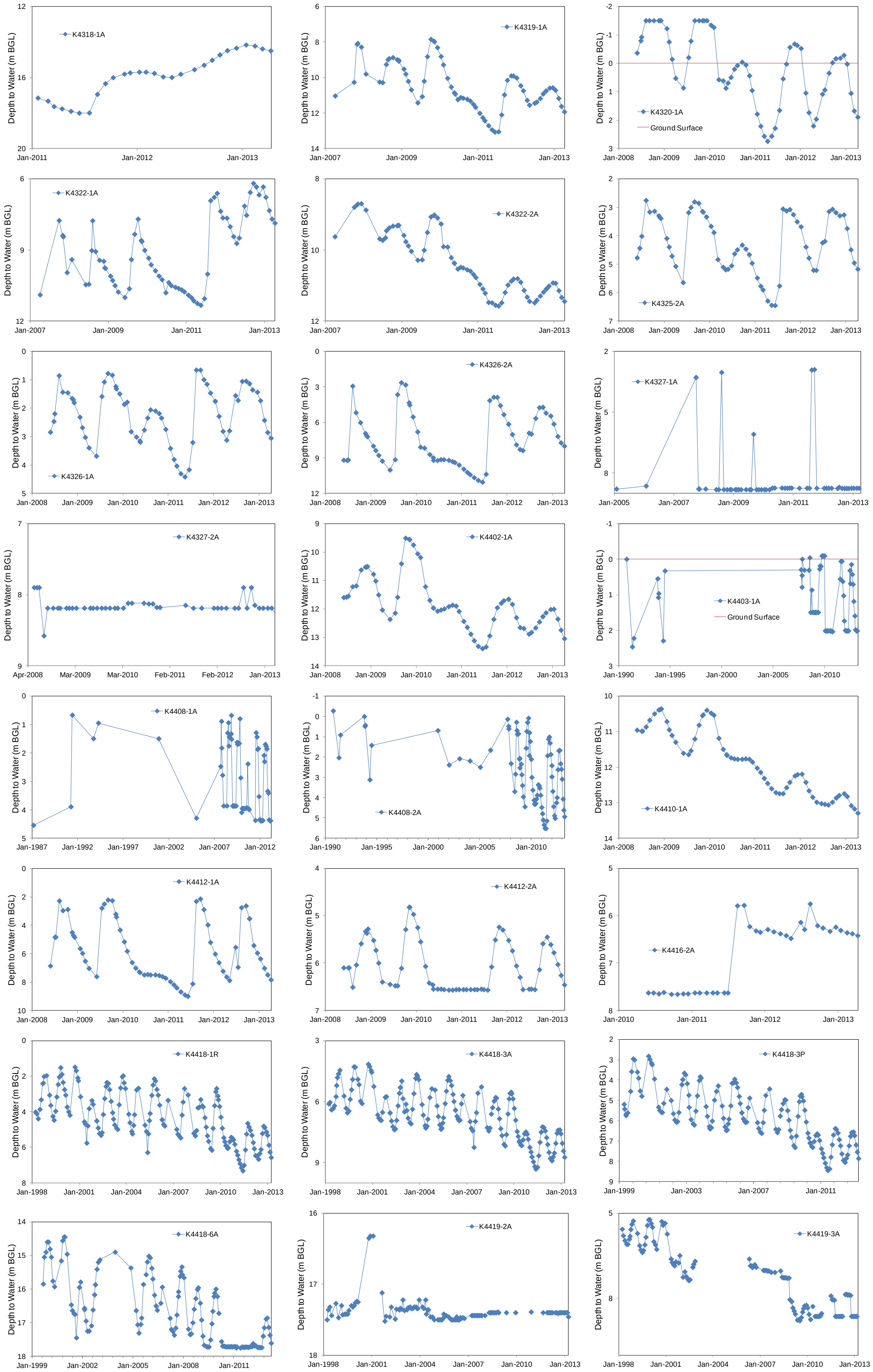

Figure A2 continued

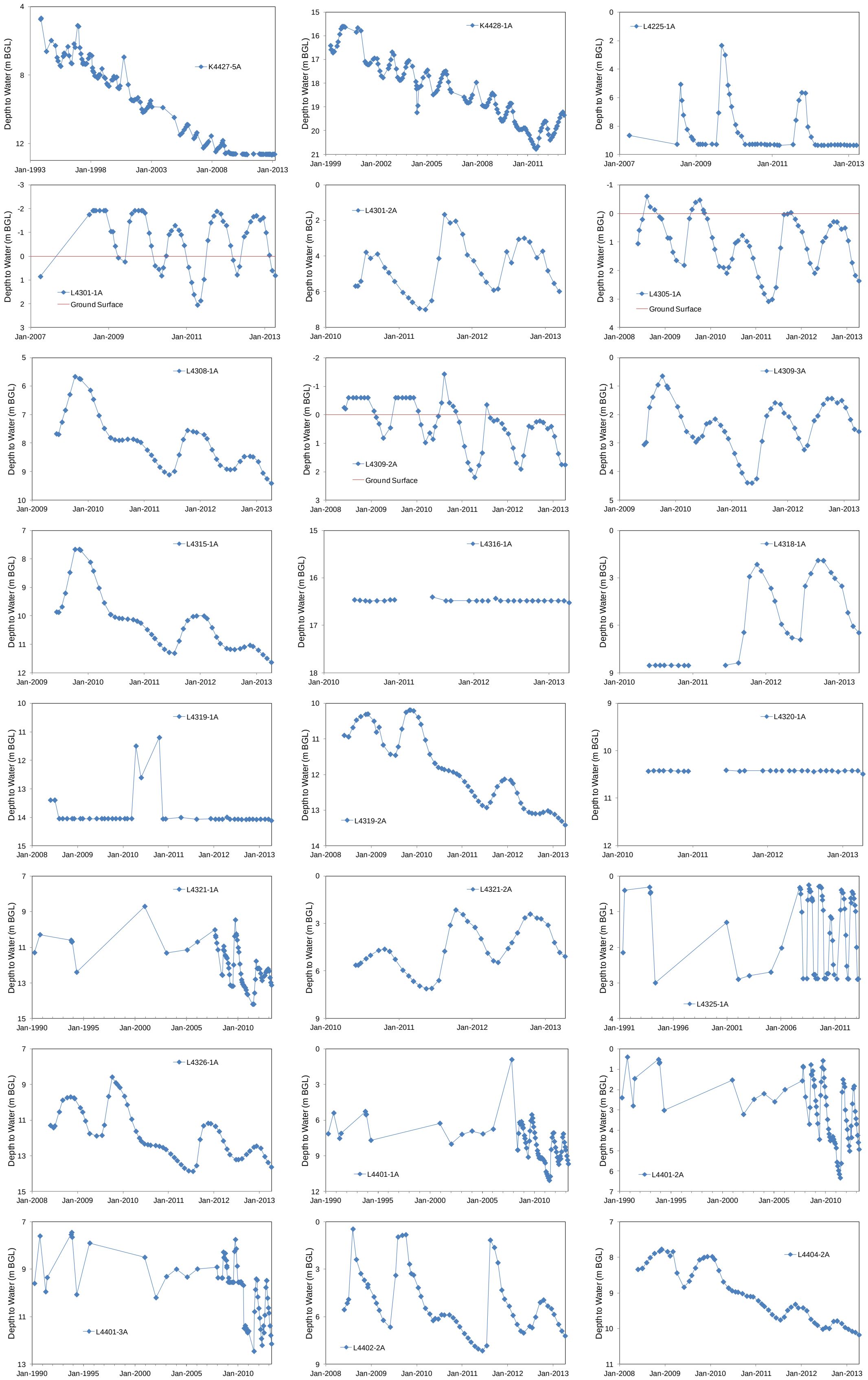

Figure A2 continued

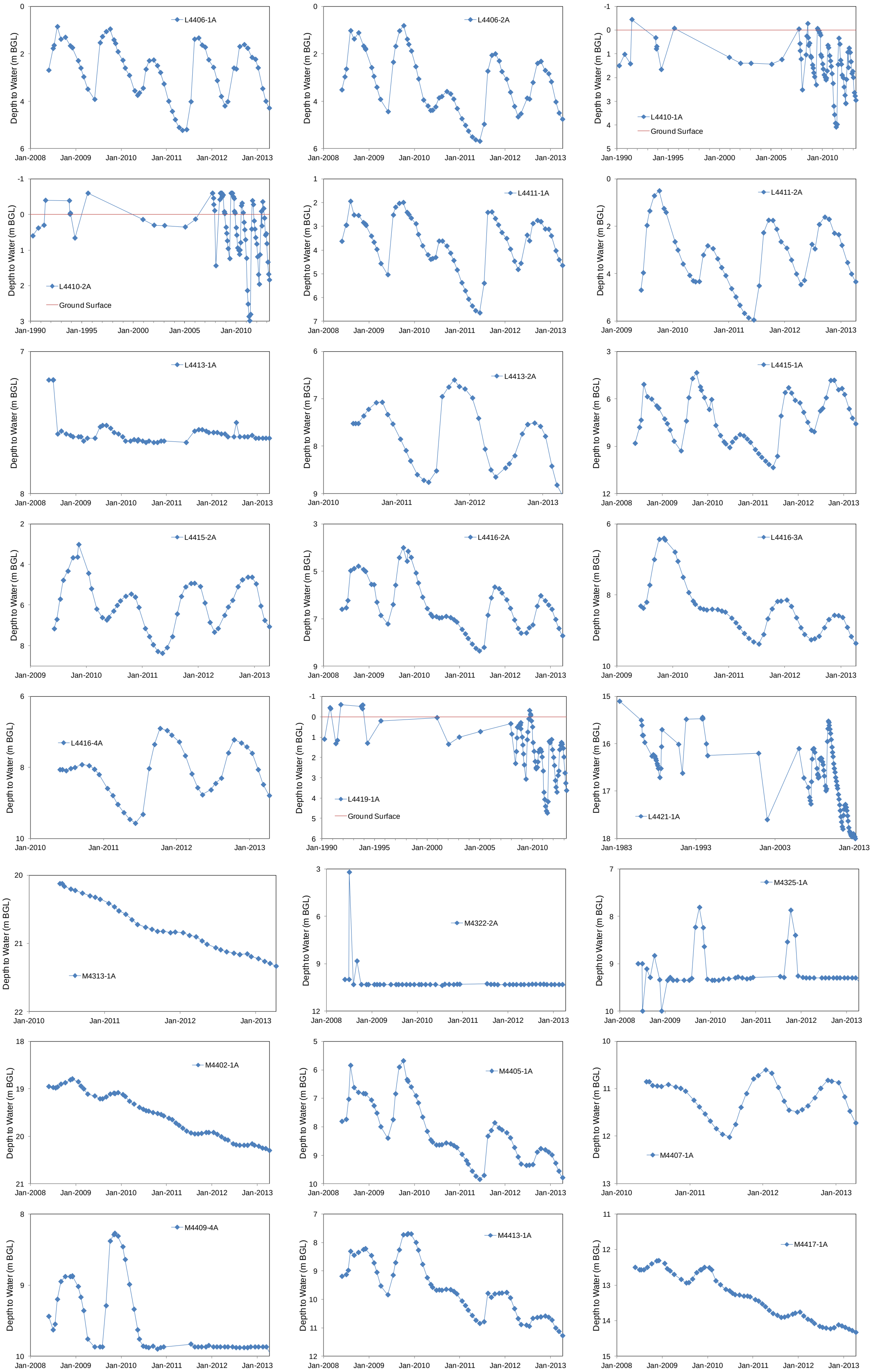

Figure A2: Hydrographs of the 96 deep groundwater piezometers in the O'Neil-to-McCoy mine area.

Table A1: A listing of the O'Neil-to-McCoy mine area piezometers including a flag as to whether they have been water-quality sampled by pumping.

Site	Easting	Northing	Sampled
J4312-1A	424759	6403896	Yes
J4312-2A	424830	6403885	Yes
J4319-1A	423905	6402623	Yes
J4319-2A	423966	6402573	
J4324-1A	424593	6401926	Yes
K4228-1A	428482	6405580	Yes
K4304-1A	428482	6404784	Yes
K4306-1A	426329	6404349	Yes
K4306-2A	426645	6404391	Yes
K4307-1A	427071	6404417	Yes
K4307-2A	426823	6404469	Yes
K4307-3A	427058	6404259	Yes
K4307-4A	427385	6404046	
K4309-1A	425584	6403645	Yes
K4309-2A	425546	6403702	Yes
K4312-1A	427676	6403882	Yes
K4312-2A	428519	6403372	Yes
K4314-1A	426010	6403385	Yes
K4314-2A	426159	6403162	Yes
K4314-3A	426576	6403052	Yes
K4315-1A	426774	6402823	
K4316-1A	427811	6403095	Yes
K4316-2A	427891	6402851	Yes
K4317-1A	425655	6402388	Yes
K4318-1A	426050	6402205	
K4319-1A	427733	6402046	Yes
K4320-1A	428070	6402448	Yes
K4322-1A	426040	6401615	Yes
K4322-2A	426712	6401800	Yes
K4325-2A	425150	6401474	Yes
K4326-1A	426118	6401051	Yes
K4326-2A	426279	6401247	Yes
K4327-1A	427151	6401286	Yes
K4327-2A	427257	6400954	
K4402-1A	426412	6400500	Yes
K4403-1A	427107	6400670	
K4408-1A	428145	6400152	Yes
K4408-2A	427836	6400240	Yes
K4410-1A	426225	6399189	Yes
K4412-1A	427686	6399508	Yes
K4412-2A	428371	6399100	Yes
K4416-2A	428331	6399145	
K4418-1R	426442	6398569	Yes
K4418-3A	426578	6398440	Yes
K4418-3P	426578	6398430	Yes
K4418-6A	426620	6398559	Yes
K4419-2A	427411	6398132	
K4419-3A	426771	6398112	
K4427-5A	427499	6396947	Yes
K4428-1A	427543	6397097	Yes
L4225-1A	428851	6405339	Yes
L4301-1A	429403	6404669	Yes
L4301-2A	429217	6405003	Yes
L4305-1A	429308	6404360	Yes
L4308-1A	431177	6404227	Yes
L4309-2A	428993	6403333	Yes
L4309-3A	429318	6403611	Yes
L4315-1A	430493	6403287	Yes
L4316-1A	431979	6402828	
L4318-1A	429782	6402532	
L4319-1A	430407	6402141	
L4319-2A	430584	6402611	Yes
L4320-1A	432000	6402417	
L4321-1A	429410	6401738	Yes
L4321-2A	428794	6401610	
L4325-1A	428641	6401447	Yes
L4326-1A	429503	6401416	Yes
L4401-1A	429176	6400577	Yes
L4401-2A	429205	6400613	Yes
L4401-3A	429258	6400646	Yes
L4402-2A	430065	6400414	Yes
L4404-2A	432123	6400463	Yes
L4406-1A	429580	6399765	Yes
L4406-2A	429651	6400278	Yes
L4410-1A	430283	6399223	Yes
L4410-2A	430111	6399320	Yes
L4411-1A	430570	6399582	Yes
L4411-2A	430476	6399299	Yes
L4413-1A	429422	6398521	
L4413-2A	428687	6398794	Yes
L4415-1A	430763	6398962	Yes
L4415-2A	431115	6398834	Yes
L4416-2A	431549	6398753	Yes
L4416-3A	431863	6398693	Yes
L4416-4A	431493	6398774	Yes
L4419-1A	430515	6398336	Yes
L4421-1A	428761	6397643	Yes
M4313-1A	432016	6403007	Yes
M4322-2A	433057	6401690	
M4325-1A	432898	6401274	
M4402-1A	433690	6400780	Yes
M4405-1A	432590	6400040	Yes
M4407-1A	434707	6400139	
M4409-4A	432781	6399466	Yes
M4413-1A	432836	6398942	Yes
M4417-1A	432375	6398492	Yes

Table A2: A listing of the water-quality data for the O'Neil-to-McCoy mine area piezometers for 2007 to 2012.

Site	Date	Salinity (mg/L)
J4312-1A	22-Aug-08	922
J4312-1A	27-Nov-08	848
J4312-1A	17-Nov-09	805
J4312-1A	11-May-10	843
J4312-1A	8-Nov-10	852
J4312-1A	8-Mar-11	817
J4312-1A	21-Nov-12	811
J4312-2A	8-Jun-10	481
J4312-2A	8-Nov-10	462
J4312-2A	8-Mar-11	510
J4312-2A	9-Jun-11	464
J4312-2A	8-Sep-11	449
J4312-2A	8-Nov-11	527
J4312-2A	21-Nov-12	489
J4319-2A	22-Aug-08	326
J4319-2A	27-Nov-08	317
J4319-2A	10-Nov-09	326
J4319-2A	11-May-10	393
J4319-2A	8-Nov-10	340
J4319-2A	8-Nov-11	330
J4319-2A	16-Nov-12	333
J4324-1A	18-Jun-08	248
J4324-1A	27-Nov-08	243
J4324-1A	10-Nov-09	230
J4324-1A	11-May-10	242
J4324-1A	8-Nov-10	253
J4324-1A	8-Mar-11	252
J4324-1A	8-Nov-11	261
J4324-1A	16-Nov-12	348
K4228-1A	9-Jun-10	198
K4228-1A	11-Nov-10	174
K4228-1A	15-Nov-11	173
K4228-1A	20-Nov-12	172
K4304-1A	3-Apr-07	153
K4304-1A	7-Nov-07	168
K4304-1A	22-Aug-08	264
K4304-1A	4-Dec-08	139
K4304-1A	16-Nov-09	141
K4304-1A	11-May-10	151
K4304-1A	9-Mar-11	156
K4306-1A	5-Jun-08	177
K4306-1A	4-Dec-08	196
K4306-1A	16-Nov-09	178
K4306-1A	12-May-10	168
K4306-1A	10-Nov-10	170
K4306-1A	9-Mar-11	163
K4306-1A	15-Nov-11	202
K4306-1A	21-Nov-12	181
K4306-2A	19-Jun-08	179
K4306-2A	4-Dec-08	160
K4306-2A	16-Nov-09	146
K4306-2A	12-May-10	178
K4306-2A	10-Nov-10	152
K4306-2A	9-Mar-11	190
K4306-2A	15-Nov-11	147
K4306-2A	21-Nov-12	150
K4307-1A	3-Apr-07	167
K4307-1A	7-Nov-07	179
K4307-1A	21-Aug-08	135
K4307-1A	4-Dec-08	154
K4307-1A	16-Nov-09	154
K4307-1A	12-May-10	155
K4307-1A	21-Nov-12	152
K4307-2A	3-Apr-07	186
K4307-2A	7-Nov-07	190
K4307-2A	21-Aug-08	154
K4307-2A	4-Dec-08	150
K4307-2A	16-Nov-09	154
K4307-2A	12-May-10	148
K4307-2A	10-Nov-10	184
K4307-2A	15-Nov-11	159
K4307-2A	21-Nov-12	147
K4307-3A	19-Jun-08	195
K4307-3A	4-Dec-08	182
K4307-3A	16-Nov-09	185
K4307-3A	12-May-10	233
K4307-3A	9-Mar-11	198
K4309-1A	27-Nov-08	1,500
K4309-2A	8-Jun-10	743
K4309-2A	8-Nov-10	4,767
K4309-2A	8-Mar-11	2,918
K4309-2A	9-Jun-11	2,175
K4309-2A	8-Nov-11	6,275
K4309-2A	11-Dec-12	1,848
K4312-1A	10-Jun-08	185
K4312-1A	4-Dec-08	150
K4312-1A	16-Nov-09	152
K4312-1A	12-May-10	155
K4312-2A	8-Jun-10	192
K4312-2A	15-Nov-10	176
K4312-2A	9-Mar-11	174
K4312-2A	9-Mar-11	171
K4312-2A	15-Nov-11	192
K4312-2A	20-Nov-12	166
K4314-1A	3-Apr-07	242
K4314-1A	6-Nov-07	312
K4314-1A	21-Aug-08	235
K4314-1A	27-Nov-08	291
K4314-1A	10-Nov-09	272
K4314-1A	12-May-10	274
K4314-1A	8-Nov-10	344
K4314-1A	8-Mar-11	286
K4314-1A	9-Jun-11	314
K4314-1A	8-Sep-11	253
K4314-1A	8-Nov-11	225
K4314-1A	21-Nov-12	283
K4314-2A	24-Jun-08	563
K4314-2A	27-Nov-08	613
K4314-2A	10-Nov-09	671
K4314-2A	12-May-10	729
K4314-2A	9-Nov-10	605
K4314-2A	8-Mar-11	533
K4314-2A	9-Jun-11	507

K4314-2A	8-Sep-11	681
K4314-2A	8-Nov-11	539
K4314-2A	21-Nov-12	517
K4314-3A	8-Jun-10	174
K4314-3A	9-Nov-10	197
K4314-3A	8-Mar-11	174
K4314-3A	9-Jun-11	194
K4314-3A	8-Sep-11	194
K4314-3A	8-Nov-11	185
K4314-3A	21-Nov-12	151
K4316-1A	4-Oct-07	79
K4316-1A	6-Nov-07	118
K4316-1A	2-Dec-08	210
K4316-2A	4-Apr-07	150
K4316-2A	6-Nov-07	176
K4316-2A	22-Aug-08	159
K4316-2A	2-Dec-08	155
K4316-2A	17-Nov-09	161
K4316-2A	13-May-10	155
K4316-2A	17-Nov-11	118
K4316-2A	20-Nov-12	160
K4317-1A	2-Apr-07	277
K4317-1A	5-Nov-07	298
K4317-1A	29-Jul-08	266
K4317-1A	28-Nov-08	263
K4317-1A	17-Nov-09	196
K4317-1A	21-May-10	303
K4319-1A	4-Apr-07	174
K4319-1A	6-Nov-07	215
K4319-1A	22-Aug-08	182
K4319-1A	2-Dec-08	191
K4319-1A	10-Nov-09	172
K4319-1A	21-May-10	229
K4319-1A	9-Mar-11	191
K4320-1A	26-Jun-08	230
K4320-1A	2-Dec-08	229
K4320-1A	17-Nov-09	229
K4320-1A	13-May-10	232
K4320-1A	9-Mar-11	228
K4320-1A	17-Nov-11	237
K4320-1A	20-Nov-12	233
K4322-1A	2-Apr-07	209
K4322-1A	5-Nov-07	248
K4322-1A	29-Jul-08	216
K4322-1A	28-Nov-08	236
K4322-1A	10-Nov-09	201
K4322-1A	12-Mar-11	186
K4322-2A	2-Apr-07	404
K4322-2A	6-Nov-07	414
K4322-2A	29-Jul-08	299
K4322-2A	27-Nov-08	394
K4322-2A	10-Nov-09	403
K4322-2A	21-May-10	486
K4322-2A	12-Mar-11	348
K4325-2A	17-Jun-08	317
K4325-2A	28-Nov-08	375
K4325-2A	10-Nov-09	304
K4325-2A	11-May-10	298
K4325-2A	17-Nov-10	354
K4325-2A	8-Mar-11	302
K4325-2A	8-Nov-11	294
K4325-2A	16-Nov-12	291
K4326-1A	24-Jun-08	192
K4326-1A	27-Nov-08	220
K4326-1A	10-Nov-09	202
K4326-1A	21-May-10	233
K4326-1A	9-Nov-10	213
K4326-1A	12-Mar-11	219
K4326-1A	11-Nov-11	213
K4326-1A	26-Nov-12	176
K4326-2A	24-Jun-08	889
K4326-2A	27-Nov-08	738
K4326-2A	10-Nov-09	646
K4326-2A	21-May-10	755
K4326-2A	9-Nov-10	692
K4326-2A	12-Mar-11	771
K4326-2A	11-Nov-11	637
K4326-2A	26-Nov-12	643
K4327-1A	28-Sep-07	112
K4402-1A	17-Jun-08	547
K4402-1A	28-Nov-08	516
K4402-1A	10-Nov-09	537
K4402-1A	21-May-10	660
K4408-1A	28-Nov-08	536
K4408-1A	11-Nov-11	1,004
K4408-1A	26-Nov-12	154
K4408-2A	7-Nov-07	223
K4408-2A	20-Aug-08	210
K4408-2A	28-Nov-08	213
K4408-2A	10-Nov-09	223
K4408-2A	14-May-10	590
K4408-2A	9-Nov-10	683
K4408-2A	12-Mar-11	629
K4408-2A	11-Nov-11	434
K4408-2A	26-Nov-12	639
K4410-1A	9-Jul-08	469
K4410-1A	28-Nov-08	424
K4410-1A	10-Nov-09	399
K4410-1A	21-May-10	586
K4412-1A	9-Jul-08	120
K4412-1A	28-Nov-08	143
K4412-1A	10-Nov-09	129
K4412-1A	14-May-10	147
K4412-1A	17-Nov-10	148
K4412-1A	8-Mar-11	144
K4412-1A	12-Mar-11	144
K4412-1A	10-Jun-11	200
K4412-1A	8-Sep-11	113
K4412-1A	11-Nov-11	147
K4412-1A	26-Nov-12	127
K4412-2A	28-Nov-08	2,700
K4412-2A	10-Nov-09	2,093
K4418-1R	21-Jul-08	350
K4418-1R	23-Nov-09	333
K4418-1R	21-May-10	1,029
K4418-1R	9-Nov-10	988
K4418-1R	10-Nov-11	416
K4418-1R	27-Nov-12	362
K4418-3A	17-Jul-08	1,311
K4418-3A	23-Nov-09	2,606

K4418-3A	21-May-10	2,256
K4418-3A	9-Nov-10	2,529
K4418-3A	12-Mar-11	2,901
K4418-3A	10-Jun-11	2,830
K4418-3A	10-Nov-11	1,233
K4418-3A	27-Nov-12	2,677
K4418-3P	17-Jul-08	3,319
K4418-3P	20-Nov-09	3,113
K4418-3P	21-May-10	3,902
K4418-3P	9-Nov-10	3,219
K4418-3P	12-Mar-11	3,148
K4418-3P	10-Jun-11	3,260
K4418-3P	10-Nov-11	2,965
K4418-6A	23-Nov-09	1,110
K4427-5A	21-Jul-08	488
K4428-1A	23-Jul-08	1,069
K4428-1A	2-Dec-09	1,290
K4428-1A	21-May-10	1,315
K4428-1A	17-Nov-10	1,229
K4428-1A	15-Mar-11	1,300
K4428-1A	18-Mar-11	1,300
K4428-1A	10-Jun-11	1,217
K4428-1A	10-Nov-11	1,293
K4428-1A	26-Nov-12	1,247
L4225-1A	18-Aug-08	140
L4225-1A	4-Dec-08	188
L4225-1A	16-Nov-09	121
L4225-1A	15-Nov-11	156
L4301-1A	18-Aug-08	151
L4301-1A	4-Dec-08	147
L4301-1A	16-Nov-09	140
L4301-1A	12-May-10	166
L4301-1A	11-Nov-10	211
L4301-1A	11-Mar-11	158
L4301-1A	15-Nov-11	197
L4301-1A	19-Nov-12	155
L4301-2A	9-Jun-10	197
L4301-2A	11-Nov-10	151
L4301-2A	9-Mar-11	160
L4301-2A	15-Nov-11	122
L4301-2A	20-Nov-12	127
L4305-1A	6-Jun-08	296
L4305-1A	4-Dec-08	290
L4305-1A	12-Nov-09	306
L4305-1A	12-May-10	297
L4305-1A	11-Nov-10	304
L4305-1A	9-Mar-11	308
L4305-1A	15-Nov-11	291
L4305-1A	20-Nov-12	296
L4308-1A	22-Jun-09	796
L4308-1A	12-Nov-09	839
L4308-1A	26-May-10	731
L4308-1A	16-Nov-10	833
L4308-1A	11-Mar-11	776
L4308-1A	16-Nov-11	790
L4308-1A	22-Nov-12	782
L4309-2A	6-Jun-08	298
L4309-2A	4-Dec-08	279
L4309-2A	12-Nov-09	314
L4309-2A	12-May-10	398

L4309-2A	11-Nov-10	347
L4309-2A	11-Mar-11	349
L4309-2A	15-Nov-11	350
L4309-2A	20-Nov-12	372
L4309-3A	22-Jun-09	345
L4309-3A	12-Nov-09	329
L4309-3A	13-May-10	388
L4309-3A	16-Nov-10	344
L4309-3A	9-Mar-11	343
L4309-3A	15-Nov-11	321
L4309-3A	20-Nov-12	330
L4315-1A	22-Jun-09	476
L4315-1A	12-Nov-09	439
L4315-1A	26-May-10	443
L4315-1A	16-Nov-10	452
L4315-1A	11-Mar-11	515
L4315-1A	16-Nov-11	458
L4315-1A	22-Nov-12	459
L4319-2A	30-Jun-08	546
L4319-2A	4-Dec-08	669
L4319-2A	12-Nov-09	665
L4319-2A	26-May-10	695
L4321-1A	7-Nov-07	184
L4321-1A	18-Aug-08	144
L4321-1A	2-Dec-08	237
L4321-1A	12-Nov-09	239
L4321-1A	13-May-10	285
L4321-1A	17-Nov-11	744
L4325-1A	4-Oct-07	90
L4325-1A	6-Nov-07	135
L4325-1A	25-Aug-08	172
L4325-1A	2-Dec-08	126
L4325-1A	12-Nov-09	108
L4325-1A	15-Nov-10	178
L4325-1A	17-Nov-11	123
L4325-1A	20-Nov-12	147
L4326-1A	20-Jun-08	266
L4326-1A	2-Dec-08	397
L4326-1A	16-Nov-09	377
L4326-1A	13-May-10	403
L4326-1A	14-Mar-11	428
L4401-1A	7-Nov-07	556
L4401-1A	25-Aug-08	431
L4401-1A	2-Dec-08	372
L4401-1A	12-Nov-09	347
L4401-1A	13-May-10	345
L4401-1A	15-Nov-10	356
L4401-1A	17-Nov-11	436
L4401-1A	27-Nov-12	444
L4401-2A	25-Aug-08	489
L4401-2A	2-Dec-08	491
L4401-2A	12-Nov-09	500
L4401-2A	13-May-10	454
L4401-2A	15-Nov-10	473
L4401-2A	14-Mar-11	422
L4401-2A	17-Nov-11	381
L4401-2A	27-Nov-12	480
L4401-3A	25-Aug-08	490
L4402-2A	20-Jun-08	168
L4402-2A	2-Dec-08	166

L4402-2A	18-Nov-09	134
L4402-2A	13-May-10	207
L4402-2A	15-Nov-10	178
L4402-2A	11-Mar-11	245
L4402-2A	14-Mar-11	408
L4402-2A	17-Nov-11	200
L4402-2A	21-Nov-12	159
L4404-2A	30-Jun-08	239
L4404-2A	3-Dec-08	278
L4404-2A	11-Nov-09	235
L4404-2A	26-May-10	245
L4404-2A	16-Nov-10	249
L4404-2A	11-Mar-11	245
L4404-2A	16-Nov-11	246
L4404-2A	23-Nov-12	245
L4406-1A	9-Jul-08	261
L4406-1A	3-Dec-08	235
L4406-1A	17-Nov-09	229
L4406-1A	14-May-10	246
L4406-1A	15-Nov-10	247
L4406-1A	14-Mar-11	236
L4406-1A	11-Nov-11	208
L4406-1A	27-Nov-12	230
L4406-2A	20-Jun-08	204
L4406-2A	2-Dec-08	200
L4406-2A	17-Nov-09	77
L4406-2A	13-May-10	385
L4406-2A	15-Nov-10	232
L4406-2A	14-Mar-11	521
L4406-2A	17-Nov-11	581
L4406-2A	27-Nov-12	241
L4410-1A	8-Nov-07	224
L4410-1A	20-Aug-08	211
L4410-1A	3-Dec-08	173
L4410-1A	11-Nov-09	179
L4410-1A	14-May-10	216
L4410-1A	15-Nov-10	203
L4410-1A	14-Mar-11	198
L4410-1A	11-Nov-11	167
L4410-1A	26-Nov-12	157
L4410-2A	25-Sep-07	206
L4410-2A	8-Nov-07	227
L4410-2A	20-Aug-08	209
L4410-2A	3-Dec-08	199
L4410-2A	11-Nov-09	200
L4410-2A	14-May-10	251
L4410-2A	15-Nov-10	201
L4410-2A	14-Mar-11	208
L4410-2A	26-Nov-12	206
L4411-1A	30-Jun-08	185
L4411-1A	2-Dec-08	189
L4411-1A	18-Nov-09	222
L4411-1A	14-May-10	203
L4411-1A	16-Nov-10	199
L4411-1A	15-Mar-11	202
L4411-1A	11-Nov-11	169
L4411-1A	27-Nov-12	179
L4411-2A	22-Jun-09	411
L4411-2A	18-Nov-09	371
L4411-2A	14-May-10	348

L4411-2A	16-Nov-10	359
L4411-2A	15-Mar-11	422
L4411-2A	11-Nov-11	365
L4411-2A	27-Nov-12	418
L4413-2A	9-Jun-10	459
L4413-2A	17-Nov-10	382
L4413-2A	12-Mar-11	411
L4413-2A	10-Jun-11	387
L4413-2A	8-Sep-11	447
L4413-2A	11-Nov-11	376
L4413-2A	26-Nov-12	414
L4415-1A	14-Jul-08	221
L4415-1A	3-Dec-08	221
L4415-1A	12-Nov-09	223
L4415-1A	14-May-10	214
L4415-1A	17-Nov-10	208
L4415-1A	14-Mar-11	229
L4415-1A	10-Nov-11	204
L4415-1A	27-Nov-12	209
L4415-2A	22-Jun-09	417
L4415-2A	12-Nov-09	421
L4415-2A	14-May-10	387
L4415-2A	17-Nov-10	431
L4415-2A	14-Mar-11	403
L4415-2A	16-Nov-11	416
L4415-2A	23-Nov-12	442
L4416-2A	14-Jul-08	1,288
L4416-2A	3-Dec-08	1,827
L4416-2A	12-Nov-09	1,532
L4416-2A	14-May-10	1,498
L4416-2A	17-Nov-10	1,547
L4416-2A	11-Mar-11	1,499
L4416-2A	10-Jun-11	1,461
L4416-2A	16-Nov-11	1,520
L4416-2A	23-Nov-12	1,492
L4416-3A	22-Jun-09	451
L4416-3A	12-Nov-09	366
L4416-3A	14-May-10	389
L4416-3A	17-Nov-10	396
L4416-3A	11-Mar-11	414
L4416-3A	11-Mar-11	448
L4416-3A	16-Nov-11	404
L4416-3A	23-Nov-12	378
L4416-4A	9-Jun-10	2,160
L4416-4A	17-Nov-10	2,254
L4416-4A	14-Mar-11	2,406
L4416-4A	10-Jun-11	2,405
L4416-4A	16-Nov-11	2,335
L4416-4A	23-Nov-12	2,376
L4419-1A	22-Jul-08	889
L4419-1A	3-Dec-08	876
L4419-1A	11-Nov-09	259
L4419-1A	21-May-10	438
L4419-1A	17-Nov-10	831
L4419-1A	14-Mar-11	783
L4419-1A	10-Nov-11	416
L4419-1A	26-Nov-12	374
L4421-1A	8-Nov-07	111
L4421-1A	20-Nov-09	72
L4421-1A	17-Nov-10	156

L4421-1A	10-Nov-11	139
L4421-1A	26-Nov-12	164
M4313-1A	9-Jun-10	1,094
M4313-1A	16-Nov-10	1,035
M4313-1A	11-Mar-11	1,001
M4313-1A	9-Jun-11	991
M4313-1A	16-Nov-11	1,047
M4313-1A	22-Nov-12	1,074
M4402-1A	21-Jul-08	693
M4402-1A	3-Dec-08	673
M4402-1A	12-Nov-09	705
M4402-1A	14-May-10	676
M4405-1A	21-Jul-08	610
M4405-1A	3-Dec-08	616
M4405-1A	11-Nov-09	536
M4405-1A	14-May-10	570
M4405-1A	16-Nov-10	589
M4405-1A	11-Mar-11	596
M4405-1A	16-Nov-11	558

M4405-1A	23-Nov-12	607
M4409-4A	17-Jul-08	243
M4409-4A	3-Dec-08	203
M4409-4A	11-Nov-09	188
M4409-4A	14-May-10	189
M4413-1A	17-Jul-08	332
M4413-1A	3-Dec-08	324
M4413-1A	11-Nov-09	336
M4413-1A	14-May-10	415
M4413-1A	16-Nov-10	374
M4413-1A	11-Mar-11	324
M4413-1A	11-Mar-11	344
M4413-1A	16-Nov-11	339
M4413-1A	23-Nov-12	320
M4417-1A	14-Jul-08	535
M4417-1A	3-Dec-08	680
M4417-1A	12-Nov-09	600

APPENDIX B – Stream-Salinity Data for the O'Neil-to-McCoy Mine Area

Figure B1 shows the locations of the 36 manual-sampling, stream-salinity monitoring sites in the O'Neil-to-McCoy mine area and Table B1 lists their locations (m GDA94). The sample data is plotted in Figure B2.

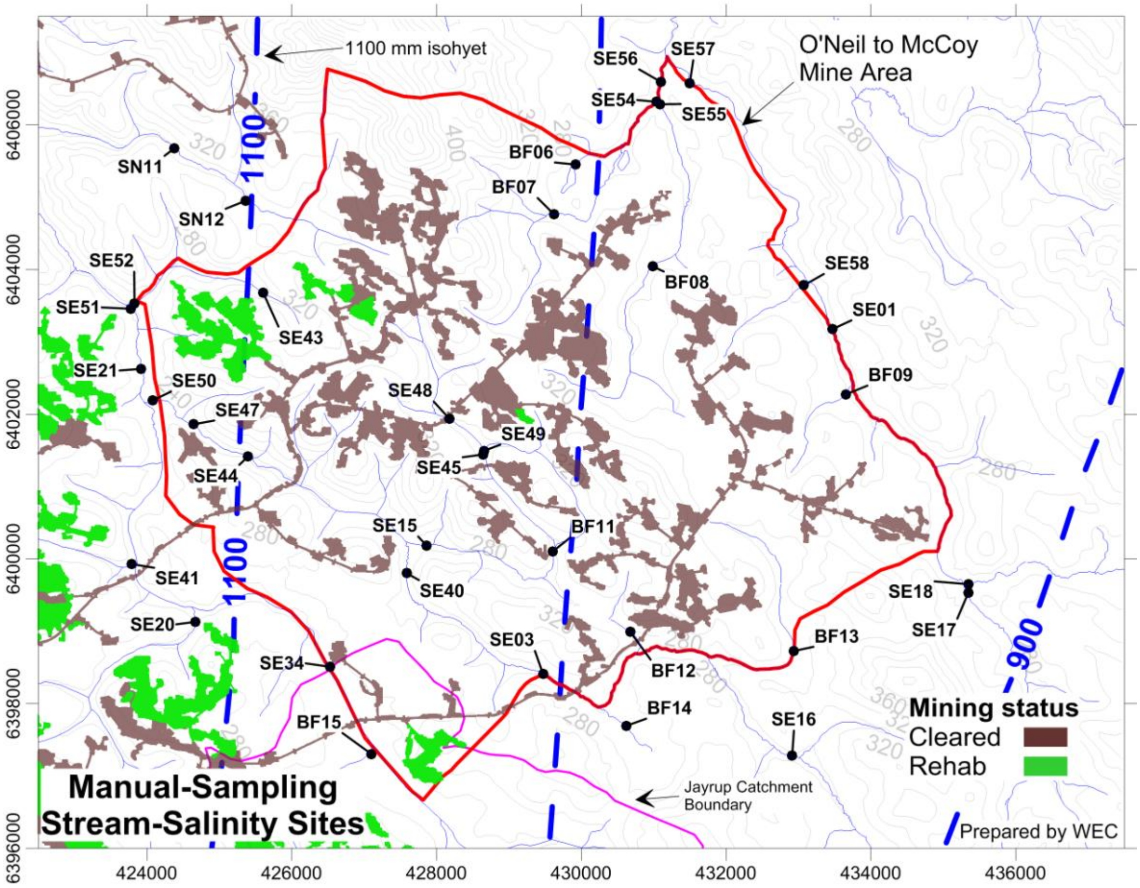

Figure B1: Location of the 36 manual-sampling, stream-salinity monitoring sites in the O'Neil-to-McCoy mine area.

Table B1: Listing of the 36 manual-sampling, stream-salinity monitoring sites in the O'Neil-to-McCoy mine area along with their locations (m GDA94).

Site	Easting	Northing	Site	Easting	Northing
BF06	429920	6405452	SE40	427590	6399802
BF07	429624	6404763	SE41	423789	6399929
BF08	430984	6404045	SE43	425606	6403679
BF09	433651	6402274	SE44	425394	6401416
BF11	429605	6400104	SE45	428646	6401445
BF12	430676	6398990	SE47	424643	6401861
BF13	432931	6398726	SE48	428177	6401938
BF14	430620	6397693	SE49	428654	6401494
BF15	427099	6397303	SE50	424082	6402193
SE01	433467	6403177	SE51	423778	6403458
SE03	429471	6398407	SE52	423828	6403529
SE15	427865	6400181	SE54	431039	6406319
SE16	432911	6397281	SE55	431087	6406286
SE17	435343	6399531	SE56	431100	6406594
SE18	435343	6399651	SE57	431497	6406579
SE20	424667	6399130	SE58	433073	6403783
SE21	423919	6402628	SN11	424377	6405677
SE34	426527	6398509	SN12	425365	6404953

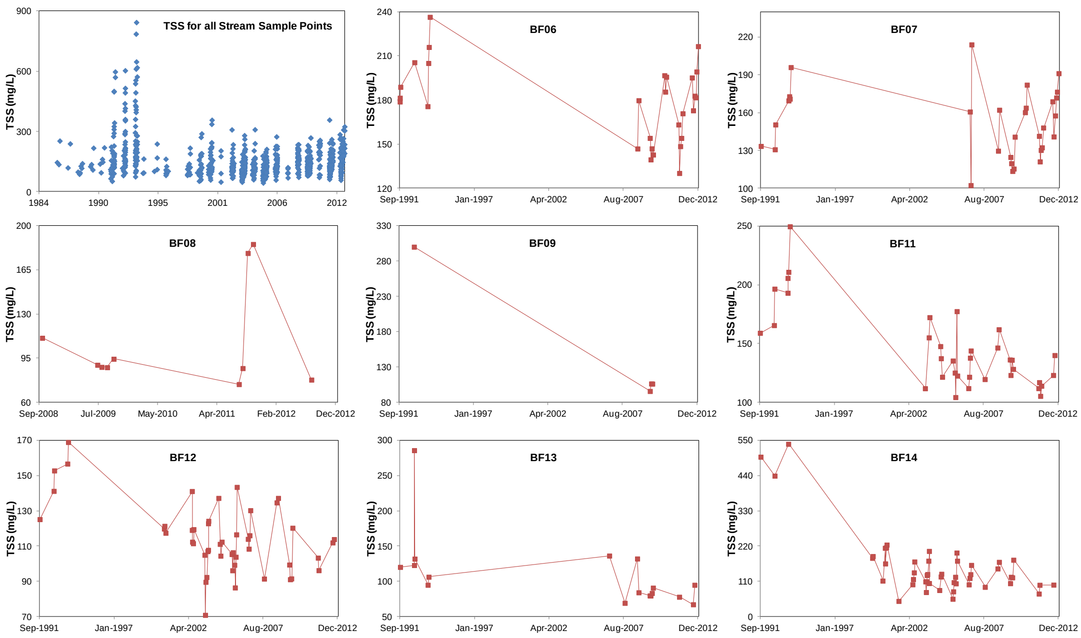

Figure B2 continued.

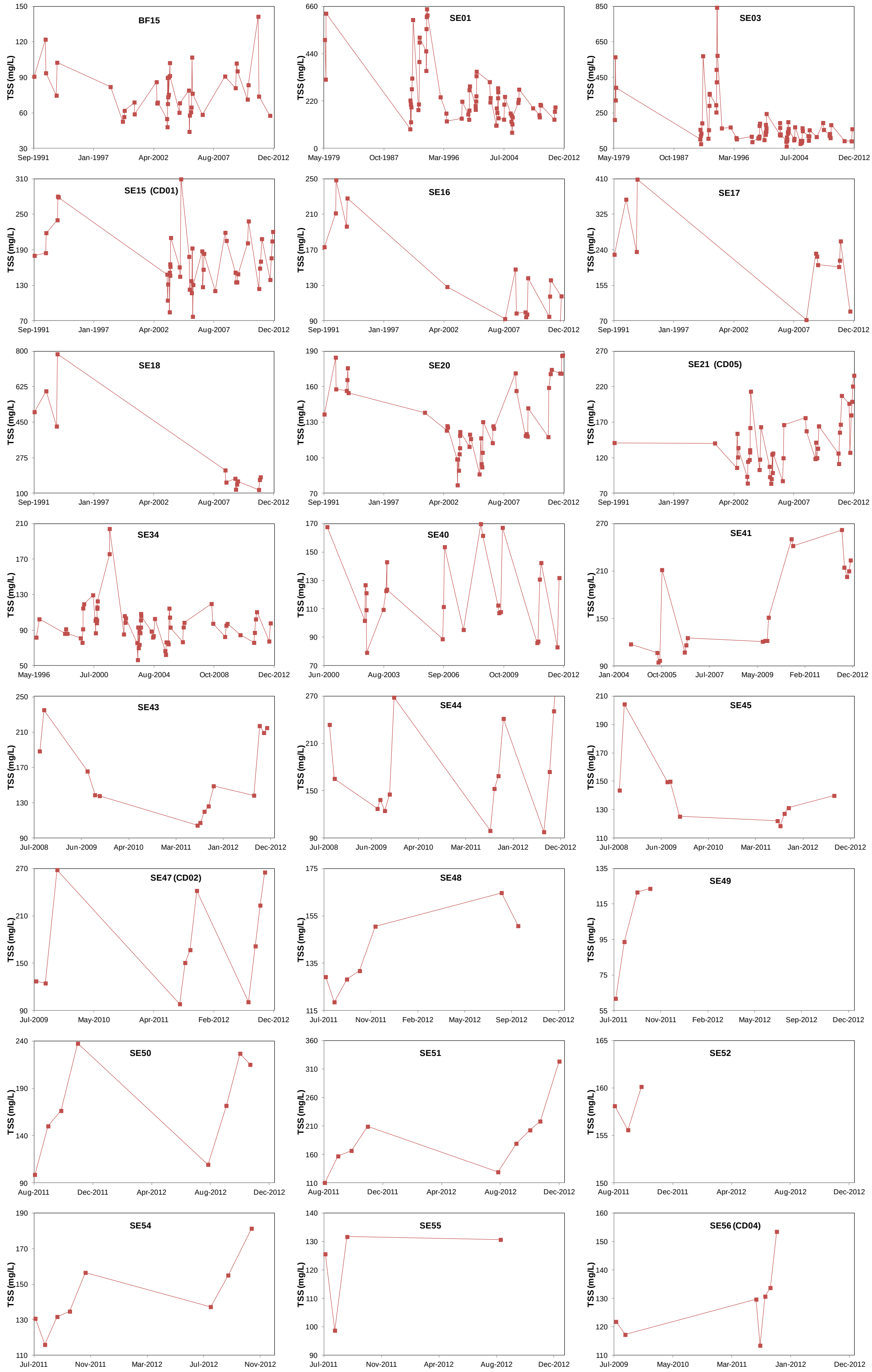

Figure B2 continued.

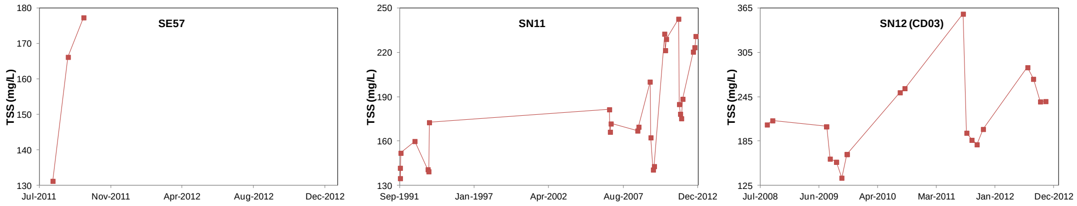

Figure B2: Plots of stream-salinity for 35 manual-sampling, stream-salinity monitoring sites in the O'Neil-to-McCoy mine area. Note that SE58 isn't plotted as no sample has yet been collected there.

DATA
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Analysis of Turbidity Events

Final Report

April 2023

Project: ALCOA/31

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Client: ALCOA

Project: ALCOA/31

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Executive Summary

Alcoa has commissioned Data Analysis Australia (DAA) to undertake a study to identify and quantify relationships between turbidity, mining activity and catchment characteristics including slope and area cleared. This will assist in understanding causes of **high turbidity events**, particularly those associated with drainage events, and how to mitigate them in the future. Additionally, this study may also guide quality control processes for Alcoa's turbidity data collection and processing in current and future mining regions, providing the framework for routine monitoring and statistical assessment.

Data from turbidity monitors are subject to numerous errors, including sensor saturation, obstruction by leaves or debris and streams flushing or drying out. Alcoa provided data for 27 monitors in the Huntly region from four data sources with varying degrees of coverage and error.

Interim results, not reported here, were obtained using a smaller dataset of six monitors for the period 2021-2022 that has been cleaned of gross errors caused by sensor malfunction or telemetric issues. They suggested that **the relationships between high turbidity events and the cleared percentage area and slope of catchments are more complex than can be expressed by simple univariate thresholds**. Using the smaller dataset, slope appeared to have a stronger relationship with the number of high turbidity events than clearing, with no apparent relationship between the number of high turbidity events and clearing. While not statistically significant, the area rehabilitated was suggested as an important factor with the number of high turbidity events decreasing with levels of rehabilitation.

This report describes the results of using a larger dataset for top level analysis and statistical modelling.

Top Level Analysis

A subset of 10 monitors with 80% turbidity data availability for the winter period May to September 2021 was identified and the total number of high turbidity events during that period was correlated with catchment characteristics. These included mean and maximum slope, the percentage of the catchment with slope greater than 16 degrees, mean and maximum slope of the cleared area, area cleared, area rehabilitated and several indices derived from leaf area index (LAI) data. Five of the ten catchments recorded no high turbidity events during this period.

We found a correlation of close to zero between the percentage area of catchment that has been cleared (total area cleared including areas subsequently rehabilitated) with the number of high turbidity events meaning. While there was a positive correlation between the percentage area of a catchment that has been cleared but not yet rehabilitated (ie. open area) and the number of high turbidity events, it was not significant. Mean catchment slope and the percentage area of the catchment that has been rehabilitated were the only factors found to have a significant correlation with the number of high turbidity events. This suggests that rehabilitation should be considered when managing turbidity risk.

Statistical Modelling

While the top level analysis can highlight individual relationships, multivariate analysis is critically important because the effects of multiple factors and their possible interactions can be considered simultaneously. A subset of turbidity data for 14 monitors between January 2021 and September 2022 was used to estimate a sequence of multivariate statistical models designed to consider: (1) effects of total clearing (including areas subsequently rehabilitated); (2) effects of clearing prior to rehabilitation; and (3) effects of clearing and rehabilitation combined.

The results showed that:

- Catchment slope has a significant positive effect on either the occurrence or number of high turbidity events and their number using any model, with more events in catchments with higher mean slope.
- Rainfall has a significant positive effect on both the occurrence and number of high turbidity events and their number using any model, with more events in wetter months.
- When only total percentage cleared area (including subsequently rehabilitated areas) is considered, it has no effect on the chance of high turbidity events occurring or on the number of high turbidity events if they occur.
- When the percentage area cleared but not rehabilitated is considered, it is found to have a significant positive effect on the occurrence of events but not on their number.
- When both clearing and rehabilitation are considered, percentage area rehabilitated has a significant negative effect on the chance of high turbidity events occurring.

Putting these results together, we find that as a whole, the total percentage cleared area has no significant effect (negative or positive) on high turbidity events, but the two components of it do: percentage cleared but not rehabilitated has a positive effect and percentage cleared and rehabilitated has a negative effect.

The best-fitting model can be used to predict the expected number of events in different scenarios and we can consider changes in a single factor, keeping all else constant. This shows that:

a) Risk of high turbidity events increases with increasing areas of clearing in the absence of rehabilitation.

b) Risk of high turbidity events decreases with increasing levels of rehabilitation.

c) Risk of high turbidity events increases with increasing catchment mean slope.

d) High turbidity events can be expected within uncleared catchments.

Because the factors act together to affect turbidity risk the predictions can tell a more complex story.

The modelling results strongly suggest that selection of a threshold on catchment clearing to minimise risk of high turbidity events should consider rehabilitation. Cleared areas that have not been rehabilitated pose a risk, but cleared areas that have been subsequently rehabilitated do not.

While we found that risk of high turbidity events increases with increasing catchment mean slope, it is unclear that this can be used to select a specific slope threshold for turbidity risk management. Model predictions to understand the joint effects of clearing and catchment slope on the number of high turbidity events showed a marked curvilinear response to the percentage area of the catchment that has been cleared and not rehabilitated, with the predicted number of high turbidity events increasing more rapidly when the **currently** cleared area is over 30% of the catchment. In contrast, the response to mean catchment slope is more linear.

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1. Introduction

Alcoa conducts mining activities in the Darling Range which involves clearing the forest, mining the shallow depth bauxite, then completing rehabilitation. The Alcoa Huntly Bauxite Mine located east of North Dandalup in Western Australia (WA) was established in 1976 in the North Dandalup catchment area and extended into the Serpentine catchment in 2000s.

While natural processes of stream bank erosion and sediment mobilisation exist in forested catchments, trees and other vegetation help absorb and filter water, reducing stream flow and risk of erosion and turbidity. Infrastructure (such as tracks, roads and firebreaks around powerlines) in forests is associated with increased erosion. Bauxite mining increases the risk until subsequent rehabilitation restores the forest system.

Exposed surfaces within the mining envelope present a direct risk for erosion and delivery of sediment into streams (eg. sump and drainage failures). This is managed through operational drainage design and management controls which includes application of the Alcoa WA Mining and Haul Road Drainage Design Manual.

Mining may also cause indirect risks due to forest clearing. Borg et al.[1] undertook one of the most comprehensive studies of the impact of logging on stream flow and water quality in south-west WA. They found that logging caused increased annual streamflow for 2-3 years. Stream turbidity increased in some logged catchments for 2-3 years after, then reverted to pre-logging levels. However, no increase in stream turbidity occurred in logged catchments where 30-100 metre strips of forest were retained along the streamlines.

Alcoa monitors turbidity in catchment streams along with other surface water quality parameters to measure and evaluate water resource quality relative to mining activity. Turbidity risk is managed using a range of operational practices including turbidity monitoring and maintenance of an uncleared riparian stream buffer that has historically been 20 – 50 metres wide in Huntly catchments, dependent on proximity risk, but has been increased to 100 metres for proposed mining areas as outlined in the Alcoa 2023-2027 Mining Management Plan (MMP).

High turbidity events are defined as incidents when measured Nephelometric Turbidity Units (NTU) is continuously greater than 25 for a period of one hour or longer. When these events are recorded via sensors, Alcoa investigates the cause of the turbidity event to determine whether it is due to a drainage failure event at one of their mining areas so that remedial action can be taken.

Alcoa has commissioned Data Analysis Australia (DAA) to undertake a study to identify and quantify relationships between high turbidity events, mining activity and catchment characteristics. This will assist in understanding risk factors for high turbidity events

[1] Borg, H., King, P.D. and Loh, I.C., 1987a. Stream and ground water response to logging and subsequent regeneration in the southern forest of Western Australia: Interim results from paired catchment studies. WH 34, Water Authority of Western Australia, Water Resources Directorate, Surface Water Branch, Perth, W.A.

and enable targeted management to mitigate them in the future. The study may also guide quality control processes for Alcoa's turbidity data collection and processing in current and future mining regions.

This study was performed in three stages.

Data Review and Pre-processing

The first stage involved data review and pre-processing. This included obtaining turbidity data recorded by Huntly monitors, combining the data into a single dataset and identifying a subset of monitors with sufficient data for use in this study. Because measured data from turbidity monitors are subject to numerous errors, high turbidity events detected from the turbidity data were verified prior to analysis by cross-checking them against Alcoa's investigation reports. The catchment area upstream of each monitor was used to calculate catchment characteristics that may explain high turbidity events, including slope and degrees of clearing and rehabilitation.

Top Level Analysis

The second stage considered relationships between single catchment characteristics and the number of high turbidity events occurring in catchments using correlation analysis. Statistical tests were conducted for each catchment characteristic to determine which have significant correlations with the number of high turbidity events. Comparisons of the number of events for different catchments requires a set of monitors that have good data coverage for the same time period, preferably in winter when high turbidity events are more likely to occur. We identified 10 monitors with > 80% turbidity data availability for the winter period May to September 2021 for top level analysis.

Statistical Modelling

While the top level analysis can highlight individual relationships, the many factors affecting turbidity can interact. Multivariate analysis is critically important to consider the effects of multiple factors simultaneously. Moreover, statistical modelling allows the data can be restructured so that data gaps have less impact by considering monthly counts of events and including terms to account for seasonal effects where more events occur in winter than in summer. This allows use of a longer time period of data.

The third stage of this study therefore considered relationships between multiple catchment characteristics using statistical modelling. We identified 14 monitors with greater than 70% turbidity data availability for the period January 2021 and September 2022, which covers two winters. The data were restructured to consider the number of events occurring in a month. A subset of catchment characteristics for modelling was selected to avoid collinearity. Because the counts of high turbidity events are mostly zero, a hurdle model was estimated and used to predict the number of high turbidity events for different catchment scenarios.

2. Stage 1: Data Review and Pre-Processing

The first stage of the project involved data review and pre-processing.

2.1 Turbidity Data

Turbidity monitors emit light and measure the amount scattered by particles in the sample. Measured data from turbidity monitors are subject to numerous errors, including sensor saturation, obstruction by leaves or debris, streams flushing or drying out and intermittent turbidity from animal or vehicle crossings.

Alcoa currently uses Greenspan TS1000 turbidity monitors (Figure 1) interfaced with DataTaker DT82e data loggers (Figure 2). The sensors' factory set measurement range is 1 to 100 NTU using an analogue 5-20mA signal.

Compliance monitors are located immediately upstream of neighbours or public water supply storage reservoirs in accordance with the operational requirements agreed in the Water Working Arrangements. Where telemetry is available, live data is transmitted to site to allow for a quick response to investigate elevated readings. Where transmission via telemetry is restricted, data is downloaded monthly or after every 20 mm or greater rain event. Agreed reporting limits are set by the DWER and WC, and all monitored turbidity events greater than 25 nephelometric turbidity unit (NTU) for an hour or more are reported.

Local monitors are positioned upstream from the compliance monitoring points. Local monitors provide information on the performance of the drainage infrastructure of the mine. They are generally located in streams below haul road crossings or in a series of large mine pits.

Figure 1. Turbidity monitor located within stream channel.

Figure 2. Turbidity data logger interfaced with stream channel monitor.

2.1.1 Holyoake Data

Turbidity data were sourced for 2 locations in the undisturbed Holyoake region (GHD 2022[2]), one for the 3.5 months from 15 July 2021 to 31 October 2021 (Figure 3) and the other for four months from 15 July 2021 to 16 November 2021.

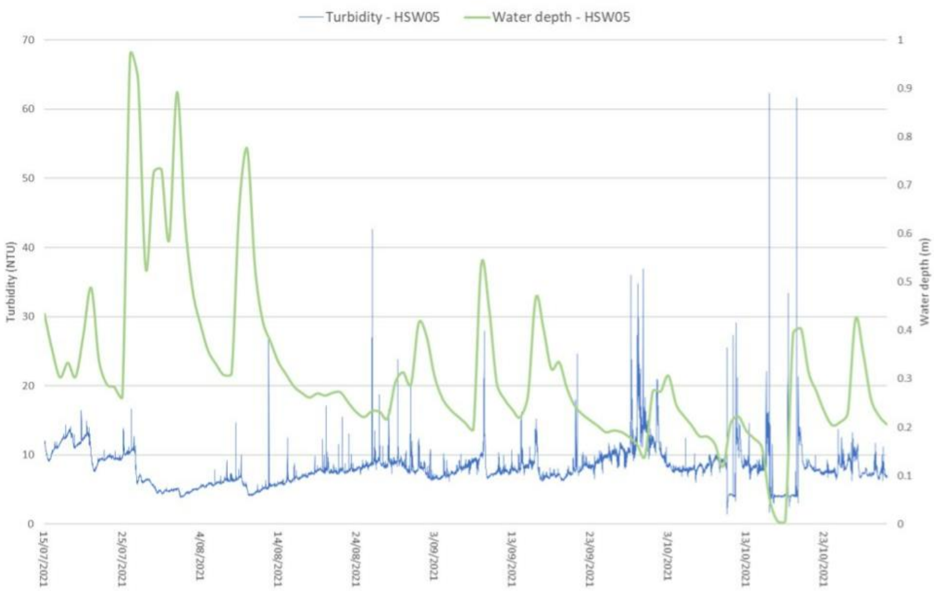

Figure 3. Holyoake turbidity and flow data (Site HSW05).

[2] GHD 2022. Surface and Groundwater Monitoring Report Myara North and Holyoake 2021 – 2022; 17 June 2022.

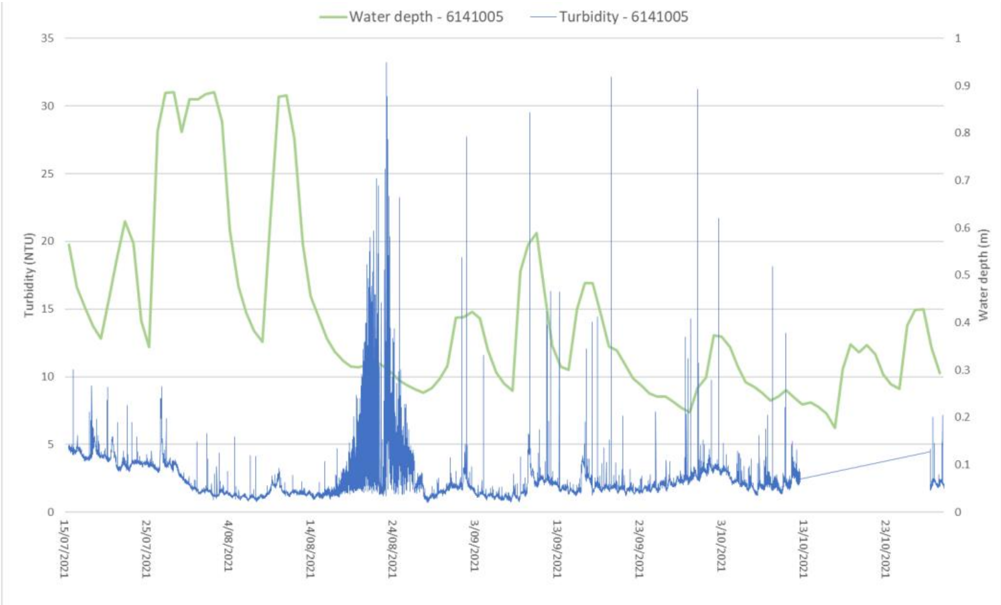

Figure 4. Holyoake turbidity and flow data (Site 6141005).

2.1.2 Huntly Data

Alcoa provided four overlapping sets of turbidity monitor data recorded in cleared catchments in the Huntly region dating back to 2016. Since then, the type of monitors and data loggers have changed, there have been multiple technologies used from transmitting data to databases and multiple databases have been used. Therefore, the data were sourced from several databases:

1. 2021-2022 Cleaned dataset: Manually cleaned data interpolated to 6-minute intervals for six Huntly monitors (PD01, PD02, SE10, SE51, SE59 and SE61) for the period from January 2021 to September 2022. This data has been cleansed of gross errors resulting from monitor malfunction or data telemetry issues but may still include other errors where high NTU readings are not due to water turbidity.

2. 2016-2022 Raw dataset: Data for 27 monitors (including the six listed above) for the period December 2016 to September 2022. The data are a mix of interpolated 6-minute interval data and irregularly spaced raw data that have been sourced from multiple databases.

3. 2001-2020 MIDAS dataset: Data for 2 monitors for the period September 2001 to June 2020 recorded interpolated to 6-minute intervals and sourced from the MIDAS database.

4. 2020-2022 Osisoft dataset: Data for 11 monitors for the period January 2020 to September 2022. The data are a mix of interpolated 6-minute interval data and irregularly spaced raw data that have been sourced from the Osisoft database.

Each of the four datasets were cleaned to remove data with missing timestamps, duplicates and zeroes before being combined into a single dataset. The 2021-2022 Cleaned data were used whenever these were available. Where the Cleaned data were unavailable, the Osisoft data were patched into fill gaps. If neither the Cleaned or Osisoft data were available, the Raw data were used. If there were no other data, the MIDAS data were used.

There were 30 monitors with unique IDs but only 25 of the IDs could be matched with metadata providing geolocation. Table 1 summarises the data for these 25 monitors. Appendix A contains time-series plots showing the patched data for each of the 25 monitors coloured according to the data source. Many have recorded data for a few months meaning they cannot be used in this study. Others exhibit substantial gaps where data are missing. Of the 25 monitors, we found:

1. 10 monitors with greater than 80% data coverage for the winter period from May to September 2021 to use for Top Level Analysis: DB01, DB02, PD01, SE10, SE48, SE51, SE52, SE53, SE59 and SE61.

2. 14 monitors with long-term coverage and greater than 70% data coverage for the period January 2021 and September 2022, which covers two winters to use for Statistical Modelling: DB01, DB02, ND06, ND07, PD01, PD02, SE10, SE48, SE51, SE52, SE53, SE59, SE61, SE62.

The first set is a subset of the second, therefore a total of 14 monitors were identified for use in this study and the time under consideration was limited to the period from January 2021 to September 2022. The 14 monitors include 11 compliance and 3 local monitors.

Table 1. Turbidity Data Temporal Coverage and Availability (25 Monitors).

ID	Start Date	End Date	Duration	NTU Availability	Jan 2021 – Sep 2022 Availability	May – Sep 2021 Availability
DB01	31/12/2016	07/09/2022	2,076 days	85%	81%	80%
DB02	31/12/2016	18/09/2022	2,087 days	73%	89%	92%
ND04	14/09/2001	29/09/2022	7,685 days	62%	0%	0%
ND06	31/12/2016	17/08/2022	2,055 days	61%	81%	55%
ND07	26/02/2021	03/07/2022	492 days	70%	70%	52%
ND14	04/06/2018	30/08/2022	1,548 days	12%	25%	10%
PD01	27/02/2019	30/09/2022	1,311 days	76%	80%	93%
PD02	18/05/2017	30/09/2022	1,961 days	56%	89%	73%
PD03	08/11/2021	29/09/2022	325 days	30%	30%	0%
SE01	17/03/2022	18/08/2022	154 days	34%	34%	0%
SE02	30/06/2022	18/08/2022	49 days	56%	56%	0%
SE05	01/07/2022	29/09/2022	90 days	71%	71%	0%
SE06	24/03/2022	04/10/2022	194 days	59%	58%	0%
SE07	14/06/2022	24/08/2022	71 days	91%	91%	0%
SE10	31/12/2016	30/09/2022	2,099 days	49%	80%	88%
SE12	14/06/2022	12/07/2022	28 days	100%	100%	0%
SE34T	13/02/2009	20/09/2022	4,967 days	43%	1%	0%
SE48	31/12/2016	04/10/2022	2,103 days	60%	75%	88%
SE51	14/07/2017	24/09/2022	1,898 days	75%	94%	95%
SE52	31/12/2016	18/09/2022	2,087 days	52%	76%	89%
SE53	31/12/2016	24/08/2022	2,062 days	65%	59%	100%
SE59	27/06/2019	30/09/2022	1,191 days	89%	85%	84%
SE60	14/06/2022	29/09/2022	107 days	98%	98%	0%
SE61	04/02/2021	30/09/2022	603 days	85%	85%	93%
SE62	26/02/2021	07/09/2022	558 days	40%	40%	38%

2.2 High Turbidity Events

For the purposes of this study, we define a high turbidity event based on the data alone, without categorisation of the cause, as **any occasion** when turbidity measurements exceed 25 NTU for one hour or longer. This includes both direct and indirect effects of mining. We further characterise true and false events, where readings for true events arise from an actual increase in water turbidity.

High NTU readings can occur in the absence of water turbidity, leading to detection of **false high turbidity events**. Such events may be caused by intermittent sensor saturation, obstruction by leaves or debris or when streams are dry. False events typically exhibit abrupt peaks/spikes or 'city skyline' patterns that flatline at maximum NTU (Figure 5).

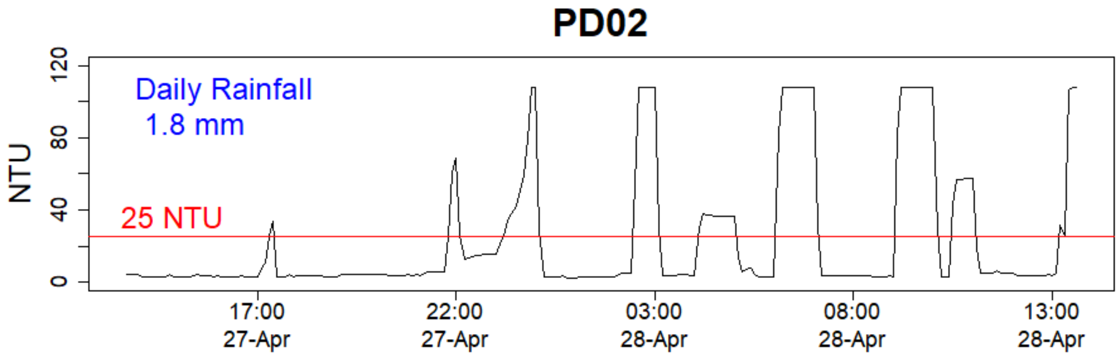

Figure 5. False high turbidity event showing a regular 'city skyline' pattern with tabletop flatlines for max stream turbidity measurements that are accompanied with sharp turbidity inclines and declines for each specific event.

In contrast, **true high turbidity events** are caused by an actual increase in stream water turbidity (e.g. from stream bank erosion, animal or vehicle crossings or sediment laden water entering a stream from operational mining areas). When graphed over time, true turbidity events typically show either a gradual (Figure 6) or sharp (Figure 7) increase in NTU following by a gradual decrease as the turbidity resolves. This is consistent with the findings of Landers and Sturm[3] and arises from the gradual process of dispersion of suspended solids over time.

True events are usually associated with rainfall events that cause runoff and erosion, which is also the case for true events that are caused by mining operations. They are therefore more common in winter than in summer.

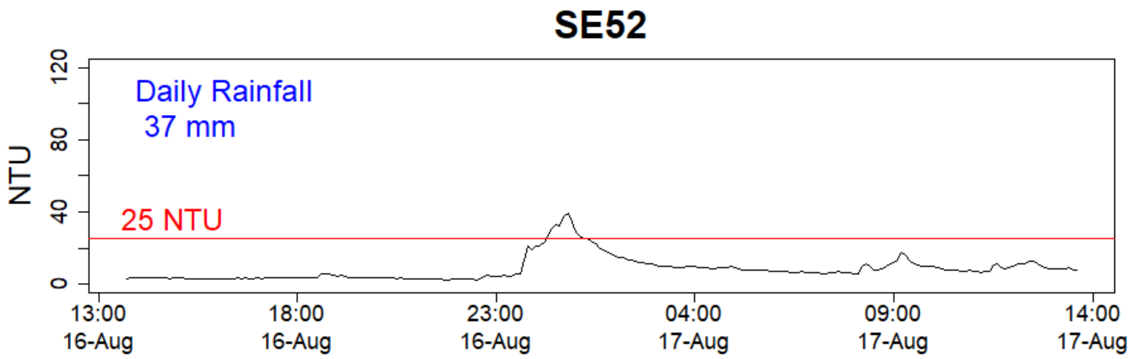

Figure 6. True turbidity event with a distinctive 'bell curve' shape before and after maximum NTU for the event.

[3] Landers, M. N. and Sturm T. W. (2013). Hysteresis in suspended sediment to turbidity relations due to particle size distributions, Water Resources Research 49, 5487-5500. DOI :10.1002/wrcr.20394

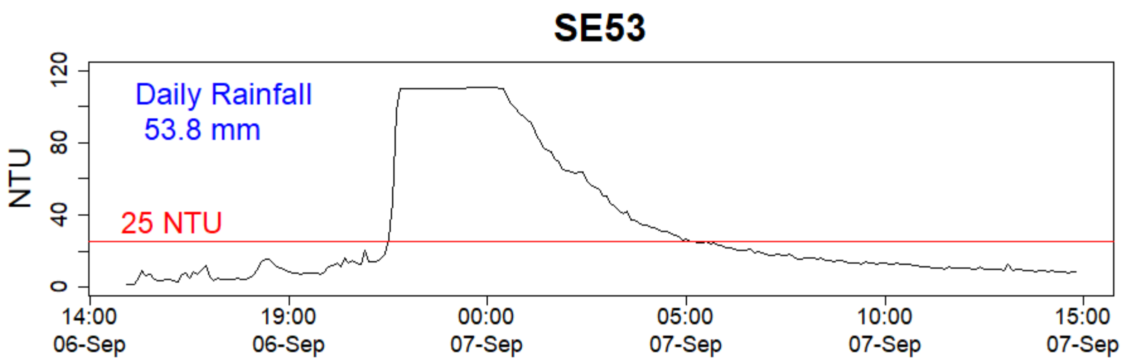

Figure 7. True high turbidity event where NTU increases sharply prior to reaching its maximum and then follows a gradual decline.

In some cases, false events exhibit a similar NTU pattern to true events (Figure 8). They can sometimes be distinguished from true events by considering rainfall and water flow data; if there is no flow, there cannot be turbidity. In other cases, they are assumed to be true until Alcoa can conduct a physical site inspection to determine the whether the high NTU reading is due to water turbidity.

While it is generally the case that events are more likely to occur after rainfall, events caused by mining-related drainage failures can release turbid waters into streams in the absence of rainfall.

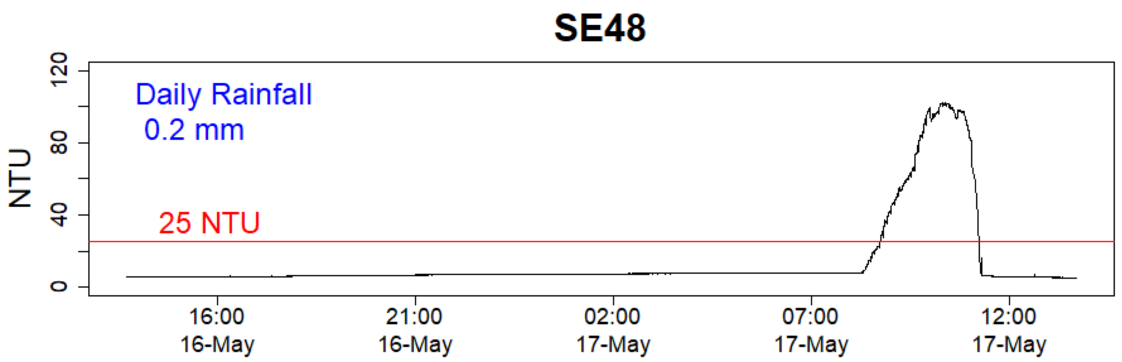

Figure 8. False high turbidity event with a sharp decline in NTU after its maximum caused by removal of a sensor obstruction.

2.2.1 Holyoake Data

No high turbidity events were detected by the two monitors in the undisturbed Holyoake catchment. However, both recorded occurrences of NTU above 25. One (HSW05) recorded 10 NTU peaks of NTU above 25, most were very short but one lasted for 10 minutes. The other (614005) recorded 21 peaks of NTU above 25, three for twenty minutes.

2.2.2 Huntly Data

Detection of high turbidity events for the 2021-2022 14-monitor patched Huntly dataset followed a well-established statistical methodology, which included cross-validation and verification as follows:

1. Detection and verification of events from the 6-monitor 2021-2022 Cleaned dataset. This involved cross-tabulating the event dates and locations of all high turbidity events with Alcoa's investigation records to determine whether they had been investigated. Investigated events were verified as true or false based on the results of the investigation. Any events that could not be verified were labelled true and retained in the dataset.
2. Development and cross-validation of an algorithm for removing detected false events using the verified events from Step 1. The algorithm was designed to remove as many false events as possible while retaining close to 100% of true events.
3. Detection, cleaning and verification of events from the 2021-2022 14-monitor Huntly dataset.

The detailed statistical methodology for each steps is described in Appendix C.

While it is generally the case that turbidity events tend to occur after rainfall, classification of high turbidity events as false based on rainfall data was not possible because of events caused when mining-related drainage failures release turbid waters into streams.

2.3 Spatial Data

Spatial data obtained from Alcoa included:

- A digital elevation model (DEM) at 5m resolution interpolated from contour data obtained from the WA Department of Land Administration (DOLA), now known as Landgate.
- Slope derived from the DEM.
- Monthly clearing maps from 1990 to August 2022.
- Annual rehabilitation maps from 1973 to 2021.
- Annual leaf area (LAI) index maps (scaled to between 0 and 6).
- Stream network map.

The location of turbidity monitors has been determined by mining locations and they are not necessarily located at catchment outlets. Because high turbidity events arise from surface and groundwater runoff, events measured by a monitor are only influenced by conditions upstream of the monitor's location. The location of turbidity monitors has been determined by mining locations and they are not necessarily located at conventionally defined catchment outlets. Consequently, this study has used the DEM to derived upstream catchment areas for each monitor used int this study. This process was performed using a sequence of Whitebox Tools[4] to breach and fill depressions in the DEM, create flow accumulation and pointer grids, snap monitor locations to streamlines and delineate watersheds.

The monitors and their upstream catchments are shown in Figure 9.

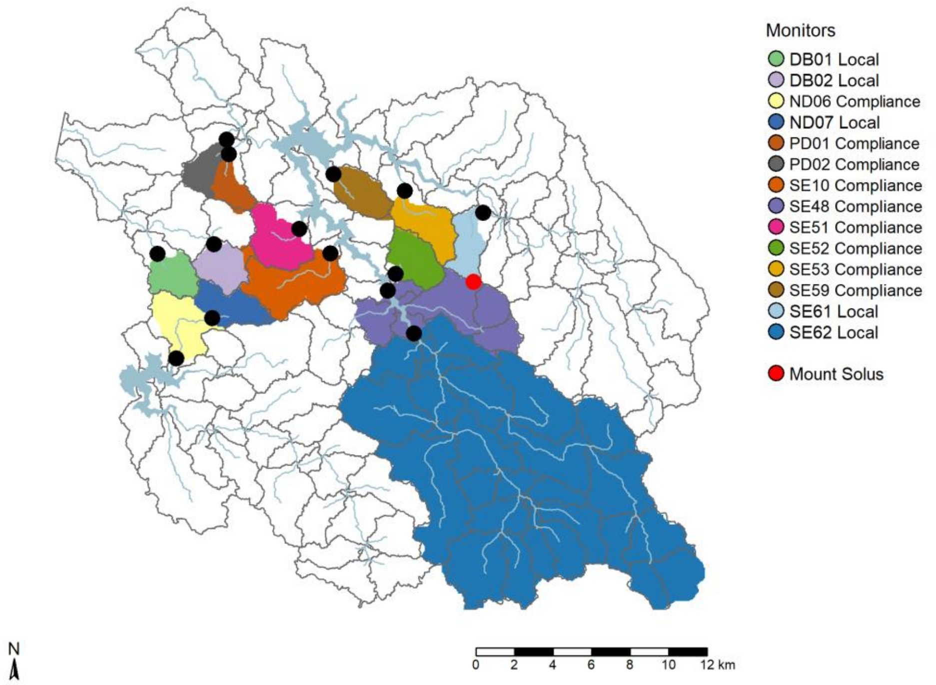

Figure 9. Upstream catchments calculated for the 14 turbidity monitors used in this study.

Appendix B includes time-series plots showing the area of upstream catchment cleared and revegetated for each monitor, and the distribution of the slopes in each catchment. The entire period since clearing is included in the clearing/revegetation time-series to allow interpretation of possible delayed effects on turbidity; note that the axis scales vary.

2.4 Rainfall Data

Rainfall recorded at Mount Solus (location shown in Figure 9) was sourced from the Bureau of Meteorology. Rainfall for January 2021 to September 2022 is shown in Figure 8. The year 2021 experienced the wettest July within the Mt Solus weather station record 2004 to 2022 (current) and 2022 May to August had above median rainfall as shown in Figure 11.

[4] Lindsay, J. B. (2016). Whitebox GAT: A case study in geomorphometric analysis. Computers & Geosciences, 95: 75-84. DOI: 10.1016/j.cageo.2016.07.003.

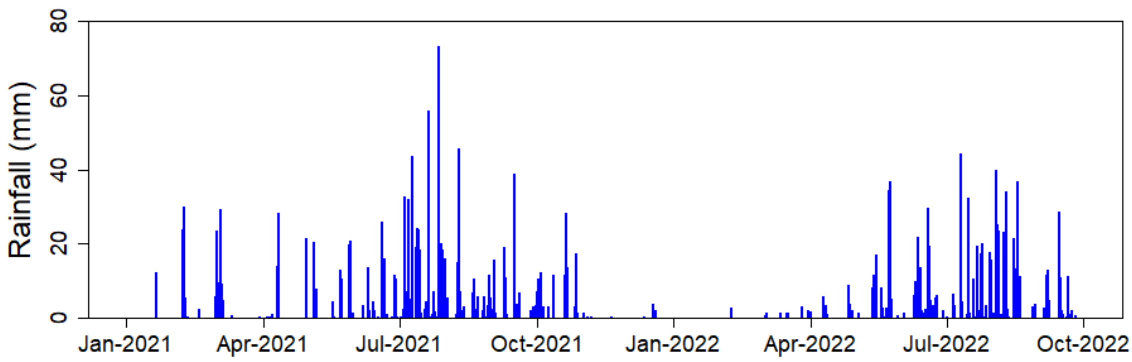

Figure 10. 2021 and 2022 daily rainfall recorded at Mount Solus.

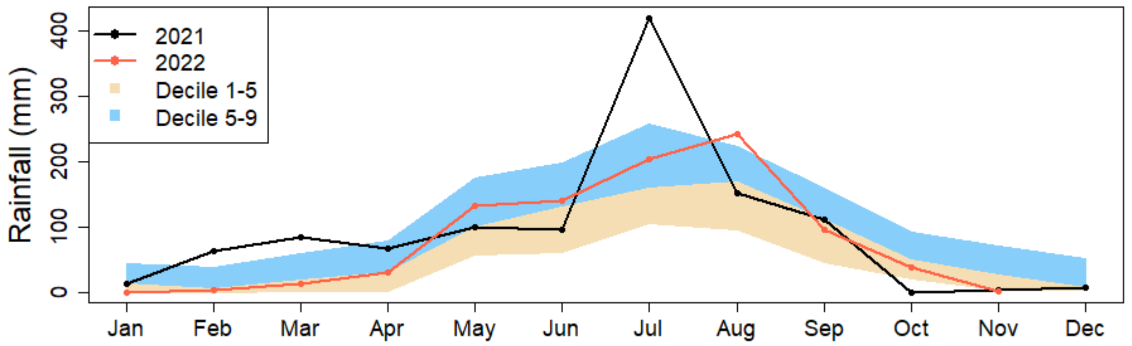

Figure 11. 2021 and 2022 monthly rainfall recorded at Mount Solus compared with historical rainfall (2004 to 2022) deciles.

2.5 Catchment Characteristics

For each monitor, we calculated catchment characteristics that could potentially impact risk of high turbidity events. These included:

- Catchment area (hectares).
- Area of the catchment with slopes higher than 16%.
- Mean and maximum catchment slope (%).
- Mean and maximum slope of the cleared part of the catchment (%).
- Area of the catchment that has been cleared, including includes areas that have subsequently been rehabilitated (hectares and percent of catchment).
- Area of the catchment that has been cleared and subsequently rehabilitated (hectares and percent of catchment).
- Area of the catchment that has been cleared and has not yet been rehabilitated (hectares and percent of catchment).
- LAI anomaly, being the difference between LAI at the time of the event and the long-term (1972 – 2022) mean LAI.
- LAI recovery, being the difference between LAI in rehabilitated parts of the catchment and LAI in the uncleared parts of the catchment.

Clearing, rehabilitation and leaf area index characteristics were calculated for each month from January 2021 to September 2022.

3. Stage 2: Top Level Analysis

The second stage of the project conducts correlation analyses to provide insight into the relationships between turbidity events and characteristics of their upstream catchment, including slope, clearing and rehabilitation.

3.1 Data for Top Level Analysis

To allow the number of events at each monitor to be directly compared, top level analysis requires a set of monitors that have good data coverage for a particular period of data, preferably in winter when high turbidity events are more likely to occur. We identified 10 monitors for use in top level analysis with > 80% turbidity data availability for the winter period May to September 2021: DB01, DB02, PD01, SE10, SE48, SE51, SE52, SE53, SE59 and SE61. Five of the 10 monitors experienced no high turbidity events. The other five experienced between 4 and 15 events.

Interim Report 2: Top Level Analysis of 2021-2022 Dataset reported the results of top-level analysis of the 6-monitor 2021-2022 Cleaned dataset. Upstream catchment characteristics were calculated at the time of event occurrences and averaged for each catchment. This approach cannot be used for catchment with no events, so we have adopted a different approach. We determined that minimal clearing and rehabilitation occurred during the 5-month period being considering, and therefore calculated clearing and rehabilitation areas and percentages at the end of the period, 30 September 2021.

Table 2 summarises the upstream catchment characteristics and numbers of high turbidity events for each monitor. The mean and maximum slope were calculated from the 5m resolution slope map.

Table 2. Summary of May to September 2021 data used for the top level analysis. Note that the areas cleared are the total areas cleared including areas that have been subsequently rehabilitated.

ID	Area (ha)	Area > 16% Slope (ha)	Mean Slope (%)	Max Slope (%)	Mean Slope of Cleared Area (%)	Max Slope of Cleared Area (%)	Area Cleared (ha)	Area Cleared > 16% Slope (ha)	Area Rehabilitated (ha)	Area Rehabilitated > 16% Slope (ha)	Number of Events
DB01	492	21	8.9	26.8	10.3	24.7	160	8	155	8	0
DB02	519	2	6.5	21.2	6.7	17.9	203	0	79	0	0
PD01	376	57	10.4	49.6	11.4	25.2	95	17	11	6	7
SE10	1,198	147	9.0	48.8	8.9	27.8	448	49	112	2	0
SE48	18,301	1,505	7.7	97.0	8.5	27.2	3,241	186	2,505	105	0
SE51	749	111	10.8	32.1	10.9	25.1	369	48	42	2	10
SE52	609	274	15.7	64.0	14.2	34.8	186	77	13	4	4
SE53	675	211	12.9	40.3	11.6	34.0	273	68	19	10	0
SE59	573	37	9.7	28.7	9.7	22.8	192	9	0	0	8
SE61	515	215	15.8	66.0	13.0	29.6	141	45	6	0	15

3.2 Methodology

The relationships between number of high turbidity events and individual catchment characteristics are explored using correlation plots. Each point in the plots represents a particular turbidity monitor and its associated upstream catchment area. For each plot, the line of best fit between the catchment characteristic shown on the x-axis and the number of turbidity events shown on the y-axes is drawn in black.

The R value shown in the plots is the Pearson's correlation coefficient which ranges in value from -1 to 1. Negative R values indicate a negative relationship where higher values on the x-axis correspond to lower numbers of events. Positive R values indicate a positive relationship where higher values on the x-axis correspond to higher numbers of events. The strength of the relationship is indicated by the magnitude of R where R values of zero mean there is no relationship, R values of -1 indicate a strong negative relationship and R values of 1 indicate a strong positive relationship.

The p-value is an indicator of statistical significance of the linear relationship, or how confident we are that a real relationship exists, with lower values indicating that the relationship is more likely to be real and not due to chance. A p-value of 0.1 means that there is a 10% chance the identified relationship may be due to chance and a p-value of 0.05 means there is only a 5% chance that the relationship may be due to chance. We say that a relationship is statistically significant at the 0.1 level if $p \leq 0.1$ or at the 0.05 level if $p \leq 0.05$.

Statistical significance is affected by the size of the dataset used, making it difficult to find statistically significant relationships using smaller datasets. This makes sense because larger datasets provide more information, and we can therefore be more confident about the conclusions we can reach from the data. The results presented in this section should therefore be interpreted cautiously as they are limited by the small number of monitors and short time period.

3.3 Slope and Catchment Area

Figure 12 shows correlation plots for the number of events in a catchment compared with catchment area, the area of the catchment slopes greater than 16%, mean and maximum slope and the mean and maximum slope of the cleared area. The only significant relationship found is that between mean slope and number of events, such that the number of events increases with mean slope, which is significant at the 0.1 level, meaning there is only 10% probability the relationship may be due to chance. The mean slope of the cleared area is highly correlated with the mean slope of the entire catchment ($R = 0.95$, $p = < 0.001$).

The correlation plots appear to be influenced by the large catchment associated with the SE48 monitor, which is 18 times as large any other catchment. However, if SE48 is excluded, the correlations are largely unchanged, except for the area of the catchment slopes greater than 16%, which changes from $R = -0.24$ to $R = 0.2$ with neither value significant meaning that no real relationship exists.

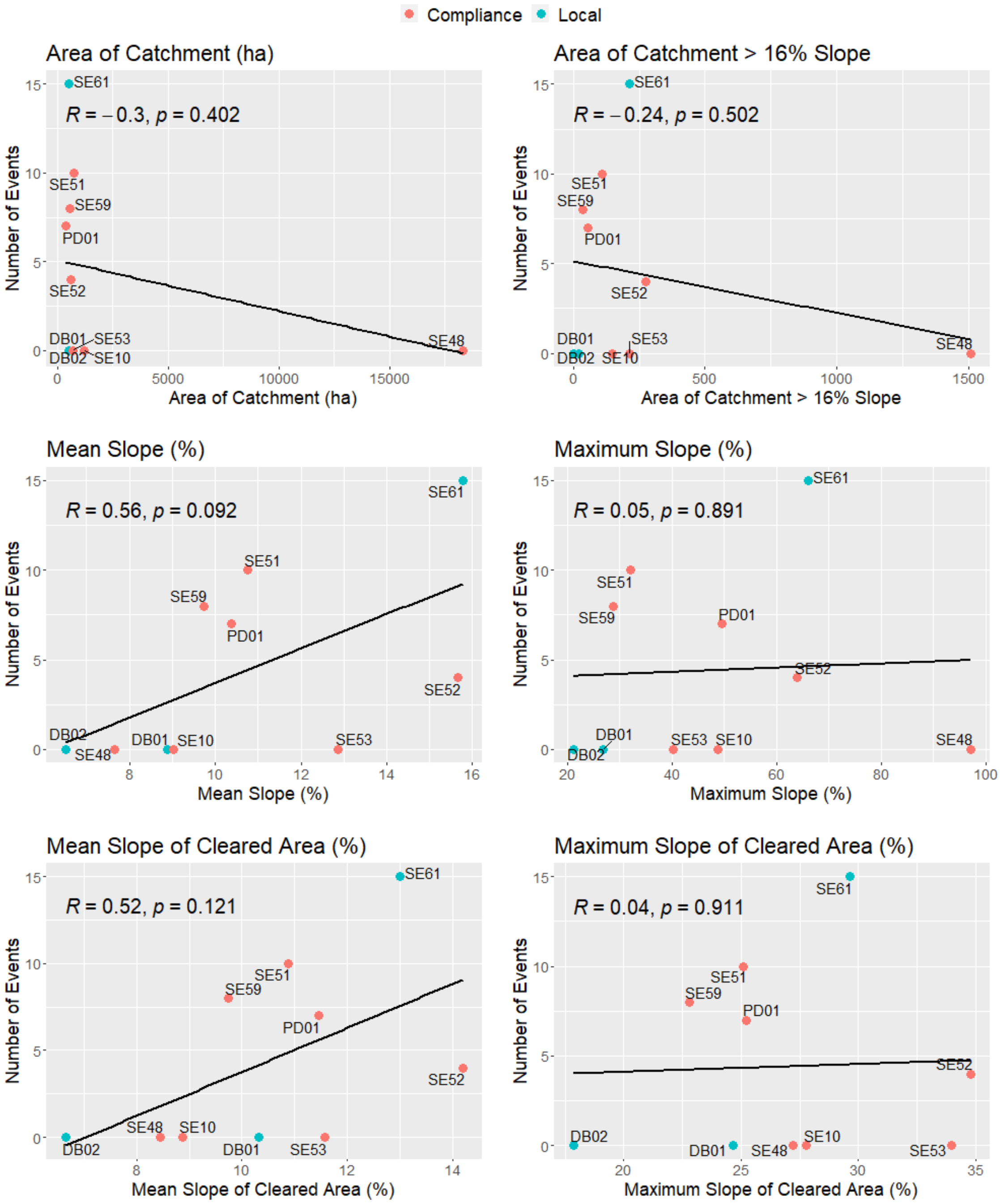

Figure 12. Correlation of the number of high turbidity events with static catchment characteristics of upstream catchments.

3.4 Clearing and Rehabilitation

Figure 13 shows the correlation between the number of events in a catchment with the area cleared (including areas subsequently rehabilitated), area rehabilitated and area cleared and not yet rehabilitated. It shows that the number of events is not significantly affected by the area of the catchment that has been cleared or rehabilitated. Again, monitor SE48 appears to be an outlier. If SE48 is removed, the relationships between the cleared area with slopes greater than 16% and current cleared area become positive but not significant.

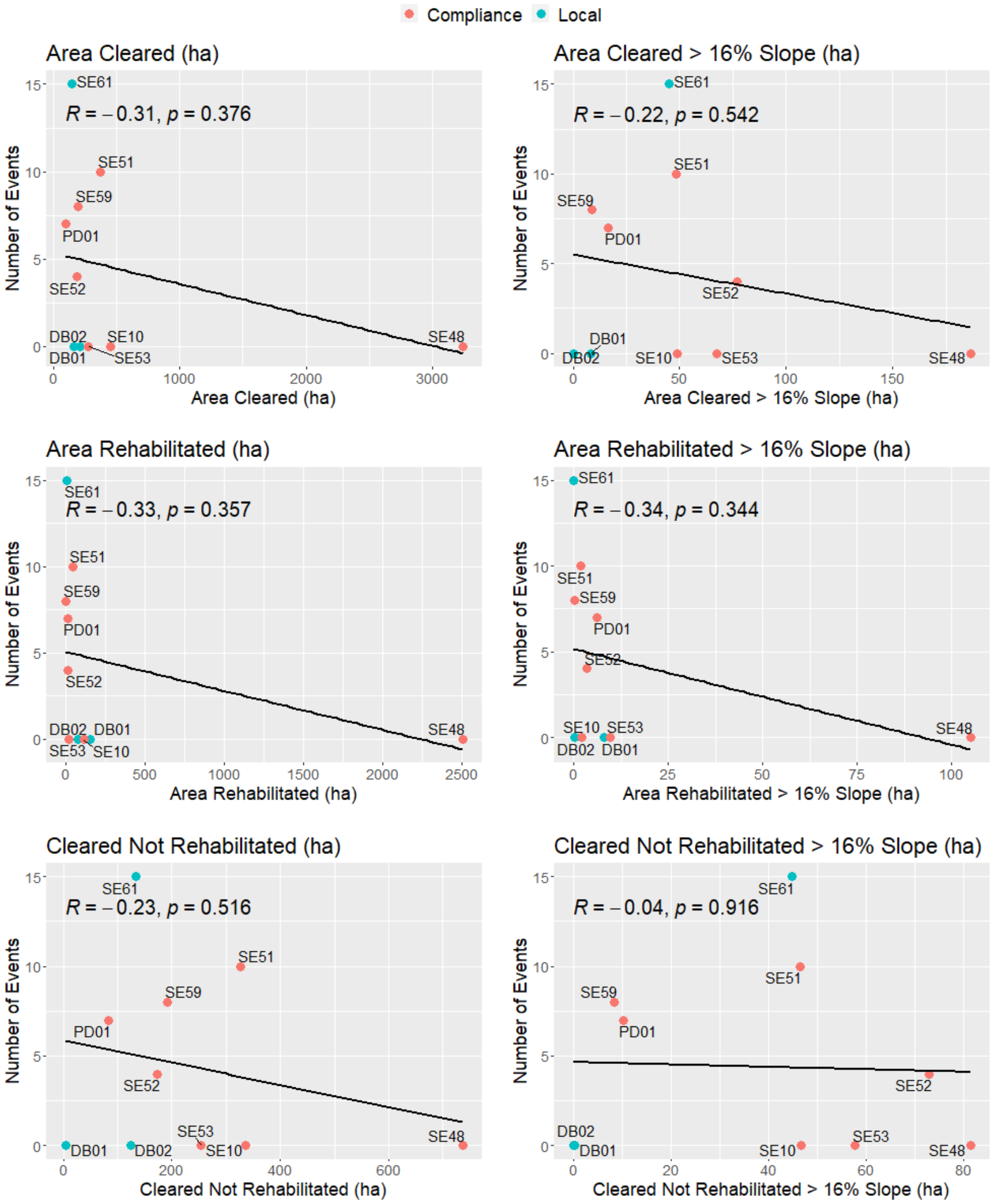

Figure 13. Correlation of the number of high turbidity events with area cleared (including areas subsequently rehabilitated), area rehabilitated, and area cleared but not yet rehabilitated (left column) and the same for parts of the catchment with slopes greater than 16% (right column).

Figure 14 shows the correlation between the number of events in a catchment with the percentage of the catchment that has been cleared (including areas subsequently rehabilitated), the percentage that has been rehabilitated and percentage cleared and not yet rehabilitated. There is a significant negative relationship (at the 0.1 level) between the percentage of the catchment that has been rehabilitated, with fewer high turbidity events occurring in catchments with more rehabilitation. The relationship between the percentage area of the catchment that has been cleared but not yet rehabilitated is positive but not significant.

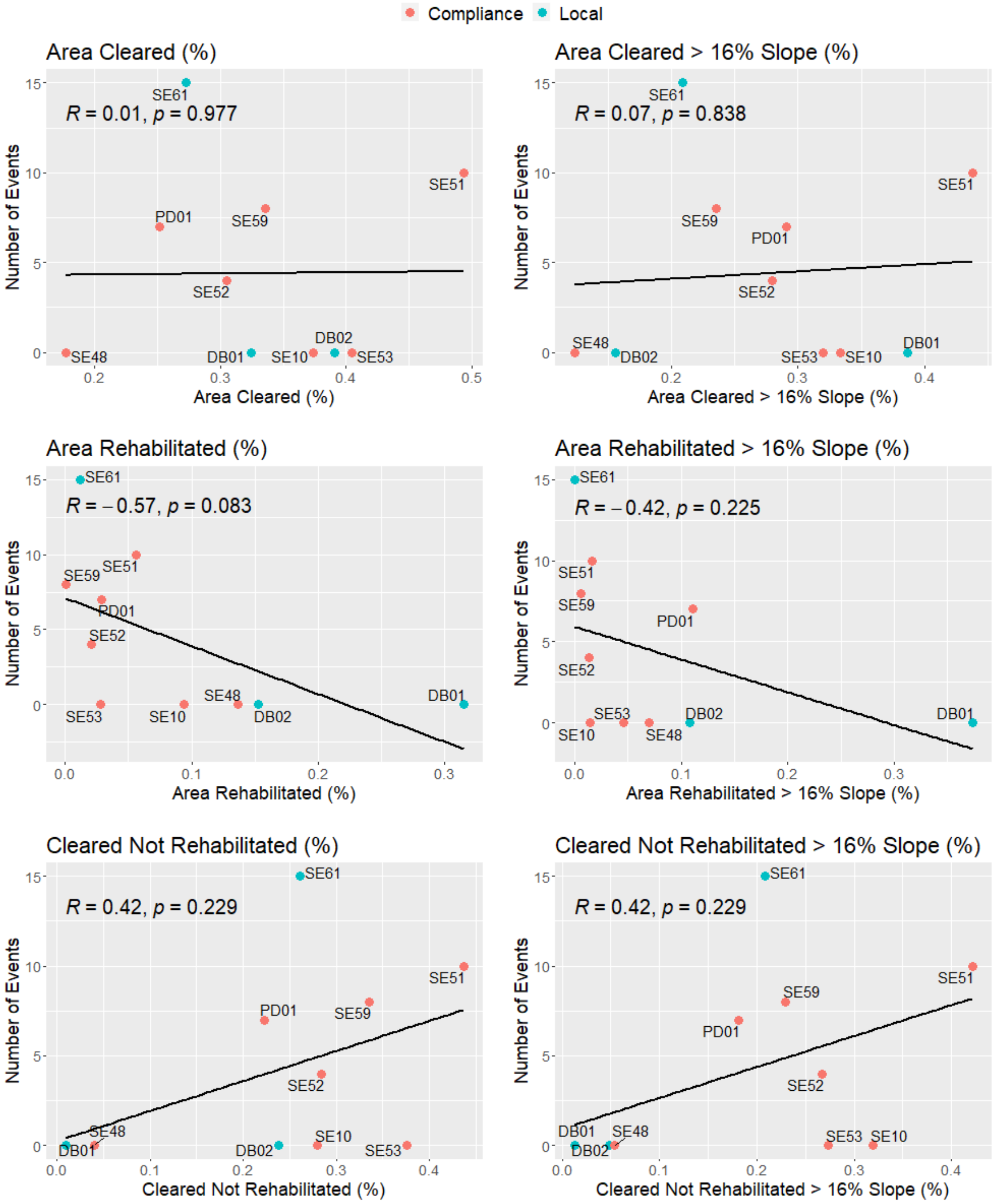

Figure 14. Correlation of the number of high turbidity events with percentage area cleared (including areas subsequently rehabilitated), percentage area rehabilitated, and percentage area cleared but not yet rehabilitated (left column) and the same for parts of the catchment with slopes greater than 16% (right column).

3.5 Leaf Area Index

Figure 15 shows the correlation between the number of events in variables derived from the LAI data. The LAI anomaly is the difference between LAI at the time of the event and the long-term (1972 – 2022) mean LAI. Higher values indicate the LAI in the catchment at the time of the event is greater than average LAI. LAI recovery compares the LAI in the rehabilitated parts of the catchment to LAI for the uncleared part of the catchment. Higher values indicate the LAI of the rehabilitated area is greater than the LAI of the uncleared area. There is no relationship between number of events and LAI anomaly, and a small non-significant positive relationship with number of events and LAI recovery. This positive relationship indicates some positive effect of hydrological recovery in the catchments.

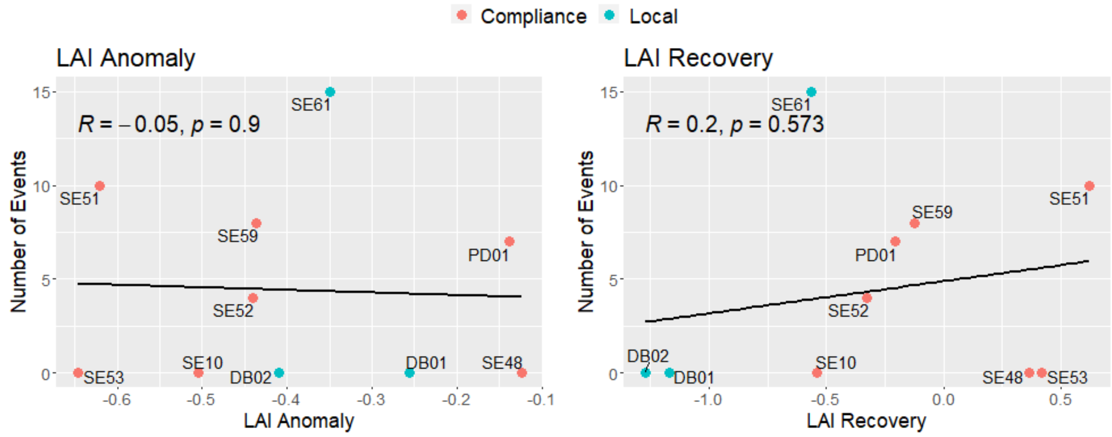

Figure 15. Correlation of the number of high turbidity events with LAI index anomaly (the difference between LAI in September 2021 and the long-term LAI) and LAI recovery (the difference between LAI in the rehabilitated part of the catchment and LAI in the uncleared part of the catchment).

3.6 Summary of Results

Table 3 summarises the correlations of catchment characteristics with the number of high turbidity events in each catchment. The only significant (at the 0.1 level, meaning only a 10% probability that the relationship is due to chance) correlations are with mean catchment slope and the percentage area of the catchment that has been rehabilitated (shown in grey). The second highest correlation is with area of the catchment in hectares followed by mean slope of the cleared part of the catchment and mean slope of the whole catchment.

Table 3. Summary table of correlations with numbers of events (significant correlations are shaded grey).

Variable	R^2	*p*-value
Area (ha)	-0.30	0.402
Area > 16% Slope (ha)	-0.24	0.502
Mean Slope	0.56	0.092
Max Slope	0.05	0.891
Cleared Mean Slope	0.52	0.121
Max Cleared Slope	0.04	0.911
Area Cleared	-0.31	0.376
Area Cleared > 16% Slope	-0.22	0.542
Area Rehabilitated	-0.33	0.357
Area Rehabilitated > 16% Slope	-0.34	0.344
Area Cleared not Rehabilitated	-0.23	0.516
Area Cleared not Rehabilitated > 16% Slope	-0.04	0.916
Percent Area Cleared	0.01	0.977
Percent Area Cleared > 16% Slope	0.07	0.838
Percent Area Rehabilitated	-0.57	0.083
Percent Area Rehabilitated > 16% Slope	-0.42	0.225
Percent Area Cleared and not Rehabilitated	0.42	0.229
Percent Area Cleared and not Rehabilitated > 16% Slope	0.42	0.229
LAI Anomaly	-0.05	0.900
LAI Recovery	0.20	0.573

4. Stage 3: Statistical Modelling

The top level analysis reported in the previous section is useful for highlighting individual relationships, but the many factors affecting turbidity can act interact and it is vital to consider relationship between multiple factors simultaneously. The third stage of this study considers relationships between multiple catchment characteristics using statistical modelling. This also allows the use of a larger dataset since a statistical model can be used when there are temporal gaps in the data.

4.1 Data for Statistical Modelling

We used January 2021 to September 2022 data from 14 monitors for statistical modelling: DB01, DB02, ND06, ND07, PD01, PD02, SE10, SE48, SE51, SE52, SE53, SE59, SE61, SE62.

Data for the 14 monitors were aggregated to monthly counts of high turbidity events, and timed rehabilitation, clearing, LAI and rainfall characteristics were extracted for the 28th of each month. The temporal availability of NTU data for each month was calculated and months with less than 80% NTU availability were excluded.

Table 4 shows the counts of months with different numbers of events per month for each monitor and the total number of events for each monitor. While most months have zero or one event only, there are months with up to seven events recorded.

Table 4. Counts of months with different numbers of events and total number of events for each monitor in the statistical modelling dataset.

ID	< 80% NTU Available	Number of events per month 0	1	2	3	4	5	6	7	Number of Events
DB01	1	14	0	0	0	0	0	0	0	0
DB02	0	15	0	0	0	0	0	0	0	0
ND06	3	13	1	0	1	0	0	0	0	4
ND07	6	11	0	0	0	0	0	0	0	0
PD01	4	12	1	0	2	0	1	0	0	12
PD02	1	11	4	1	1	0	0	0	0	9
SE10	2	13	3	0	0	0	0	0	0	3
SE48	2	14	0	0	0	0	0	0	0	0
SE51	0	8	8	1	0	1	1	0	0	19
SE52	4	13	1	0	1	0	0	0	0	4
SE53	8	10	0	0	1	0	0	0	0	3
SE59	0	10	3	3	0	0	0	0	0	9
SE61	2	7	1	3	1	1	0	1	1	27
SE62	7	6	0	0	0	0	0	0	0	0

Figure 16 shows the monthly event counts for each monitor. Most of the counts are zero. This is known as zero-inflation and it affects the type of statistical models that can be used.

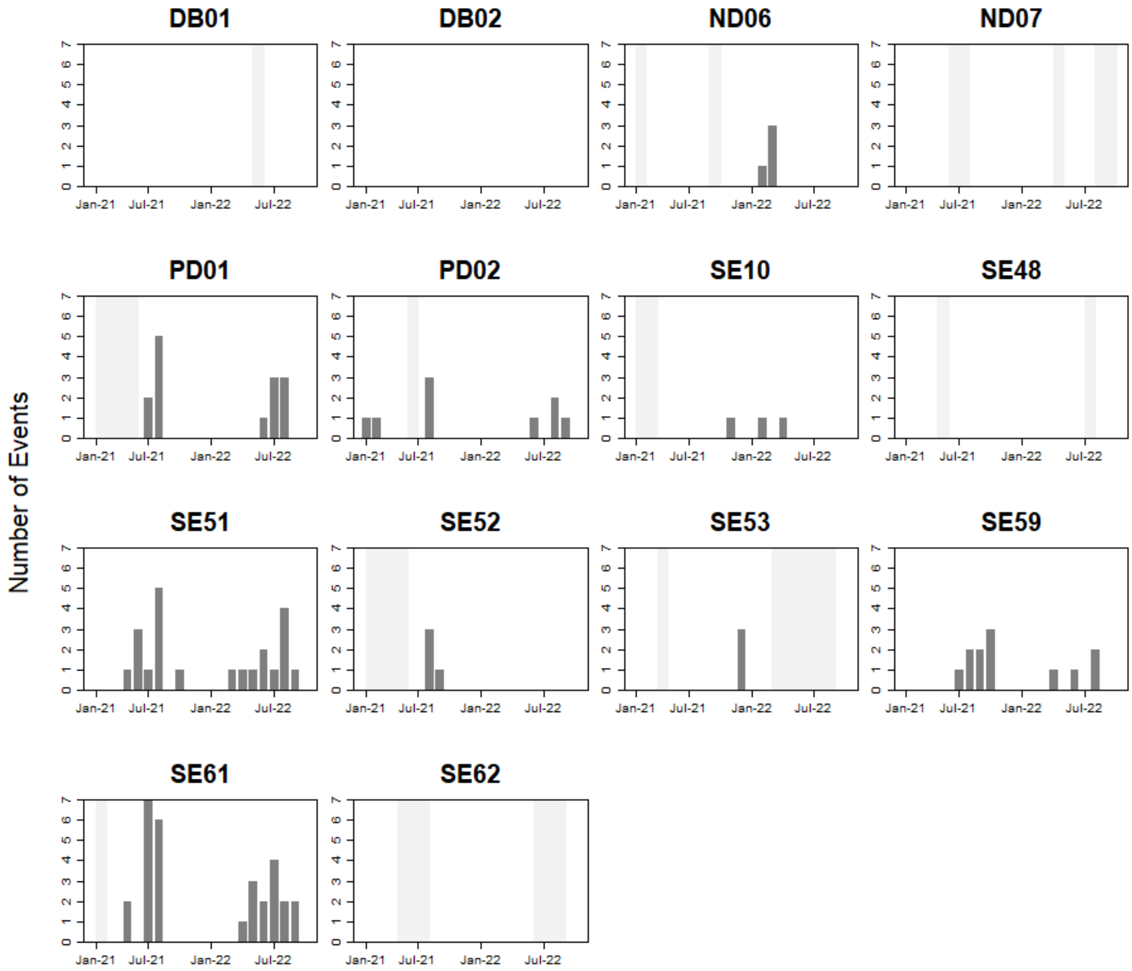

Figure 16. Monthly counts of events for each monitor in the statistical modelling dataset. Months with <80% NTU availability have been marked in grey and are excluded.

Table 5 summarises the mean monthly upstream catchment characteristics and numbers of high turbidity events for each monitor.

Table 5. Summary of mean January 2021 to September 2022 monthly data used for statistical modelling. Note that the areas cleared are the total areas cleared including areas that have been subsequently rehabilitated.

ID	Area (ha)	Area > 16% Slope (ha)	Mean Slope (%)	Max Slope (%)	Mean Slope of Cleared Area (%)	Max Slope of Cleared Area (%)	Area Cleared (ha)	Area Cleared > 16% Slope (ha)	Area Rehabilitated (ha)	Area Rehabilitated > 16% Slope (ha)
DB01	492	21	8.9	26.8	10.3	24.7	160	8	155	8
DB02	519	2	6.5	21.2	6.7	17.9	206	0	88	0
ND06	783	64	8.7	29.4	9.2	27.8	311	26	151	7
ND07	598	39	8.1	24.5	8.6	24.5	269	22	75	3
PD01	376	57	10.4	49.6	11.5	25.2	94	17	26	9
PD02	390	98	11.5	39.1	10.3	20.8	18	1	5	0
SE10	1,198	147	9.0	48.8	8.9	27.8	450	50	114	4
SE48	18,301	1,505	7.7	97.0	8.5	27.3	3,243	187	2,578	109
SE51	749	111	10.8	32.1	10.9	25.1	369	48	42	2
SE52	609	274	15.7	64.0	14.2	34.8	186	77	15	4
SE53	675	211	12.9	40.3	11.6	34.0	281	69	20	10
SE59	573	37	9.7	28.7	9.7	22.8	195	8	0	0
SE61	515	215	15.8	66.0	13.0	29.6	142	45	7	0
SE62	16,150	961	7.1	54.6	8.1	25.1	2,640	102	2,237	77

4.2 Methodology

Using a statistical model, we can consider how catchment characteristics combine to affect the number of high turbidity events in a catchment.

Trigonometric terms are useful when data are affected by seasonality; however, we found that they are correlated with rainfall and add no further explanation beyond what could be found using rainfall alone. They are therefore not included.

Poisson regression models provide a standard framework for analysis of count data. Poisson regression is a particular case of a generalised linear model (GLM). It is usually implemented with a logarithmic link function that gives the model a relative risk structure.

Because the high turbidity event counts are zero-inflated, we used a two-part hurdle model. The first part considers which catchment characteristics explain events occur or not. A binomial GLM with a logit link function is used to binary case of events versus no event. The second part of the model considers what influences the number of events when they occur. A truncated Poisson GLM with a log link function is used for the second part.

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Statistical models require that the predictor variables (the catchment characteristics) are independent. When predictor variables are correlated, they cannot independently explain changes in the dependent variable (number of events). This situation is referred to as collinearity.

Figure 17 shows that catchment area, area cleared, area rehabilitated and the equivalent areas with slopes greater that 16% are all highly correlated to each other. Similarly, the mean slope and means slope of cleared areas are highly correlated.

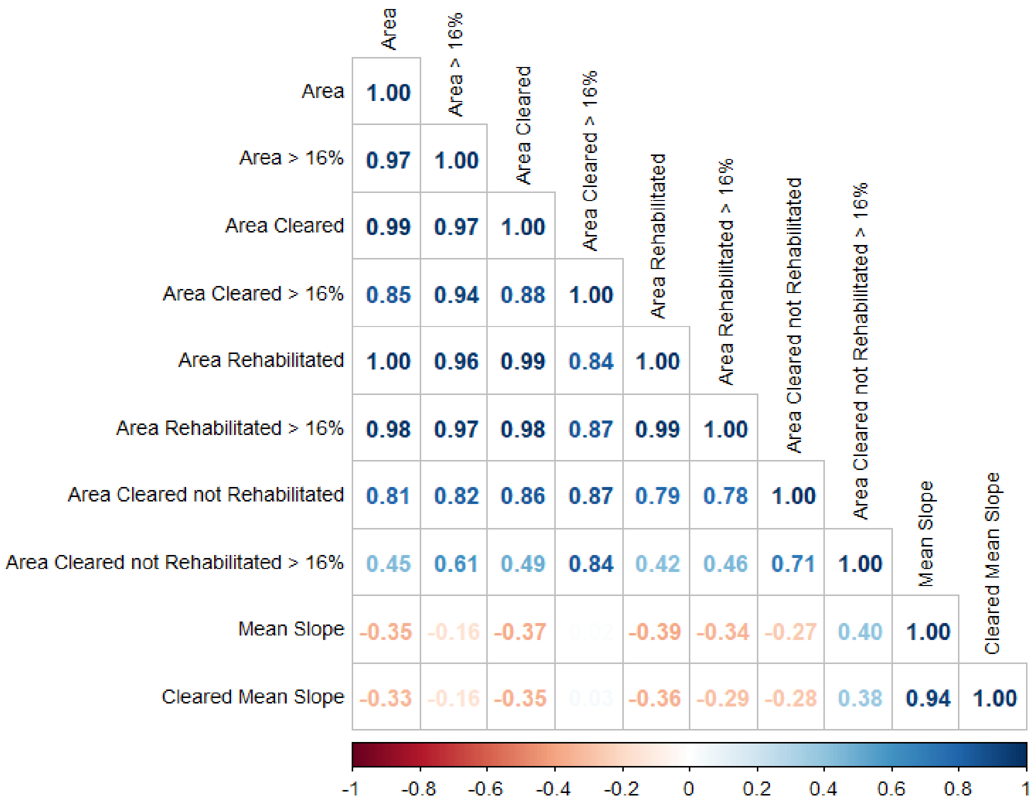


Figure 17. Cross-correlations between catchment characteristics.

We also considered whether it was more appropriate to consider areas cleared and rehabilitated in hectares or as percentages of the catchments. Figure 18 shows that if the SE48 and SE62 monitors with very large catchment area are removed, then the areas in hectares and percentages are correlated. Since catchment scale influences processes such as deposition and settlement of eroded materials and dilution by cleaner water from other parts of the catchment, we model using areas expressed as percentages of catchment area.

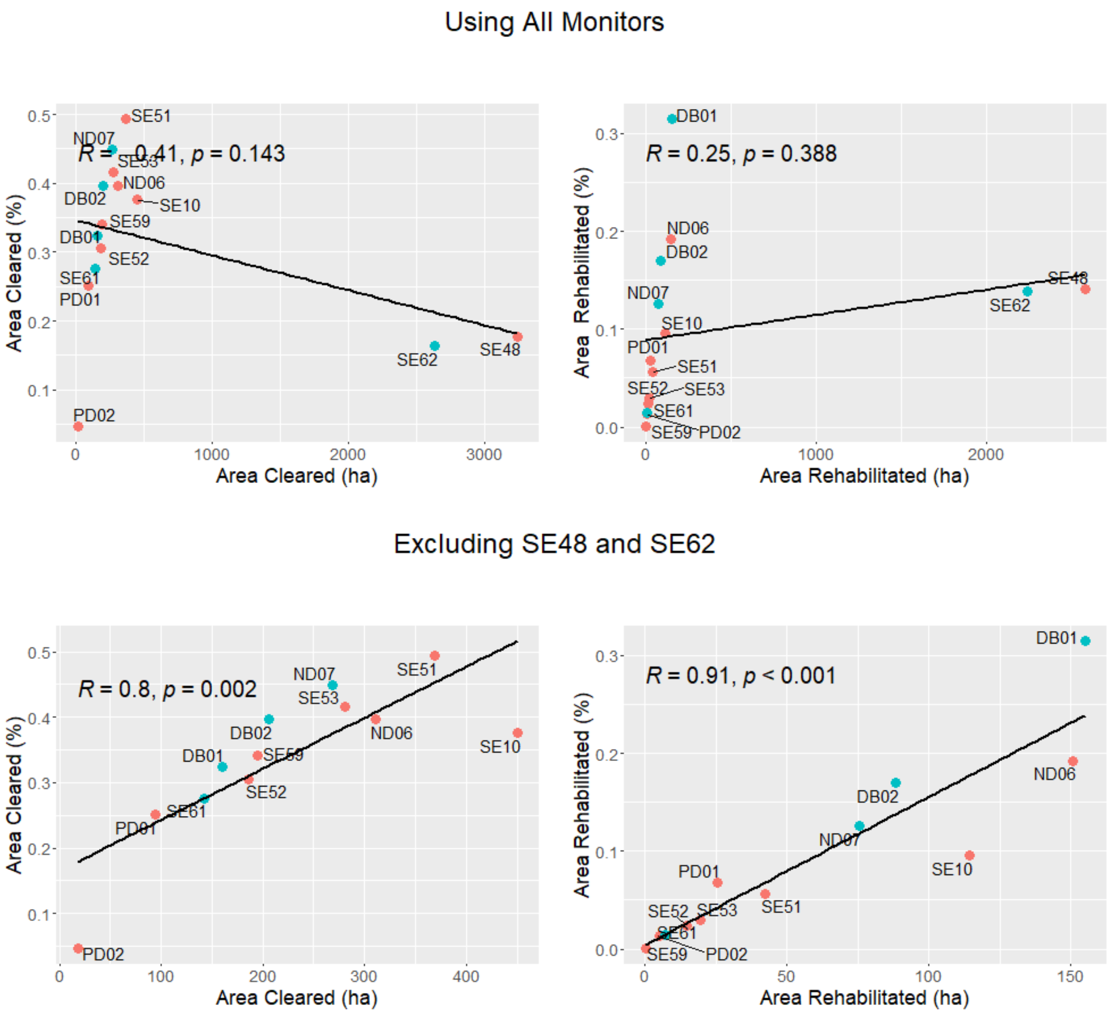


Figure 18. Correlations between areas cleared and rehabilitated in hectares and as percentages of the catchments, with and without including outliers SE48 and SE62.

To avoid issues of collinearity, we need to use a smaller subset of catchment characteristics for statistical modelling, selecting the most informative characteristic from those groups that are correlated. However, we can use different characteristics to answer different questions.

We estimate three statistical models with different sets of characteristics to answer two specific questions.

Model 1: Total Clearing

To determine how clearing influences the number of high turbidity events, we use the:

- Percentage of the catchment that has been cleared (including areas that have been subsequently rehabilitated).
- Mean catchment slope.
- Rainfall.

Model 2: Clearing Prior To Rehabilitation

To take rehabilitation into account, we consider how the currently cleared area (ie. cleared land that has not yet been rehabilitated) influences the number of high turbidity events, we use the:

- Percentage of the catchment that has been cleared but not yet rehabilitated.
- Mean catchment slope.
- Rainfall.

Model 3: Clearing and Rehabilitation

To determine the total effect of both clearing and rehabilitation, we use the:

- Percentage of the catchment that has been cleared but not yet rehabilitated.
- Percentage of the catchment that has been cleared and rehabilitated.
- Mean catchment slope.
- Rainfall.

4.3 Results

Model 1: Total Clearing

Model 1 considers how clearing influences the number of high turbidity events. Table 6 shows the estimated hurdle model coefficients, standard errors and associate *p*-values for Model 1. The stars indicate statistical significance where *p*-values where one star means a variable is statistically significant effect at the 0.05 level and more stars indicate higher significance.

Table 6. Model 1 summary.

High turbidity event occurrence model	Coefficient	SE	*p*-value
Intercept	-4.882	1.027	< 0.001 ***
Mean catchment slope (%)	0.227	0.065	< 0.001 ***
Area cleared (%)	1.663	1.6106	0.474
Rainfall (ha)	0.005	0.002	< 0.001 ***
High turbidity event count model	**Coefficient**	**SE**	***p*-value**
Intercept	-2.193	0.878	0.012 *
Mean slope (%)	0.125	0.053	0.011 *
Area cleared (%)	0.782	1.093	0.474
Rainfall (mm)	0.004	< 0.001	< 0.001 ***

The results show that:

- The total percentage area cleared (including subsequently rehabilitated areas) has no effect on the chance of high turbidity events occurring or on the number of high turbidity events if they occur.
- Catchment slope has a significant effect on both the occurrence of high turbidity events and their number, with more events in catchments with higher mean slope.
- Rainfall has a significant effect on both the occurrence of high turbidity events and their number, with more events in wetter months.

Model 2: Clearing Prior To Rehabilitation

Model 2 considers how the currently cleared area (ie. cleared land that has not yet been rehabilitated) influences the number of high turbidity events. Table 7 shows the estimated hurdle model coefficients, standard errors and associate *p*-values for Model 2. The stars indicate statistical significance where *p*-values where one star means a variable is statistically significant effect at the 0.05 level and more stars indicate higher significance.

Table 7. Model 2 summary.

High turbidity event occurrence model	Coefficient	SE	*p*-value
Intercept	-4.752	0.855	< 0.001 ***
Mean catchment slope (%)	0.183	0.065	0.005 **
Area cleared but not rehabilitated (%)	0.354	1.553	0.022 *
Rainfall (ha)	0.005	0.002	0.002 ***
Cou High turbidity event count model	**Coefficient**	**SE**	***p*-value**
Intercept	-2.295	0.795	0.015 *
Mean catchment slope (%)	0.156	0.052	0.013 *
Area cleared but not rehabilitated (%)	-0.001	1.113	0.776
Rainfall (mm)	0.005	< 0.001	< 0.001 ***

The results show that:

- Percentage area cleared but not rehabilitated has a significant effect on the chance of high turbidity events occurring.
- Percentage area cleared but not rehabilitated does not affect the number of high turbidity events if they occur.

Model 3: Clearing and Rehabilitation

Model 3 considers the total effect of both the total effect of clearing and rehabilitation. Table 8 shows the estimated hurdle model coefficients, standard errors and associate *p*-values for Model 3. The stars indicate statistical significance where *p*-values where one star means a variable is statistically significant effect at the 0.05 level and more stars indicate higher significance.

Table 8. Model 3 summary.

High turbidity event occurrence model	Coefficient	SE	*p*-value
Intercept	-2.336	1.279	0.068 **
Mean slope (%)	0.052	0.086	0.544
Area cleared but not rehabilitated (%)	2.370	1.568	0.131
Area cleared and rehabilitated (%)	-9.841	4.320	0.023 *
Rainfall (ha)	0.005	0.002	0.003 **
High turbidity event count model	**Coefficient**	**SE**	***p*-value**
Intercept	-3.028	1.045	0.004 **
Mean slope (%)	0.180	0.062	0.004 **
Area cleared but not rehabilitated (%)	0.316	1.142	0.782
Area cleared and rehabilitated (%)	7.694	3.985	0.053
Rainfall (mm)	0.005	0.001	< 0.001 ***

The results show that:

- When rehabilitation is considered, percentage area cleared but not rehabilitated has no significant effect on the chance of high turbidity events occurring or on the number of high turbidity events if they occur.
- Percentage area rehabilitated has a significant negative effect on the chance of high turbidity events occurring.

4.4 Model Predictions

Comparison of the goodness of fit of each of the three models using the Akaike Information Criterion suggests that while each of the model fits well, model 3 is the best model for making predictions given that it has the minimum AIC (Table 9). This model allows us to predict the expected number of high turbidity events given different rainfall, catchment slope, clearing and rehabilitation scenarios.

Table 9. Model Comparison.

Model	Degrees of Freedom	AIC
Model 1	8	306.37
Model 2	8	302.32
Model 3	10	296.99

This is done by combining the two parts of the model – the occurrence model and the count model – to give the most likely number of events as a continuous-valued number. In reality, the numbers of events are integers, but the continuous-valued prediction gives what would be expected on average for a given set of conditions.

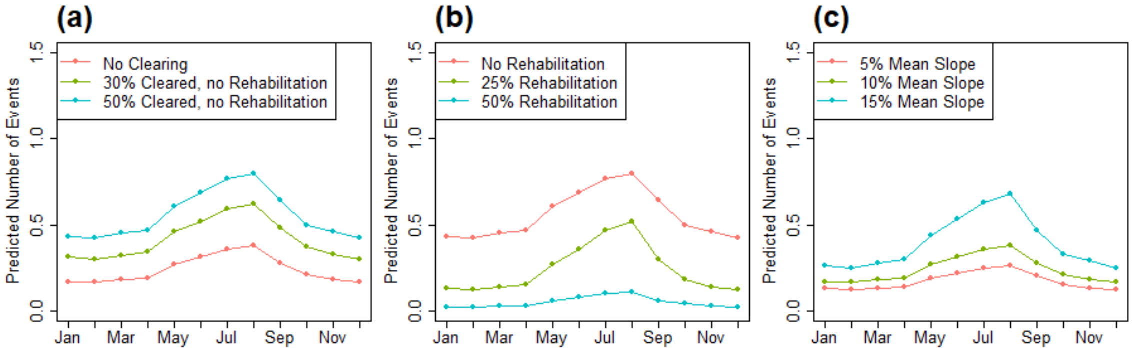


Figure 19. Model predictions for a median rainfall year: (a) Effect of changes in cleared area in a catchment with 10% mean slope; (b) Effect of changes in rehabilitation (expressed as the percentage of the catchment) where 50% of a catchment with 10% mean slope has been cleared; and (c) Model predictions showing the effect of mean slope in a catchment with no clearing.

Figure 19 shows examples of predictions that consider changes in a single factor, keeping all else constant. It shows that:

(a) Risk of high turbidity events increases with increasing areas of clearing in the absence of rehabilitation.

(b) Risk of high turbidity events decreases with increasing levels of rehabilitation.

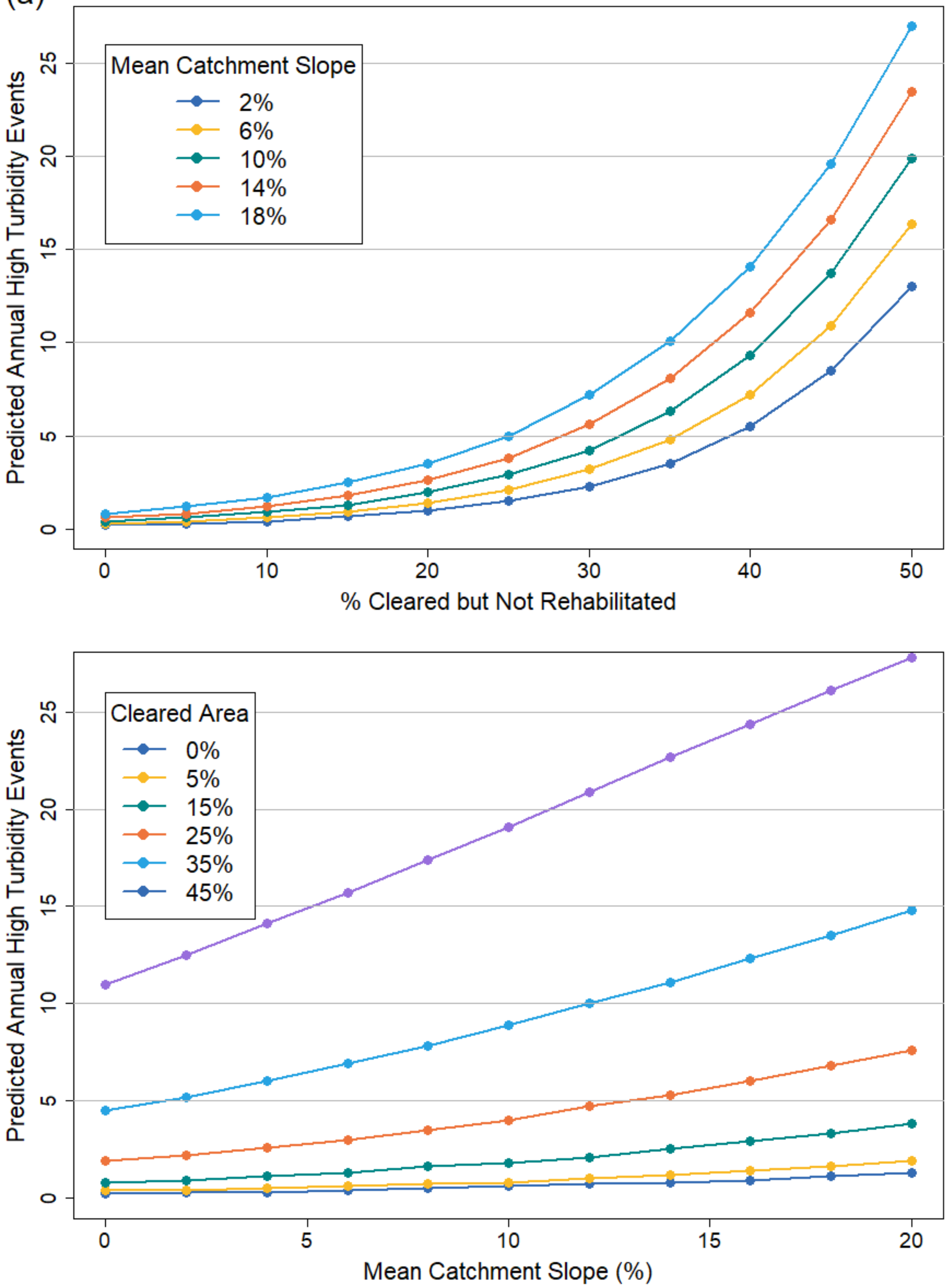
(c) Risk of high turbidity events increases with increasing catchment slopes.

Model predictions can be further explored for different scenarios using a web tool accessible from https://mnhw0z-daa.shinyapps.io/ALCOA_31_App/.

4.4.1 Predicted Effects of Catchment Slope and Clearing

Model predictions can be used to understand the joint effects of clearing and catchment slope on the number of high turbidity events.

(a)



show the predicted annual number of high turbidity events expected in a median rainfall year. Figure 20 (a) shows a marked curvilinear response to the percentage area of the catchment that has been cleared and not rehabilitated, with the predicted number of high turbidity events increasing more rapidly when the currently cleared areas is over

30%. In contrast, Figure 20 (b) shows that the response to mean catchment slope is more linear.

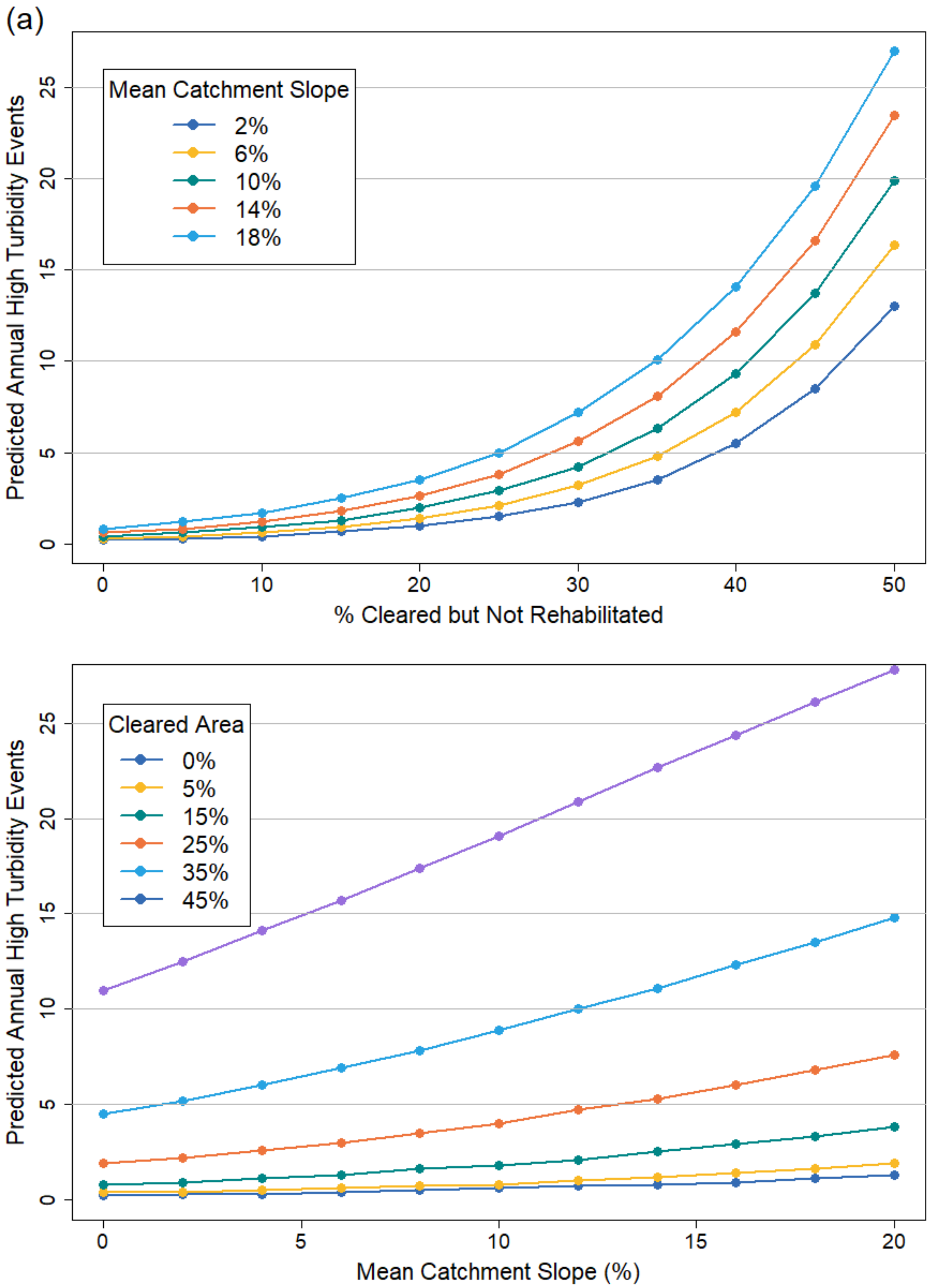


Figure 20. Predicted annual number of high turbidity events for different clearing and slope scenarios in a median rainfall year in a catchment.

5. Discussion and Conclusions

This study considered turbidity risk using NTU data collected by monitors in the Huntly mining region of Western Australia. Data from 30 monitors were sourced from multiple Alcoa databases and patched into a single dataset. Only 25 of the monitors could be geo-located, many monitors had short recording periods and most experienced data gaps where no data were available. Two set of monitors were identified for use in this study.

1. 10 monitors with greater than 80% data coverage for the winter period from May to September 2021 were used for Top Level Analysis: DB01, DB02, PD01, SE10, SE48, SE51, SE52, SE53, SE59 and SE61.

2. 14 monitors with greater than 70% data coverage for the period January 2021 and September 2022, which covers two winters were used for Statistical Modelling: DB01, DB02, ND06, ND07, PD01, PD02, SE10, SE48, SE51, SE52, SE53, SE59, SE61, SE62.

The first set is a subset of the second, therefore data from 14 monitors were used in total.

Detection of high turbidity events was made difficult by the high degree of noise in the data caused by factors other than turbid water. To avoid data cleaning that might obscure detection of high turbidity events, we adopted an approach that first detected all events, then classified them as true or false using an algorithm designed to err on the side of caution by only removing events that we could be confident were false. This left a large number of events that Alcoa cross-checked against their investigation records before removing those known to be false.

For each monitor we delineated the catchment area upstream of that monitor and calculated catchment characteristics including area, mean and maximum slope, percentage area of the catchment with slopes greater than 16%, area cleared and area rehabilitated.

Top level analysis considered relationships between individual factors affecting turbidity and the total number of high turbidity events. To ensure counts of high turbidity events could be compared across and between monitors, this needed a set of monitors with consistent data coverage for a common time period and therefore a 10-monitor May to September 2021 dataset was used. Five of the ten catchments recorded no high turbidity events during this period.

We found a correlation of close to zero between the percentage area of catchment that has been cleared (total area cleared including areas subsequently rehabilitated) with the number of high turbidity events meaning. While there was a positive correlation between the percentage area of a catchment that has been cleared but not yet rehabilitated (ie. open area) and the number of high turbidity events, it was not significant. Mean catchment slope and the percentage area of the catchment that has been rehabilitated were the only factors found to have a significant correlation with the number of high turbidity events. This suggests that rehabilitation should be considered when managing turbidity risk.

While top level analysis was useful for investigating individual relationships, multivariate analysis is critically important because the effects of multiple factors and their possible interactions can be considered simultaneously. Statistical modelling also allows the data to be restructured so that data gaps have less impact allowing use of a 14-monitor 2021-2022 dataset.

Because high turbidity events are not recorded in most months, the data were zero-inflated. We used a two-part hurdle model that first considers whether high turbidity events will occur in a month and then considers how many events will occur.

To avoid issues of collinearity due to catchment characteristics being correlated to each other, a smaller subset of catchment characteristics was used in three models designed to consider: (1) effects of total clearing (including areas subsequently rehabilitated); (2) effects of clearing prior to rehabilitation; and (3) effects of clearing and rehabilitation combined.

The results showed that:

- Catchment slope has a significant positive effect on either the occurrence or number of high turbidity events using any model, with more events in catchments with higher mean slope.
- Rainfall has a significant positive effect on both the occurrence and number of high turbidity events and their number using any model, with more events in wetter months.
- When only total percentage cleared area (including subsequently rehabilitated areas) is considered, it has no effect on the chance of high turbidity events occurring or on the number of high turbidity events if they occur.
- When the percentage area cleared but not rehabilitated is considered, it is found to have a significant positive effect on the occurrence of events but not on their number.
- When both clearing and rehabilitation are considered, percentage area rehabilitated has a significant negative effect on the chance of high turbidity events occurring.

Putting these results together, we found that as a whole, the total percentage cleared area has no significant effect (negative or positive) on high turbidity events, but the two components of it do: percentage cleared but not rehabilitated has a positive effect and percentage cleared and rehabilitated has a negative effect.

The best-fitting model can be used to predict the expected number of events in different scenarios and we can consider changes in a single factor, keeping all else constant. This shows that:

e) Risk of high turbidity events increases with increasing areas of clearing in the absence of rehabilitation.

f) Risk of high turbidity events decreases with increasing levels of rehabilitation.

g) Risk of high turbidity events increases with increasing catchment mean slope.

h) High turbidity events can be expected within uncleared catchments.

However, because the factors act together to affect turbidity risk the predictions can tell a more complex story.

The modelling results strongly suggest that selection of a threshold on catchment clearing to minimise risk of high turbidity events should consider rehabilitation. Cleared areas that have not been rehabilitated pose a risk, but cleared areas that have been subsequently rehabilitated do not.

The results also show that high turbidity events can be expected in catchments that have not been cleared, particularly in catchments with higher slopes and in higher rainfall years. Turbidity data for a few months were obtained for undisturbed Holyoake catchment. While no high turbidity events were detected, both Holyoake monitors recorded occurrences of NTU above 25 for up to ten or twenty minutes which may partially support the modelling results.

While we found that risk of high turbidity events increases with increasing catchment mean slope, it is unclear that this can be used to select a specific slope threshold for turbidity risk management. Model predictions to understand the joint effects of clearing and catchment slope on the number of high turbidity events showed a marked curvilinear response to the percentage area of the catchment that has been cleared and not rehabilitated, with the predicted number of high turbidity events increasing more rapidly when the currently cleared area is over 30% of the catchment. In contrast, the response to mean catchment slope is more linear.

6. Recommendations

6.1 Update Modelling Using Longer Data Record

The modelling results could be improved substantially by considering a longer record of turbidity data. This study compiled 2016 to 2020 turbidity data and undertook initial high turbidity event verification for 2021-2022. We recommend manual verification of detected events dating back to 2016 to expand the dataset available for modelling which would provide more confidence in modelling results and conclusions.

6.2 Baseline Monitoring Program

This study did not include data from uncleared catchments. The conclusions reached on uncleared catchments represent an extrapolation. They would be strengthened if data from uncleared catchments were available. The ideal data would be collected in catchments prior to and after clearing. We recommend that Alcoa establish a baseline monitoring program for several years prior to clearing to capture seasonal variability and directly measure the effects of mining on turbidity.

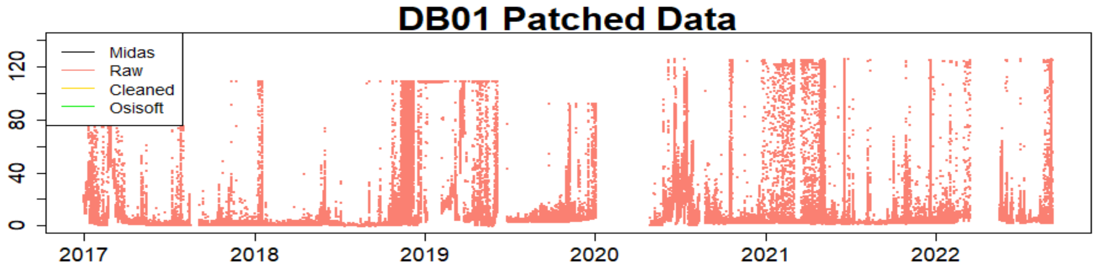
6.3 Improvements to monitoring program

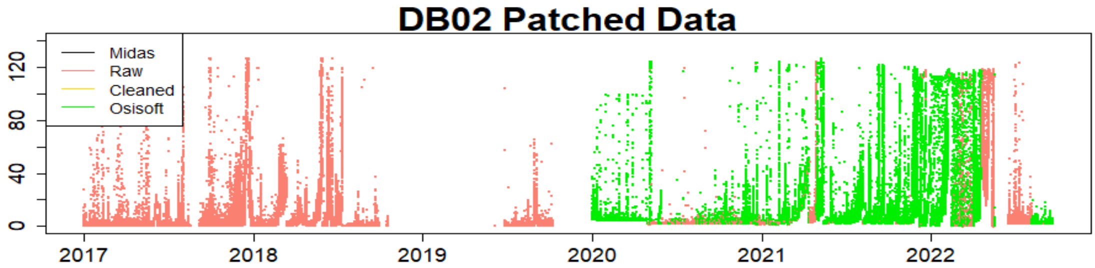
Future turbidity monitoring should endeavour to establish procedures to improve data capture and storage. We recommend recoding flow to assist with off-site detection, verification and modelling of high turbidity events, to facilitate detection and modelling of high turbidity events.

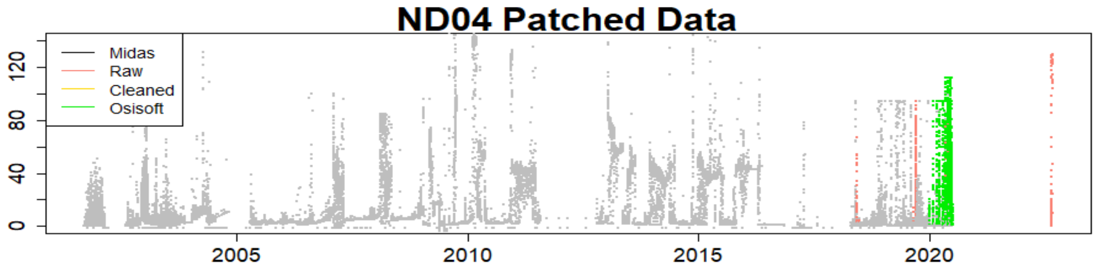
7. Study Limitations

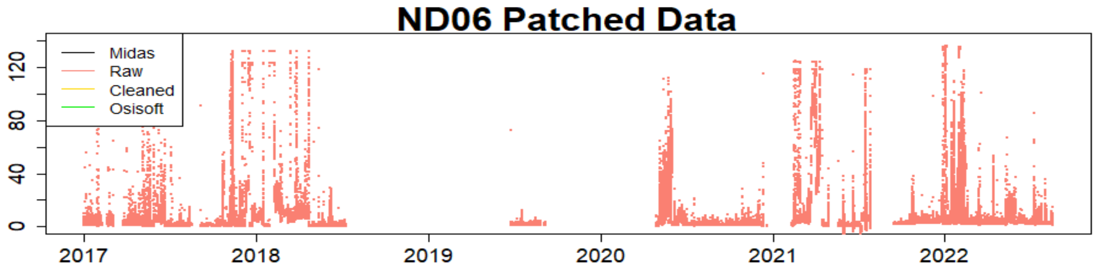
The study outcomes are limited to the dataset, the high turbidity event verification process, and statistical modelling approaches outlined herein.

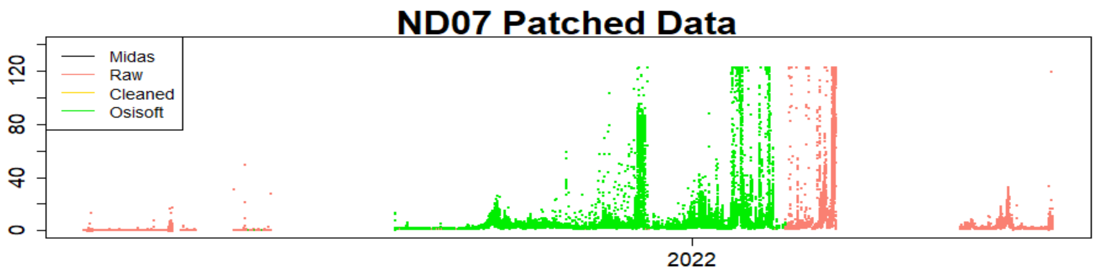
Appendix A. Time-Series Plots For 25 Huntly Monitors Showing Data Sources







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Midas
Raw
Cleaned
Osisoft
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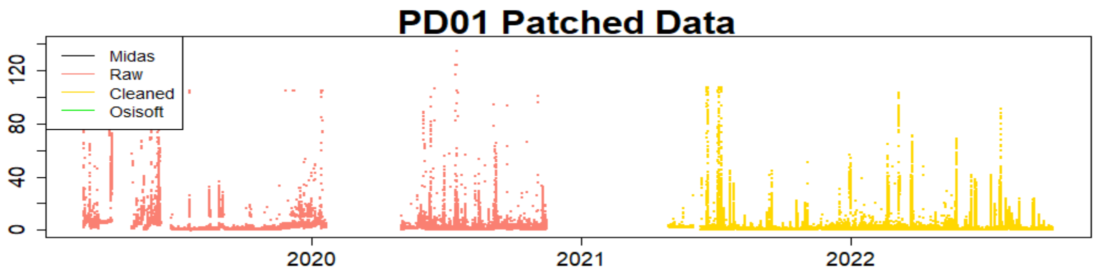
40
80
120
2022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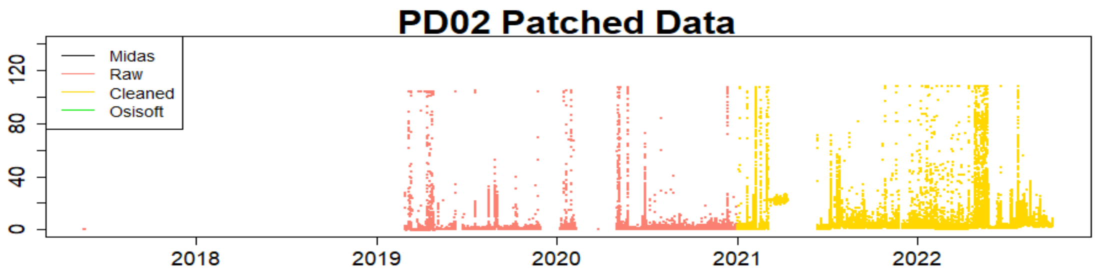
2021
2022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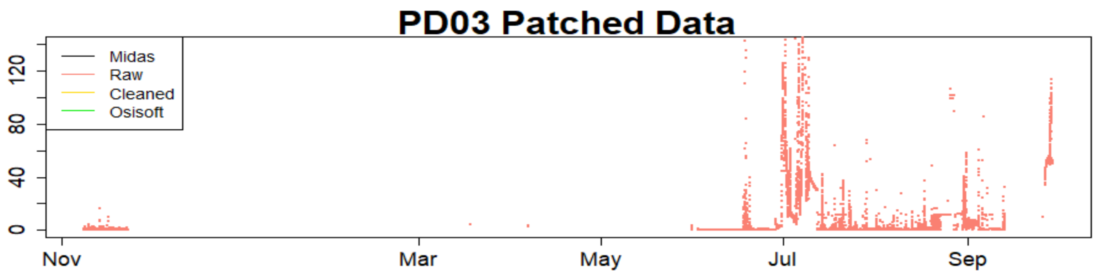
2018
2019
2020
2021
2022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Nov
Mar
May
Jul
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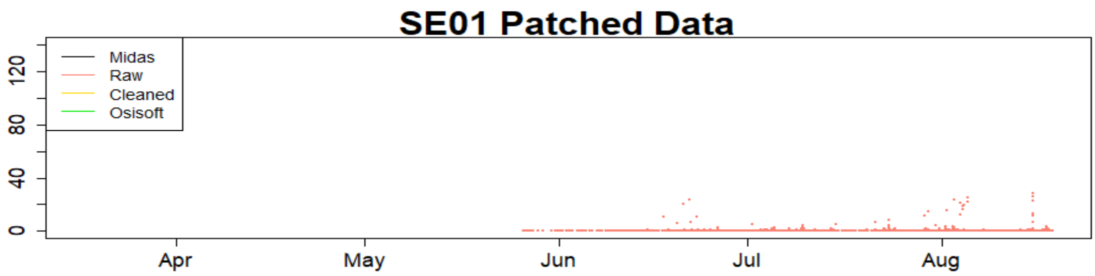
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Apr
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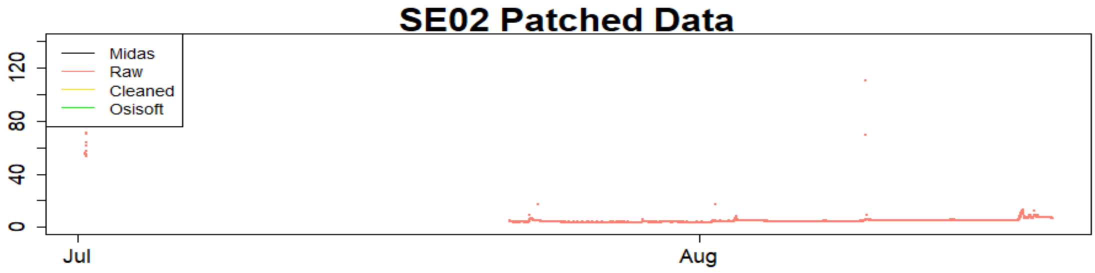
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Midas
Raw
Cleaned
Osisoft
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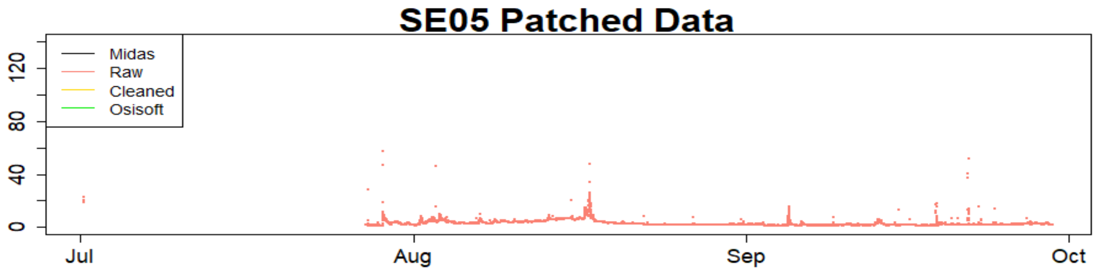
120
Jul
Aug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Cleaned
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Aug
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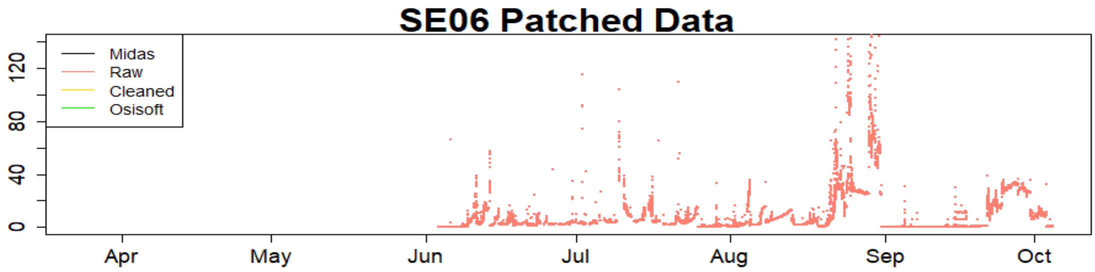
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120
Apr
May
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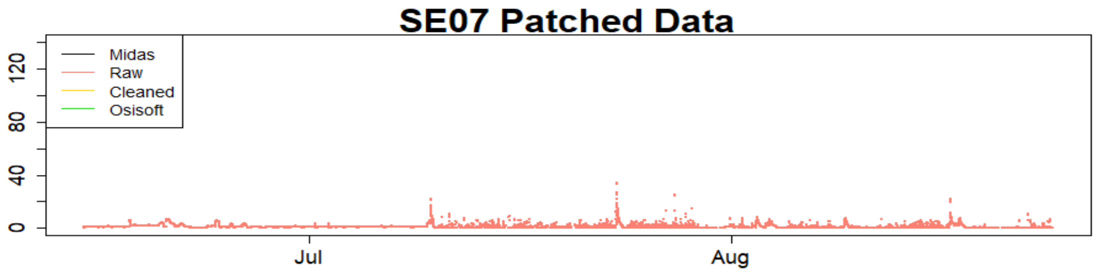
Sep
Oct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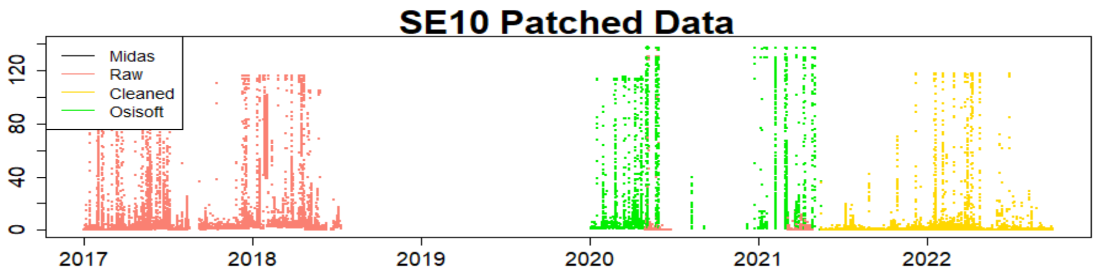
SE10 Patched Data
Midas
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Cleaned
Osisoft
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40
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120
2017
2018
2019
2020
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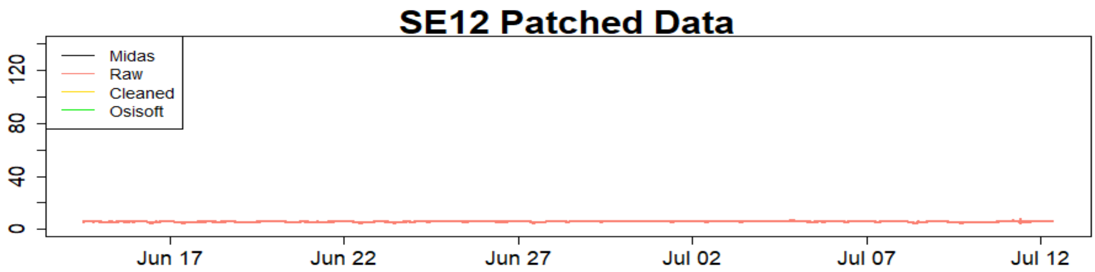
2022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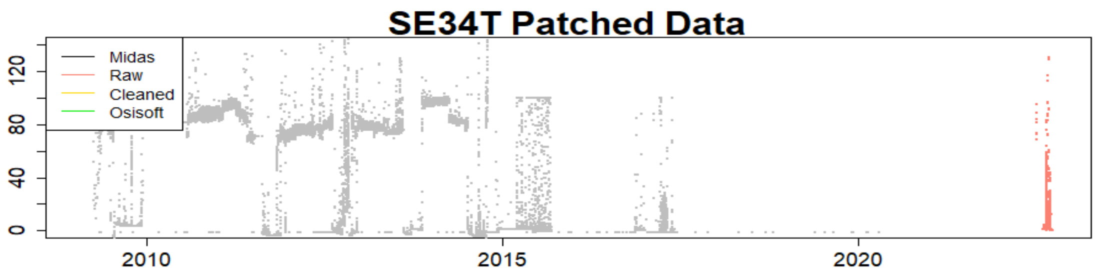
Jun 17
Jun 22
Jun 27
Jul 02
Jul 07
Jul 12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Raw
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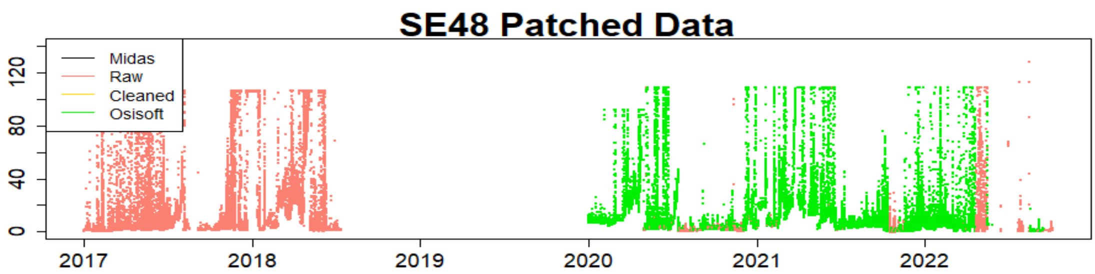
80
120
2010
2015
2020


SE48 Patched Data
Midas
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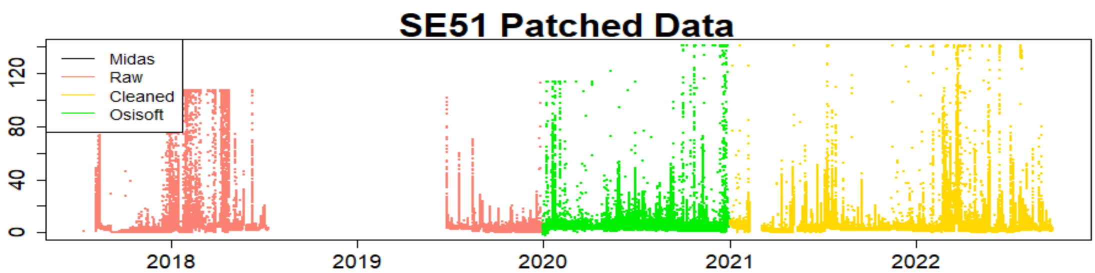
80
120
2017
2018
2019
2020
2021
2022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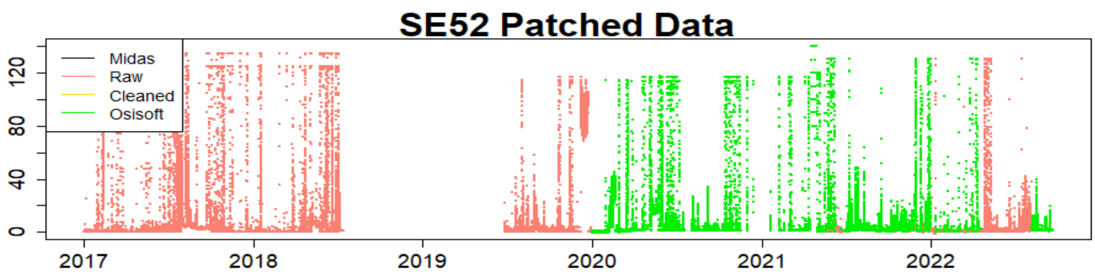
Midas
Raw
Cleaned
Osisoft
0
40
80
120
2018
2019
2020
2021
2022


SE52 Patched Data
Midas
Raw
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40
80
120
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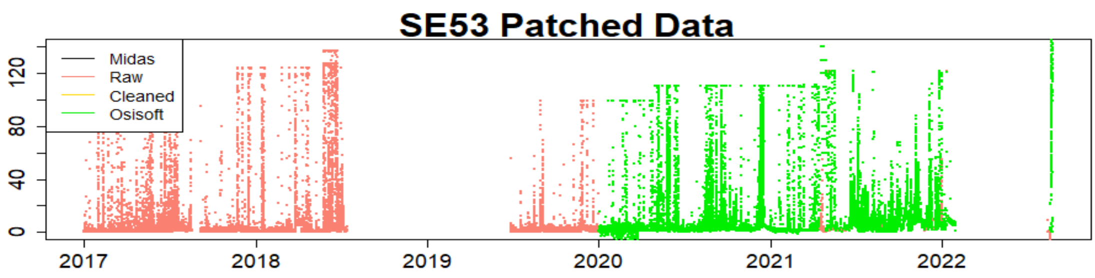
2018
2019
2020
2021
2022


SE53 Patched Data
Midas
Raw
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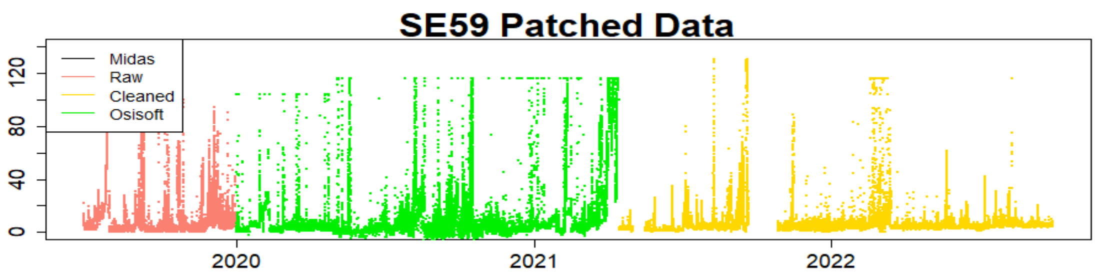
Osisoft
0
40
80
120
2017
2018
2019
2020
2021
2022


SE59 Patched Data
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Raw
Cleaned
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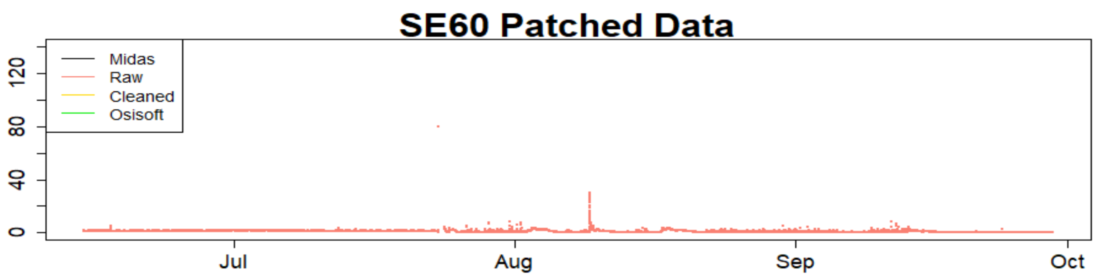
120
2020
2021
2022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Midas
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Cleaned
Osisoft
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Jul
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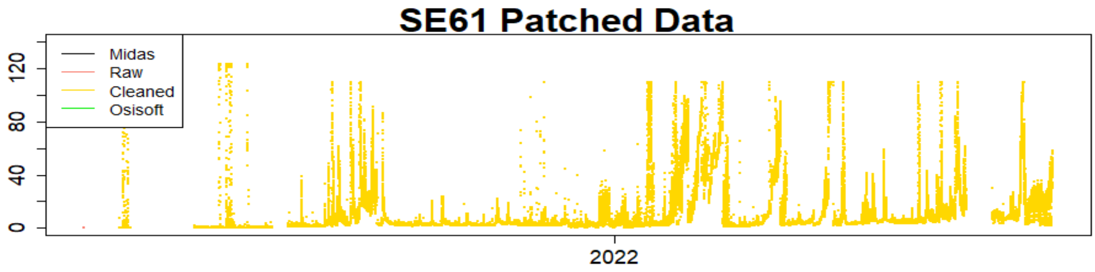
Oct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Midas
Raw
Cleaned
Osisoft
0
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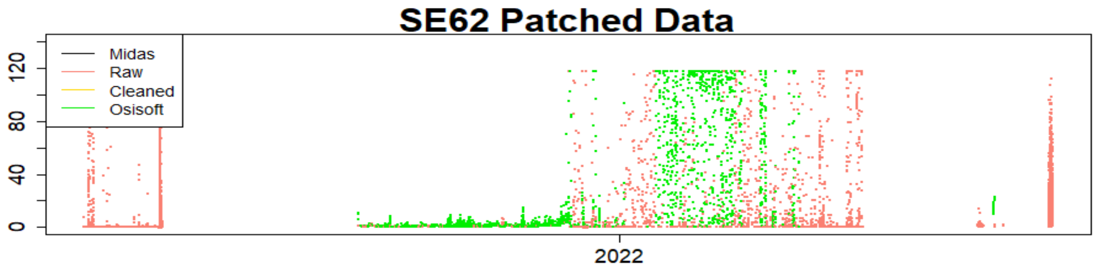
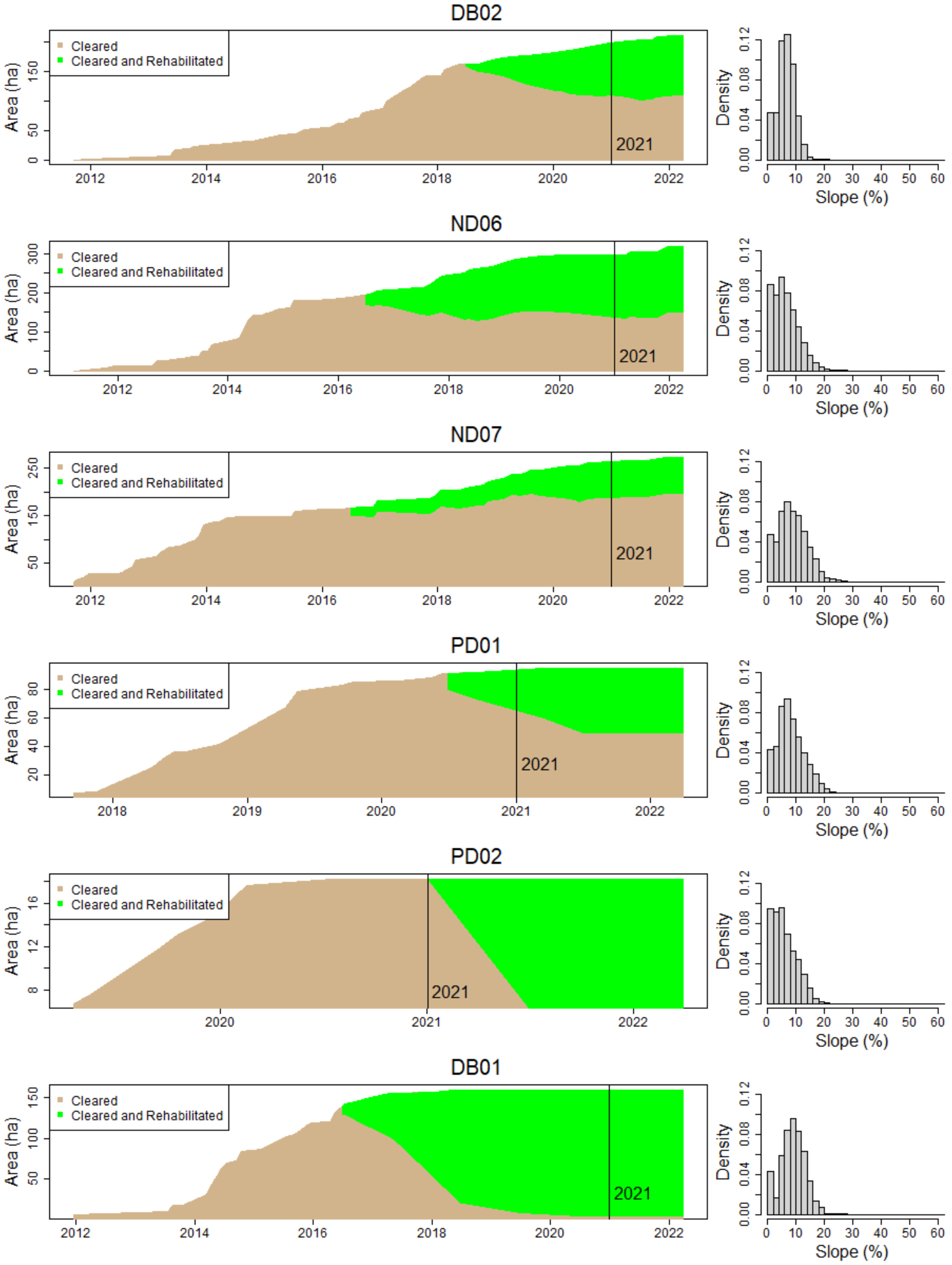
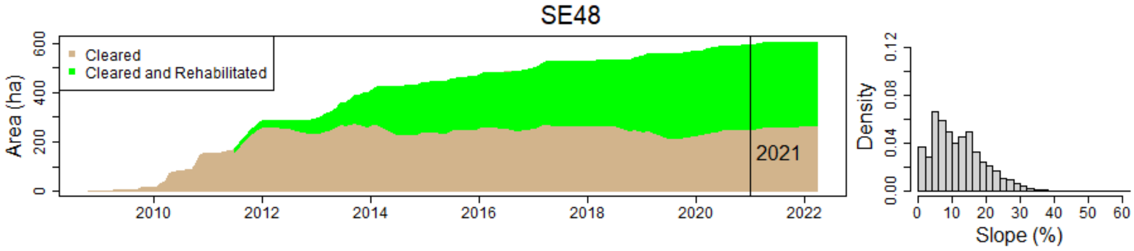
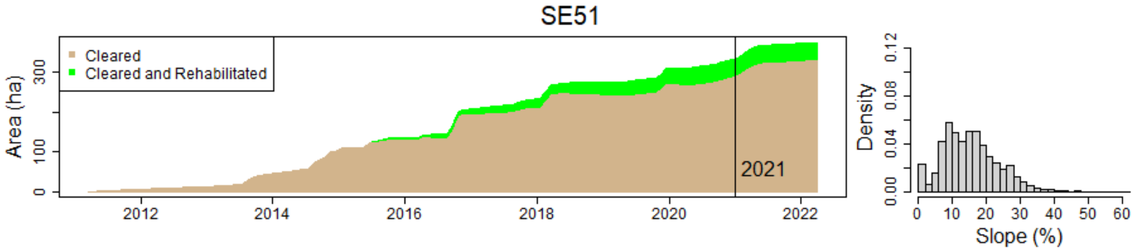
80
120
2022

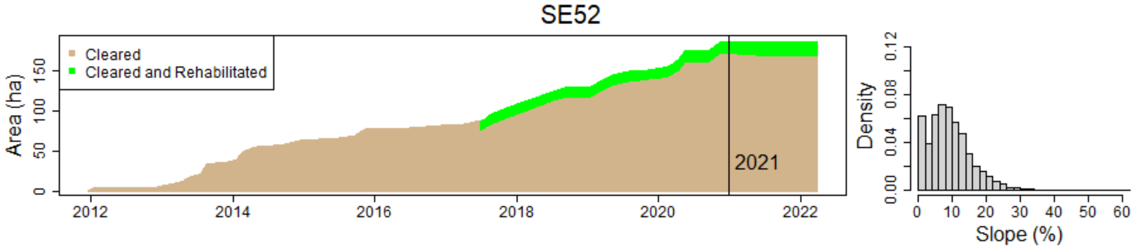

SE62 Patched Data
Midas
Raw
Cleaned
Osisoft
0
40
80
120
2022

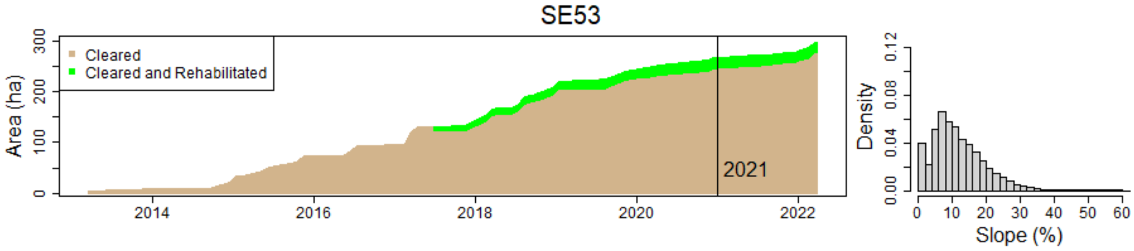
Appendix B. Clearing, Revegetation and Slope for each Catchment in the 14-monitor 2021-2022 Patched Huntly Dataset

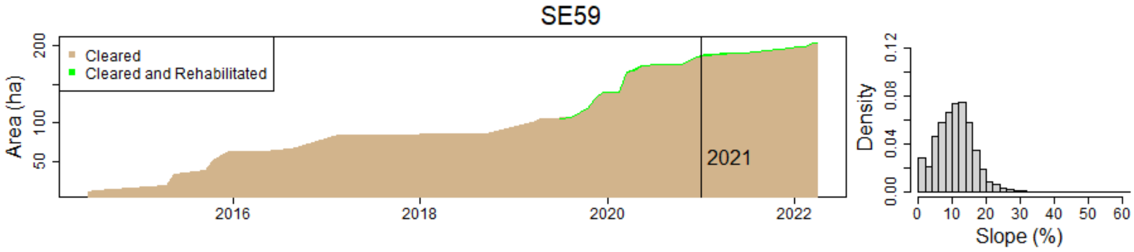


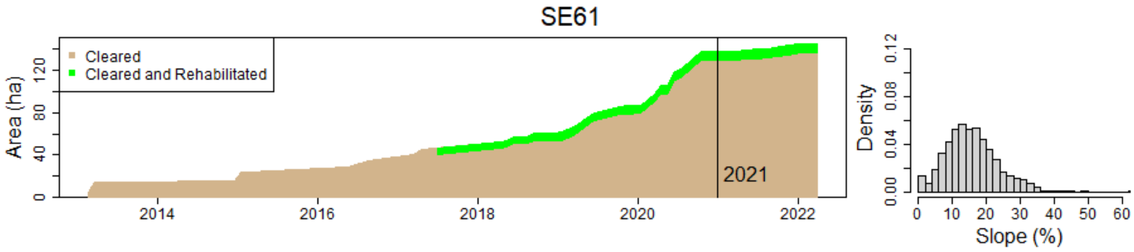

SE48
Cleared
Cleared and Rehabilitated
Area (ha)
2021
Density
Slope (%)

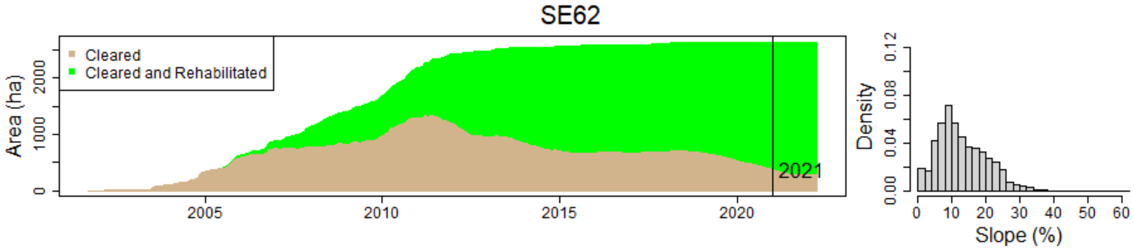

SE51
Cleared
Cleared and Rehabilitated
Area (ha)
2021
Density
Slope (%)

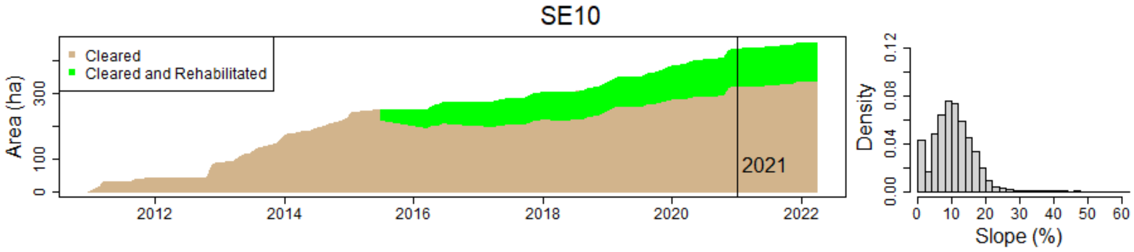

SE52
Cleared
Cleared and Rehabilitated
Area (ha)
2021
Density
Slope (%)


SE53
Cleared
Cleared and Rehabilitated
Area (ha)
2021
Density
Slope (%)


SE59
Cleared
Cleared and Rehabilitated
Area (ha)
2021
Density
Slope (%)


SE61
Cleared
Cleared and Rehabilitated
Area (ha)
2021
Density
Slope (%)


SE62
Cleared
Cleared and Rehabilitated
Area (ha)
0
1000
2000
2005
2010
2015
2020
2021
Density
0.00
0.04
0.08
0.12
0
10
20
30
40
50
60
Slope (%)


SE10
Cleared
Cleared and Rehabilitated
Area (ha)
0
100
300
2012
2014
2016
2018
2020
2022
2021
Density
0.00
0.04
0.08
0.12
0
10
20
30
40
50
60
Slope (%)

Appendix C. Detection of High Turbidity Events

Event detection for the 6-monitor 2021-2022 Cleaned Dataset

All occurrences where turbidity measurements exceeded 25 NTU for one hour or longer were extracted from the 6-minute interval 2021-2022 Cleaned turbidity data available for six monitors.

Inspection of the turbidity data for these events showed that many were influenced by various types of error in the data, such as sensor drift, sensor saturation, streams flushing or drying out and obstruction by debris that was later removed. Verification of the events was performed by cross-tabulating the events with Alcoa's investigations to determine whether they had been investigated and identified as true or false.

Verification identified 98 true high turbidity events with known causes and 5 events with causes that could not be verified. The total of 98 true and 5 unverified high turbidity events were then aggregated into unique days experiencing high turbidity events (Table 10). Plots of each event are included in Appendix A.

Table 10. High turbidity events identified from the 2021-2022 Cleaned dataset.

Monitor ID	Number of events identified from NTU data	Number of verified false events	Number of verified true events	Number of days with true events
PD01	26	8	18	14
PD02	94	82	12	9
SE10	21	18	3	3
SE51	63	41	22	22
SE59	39	25	14	12
SE61	89	55	34	29
Total	**332**	**229**	**103**	**89**

Algorithms for Cleaning False Events

Considering all periods of time for which a monitor records NTU greater than 25 for an hour or longer leads to detection of many erroneous false events, we investigated methods for classifying detected events as true or false. We aimed to identify and removing as many false events as possible while retaining all true events for analysis.

Two methods were identified for classifying detected events as true or false based on their shape characteristics. The methods were tested using the 103 verified true and false events identified for the 2021-2022 Cleaned Dataset.

Dynamic time warping (DTW) measures the similarity of two time-sequences of data by warping the curves to minimise the distance between them.

Approach One: DTW Clustering

The first approach involved calculating pairwise DTW distances between normalised NTU for all pairs of events and then clustering the events into 12 similar share groups by partitioning around medoids (PAM) model. Figure 21 shows the curve clusters.

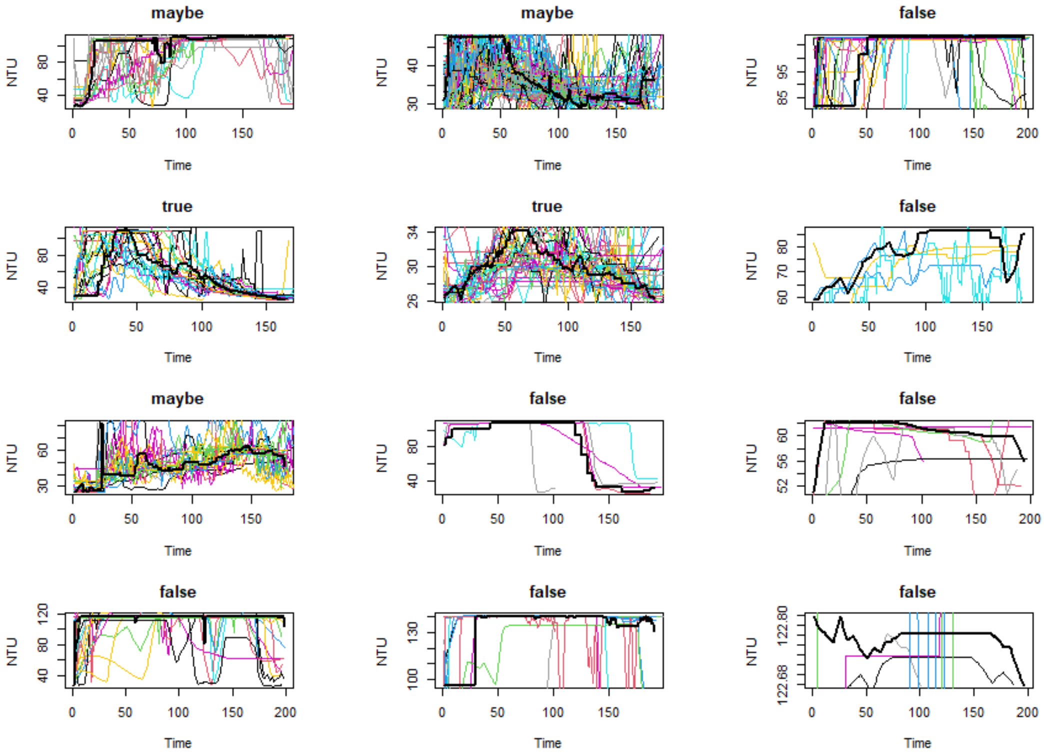


Figure 21. Clusters identified with medoids shown as black, bold line. Note that all clusters labelled 'maybe' are included in the 'true' class in Table 11 and Error! Reference source not found..

The number of true/false events in each cluster is shown in Table 11. Assigning a true/false label based on these clusters shows that this approach can identify all but 5 true events while eliminating 131 false events giving a detection accuracy for true events of 95.1%.

Table 11. PAM of DTW distances clustering into 12 clusters.

		1	2	3	4	5	6	7	8	9	10	11	12
Verified labels	**False**	16	43	61	8	14	6	17	6	8	29	15	6
	True	4	40	2	16	29	0	9	1	0	2	0	0

However, the above results test the model on the same data that was used to train the model which can lead to over-estimation of accuracy. We therefore applied 5-fold cross-validation to get a better understanding of how well the model would work for unseen data. This involved splitting the high turbidity events into five independent set of data. Each split of 20% of the data is used to test the model trained using the other 80% of the data, and the results are averaged over the 5 splits or folds. The result was a cross-validated detection accuracy for true events of 87.4% (Table 12). That is, 13 true events were mis-labelled as false.

Table 12. Cross-validated accuracy for clustered DTW distances.

		False	True
Verified labels	**False**	145	84
	True	13	90

Approach Two: Pattern Match and Delete Typical Errors

The second approach to cleaning false events used DTW distance from the most typical false event that occurred: a step-type error where NTU suddenly jumped to it maximum value for some length of time before returning to a low value, as shown in Figure 22

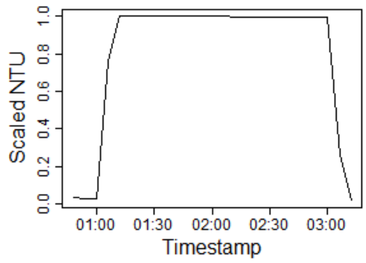


Figure 22. Normalised NTU for a typical step-type error used for pattern matching.

Mixture modelling was applied to find the optimal distance threshold for separating true and false events. When trained on the entire 103 events, this approach identified all but 5 true events while eliminating 111 false events giving a detection accuracy for true events of 95.1%. 5-fold cross-validation gave similar results (Table 13), however only around half of the false events could be successfully identified.

Table 13. Cross-validated accuracy for pattern-matched DTW distances.

		False	True
Verified labels	**False**	110	119
	True	5	98

Event detection for the 14-monitor 2021-2022 Patched Huntly Dataset

All occurrences where turbidity measurements exceeded 25 NTU for one hour or longer were extracted from the Patched Huntly turbidity data for 14 monitors with good long-term records. False turbidity events were eliminated using the second approach outlined above, events were aggregated to daily and verified manually by cross-tabulating against Alcoa's records.

Government of **Western Australia**
Department of **Water and Environmental Regulation**

GOVERNMENT OF WESTERN AUSTRALIA

Modelling long-term flow and salinity response to bauxite mining in the upper Serpentine catchment

Salinity and land use impacts series report no. 66
UNPUBLISHED REPORT
August 2019

Government of **Western Australia**
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August 2019

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Reference

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Cover photograph: Serpentine Main Dam, photograph by A Grigg.

Disclaimer

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Summary

The Serpentine Reservoir, located approximately 55 km south-east of Perth within the Northern Jarrah Forest, is one of several reservoirs in the Integrated Water Supply Scheme supplying water to metropolitan Perth and regional centres throughout south west Australia. The 664 km^2 catchment extends into the Intermediate Rainfall Zone (IRZ) where changes to forest cover have the potential to increase stream salinity, thereby posing a risk to water quality of the reservoir. Alcoa of Australia has been mining for bauxite in the Northern Jarrah Forest since the 1960's and a range of investigations have taken place to better understand the potential salinity effects of mining in the IRZ. The aim of this study was to investigate the potential effects of bauxite mining on stream flows and stream salinity into the Serpentine Reservoir, using the semi-distributed conceptual catchment hydrology model, LUCICAT, to consider possible long-term mine plans and a projected changing climate over a 40-year planning horizon.

Annual inflows to the Serpentine Reservoir were satisfactorily calibrated in the model, with a coefficient of determination of 0.82 and an NSE of 0.74. LUCICAT's modelled annual inflows agreed within three per cent of the Water Corporation's water balance inflow estimates for the reservoir, and annual flows for most internal sub-catchments were on average within seven per cent of observed flows for the complete period of records. Modelled annual flow-weighted salinity of the Serpentine Dam agreed within 40 mg/L of measured salinity at the main dam outflow which was in the range 154–170 mg/L.

Two possible mining proposals that cleared, mined and rehabilitated either nine percent or 12 per cent of the catchment, together with a no-mining comparison, were considered in the context of two future climates ('average' 914 mm/year and 'dry' 841 mm/year at the catchment centroid) to give a total of six future (2011–2050) scenarios. Model results showed that, regardless of the mining case or future climate, the projected change in inflows due to mining was no greater than approximately 2 GL/year in any one year, or five per cent of flow on an annual average basis. Both increases and decreases in flow were observed over the time series relative to the unmined alternative. On an annual average basis, the maximum increase in salinity was projected to be 5.4 mg/L or three per cent of reservoir salinity compared to the no-mining case. The effects on reservoir salinity of mining within the Upper Serpentine were therefore considered to be within acceptable limits.

LUCICAT appeared to overestimate flows subsequent to strong drought years that are not followed by wetter years, which are known to cause step-declines in groundwater connection and associated flow. It is recommended that the LUCICAT model be investigated in more detail to understand the dynamics of simulated groundwater levels in the context of these single strong drought years.

1 Introduction

The Serpentine Reservoir is one of several reservoirs in the Integrated Water Supply Scheme supplying water to metropolitan Perth and regional centres throughout South West of Western Australia. Located in the Northern Jarrah Forest on the western edge of the Darling Plateau, the reservoir catchment has experienced a 16 per cent reduction in annual rainfall since the mid-1970s, resulting in a reduction in surface inflows of almost 60 per cent when compared against flows during 1961–1975 (Petrone et al., 2010). Despite the decreased surface inflows, the reservoir still plays an important role in the storage of water from groundwater and desalination sources, and maintenance of water quality of surface inflows remains essential.

A strong rainfall gradient exists across the catchment of the Upper Serpentine, being greatest on the western edge and declining with distance inland. Along this rainfall gradient, mean annual evaporation increases, resulting in the accumulation of salts in the deep soil profiles and increasingly saline groundwater (Schofield et al., 1989). In areas of moderate rainfall with a long-term annual average of 900–1100 mm, termed the intermediate rainfall zone (IRZ), groundwater has historically been sufficiently close to the surface such that clearing of native vegetation has the potential to cause discharge of groundwater to streams leading to stream salinisation (see Peck and Williamson, 1987).

Alcoa of Australia (Alcoa) has been mining for bauxite in the Northern Jarrah Forest since the 1960s. The potential effects of bauxite mining on the salinity of the water supply catchments in the IRZ was recognised at an early stage and a range of research was initiated to address the issue (Steering Committee, 1978), leading to the development of the Joint Intermediate Rainfall Zone Research Program (JIRZRP). Under the JIRZRP, a number of experimental catchments were established in the southern headwaters of the Upper Serpentine catchment from the late 1980s, with mining and rehabilitation taking place during 2003–2011. Croton et al. (2011) reviewed progress of the trials up to and including 2009, finding an almost complete absence of responses to mining in either streamflow or stream salinity. This was attributed to the fact that, while there were groundwater rises due to mining, these were insufficient to cause discharge of saline groundwater to the streams. Similar findings were reported by Kinal and Stoneman (2011) for nearby catchments, also in the IRZ, subjected to forest thinning treatments over a comparable period. Across all catchments, the reduced rainfall being experienced has resulted in groundwater levels declining at a rate of approximately 0.5 m per year since the mid-1990s.

From 2009, mining activity expanded from the experimental catchments into the central region of the Upper Serpentine catchment under a staged entry approach to the IRZ. Initial salinity risk modelling and subsequent monitoring results concluded that, while streamflow and stream salinity responses were predicted, these increases were likely to be undetectable over natural variation within the Serpentine Reservoir (Croton et al., 2010). However, it was recognised that planned mining activity could continue within the catchment until 2030, and hence the cumulative effects of mining over an extended time period and geographical area needed to be considered.

Climate and runoff across the catchment is also expected to change over this extended period of mining. Silberstein et al. (2012) simulated runoff in catchments across South West Western Australia under climate projections based on 15 global climate models and three different global warming scenarios. For the Upper Serpentine catchment under the median climate projection, a further decline in streamflow of 24 per cent was forecast by 2030, compared to the historical (1997-2007) average streamflow.

1.1 Bauxite mining and rehabilitation

Alcoa's mining and rehabilitation process is described in detail by Koch (2007). Briefly, all commercial timber is harvested from an area to be mined, then the remaining vegetation is cleared. The upper 100 mm of topsoil, which contains the majority of seed, organic material and plant nutrients, is removed in a double stripping process. The underlying gravelly subsoil ('overburden') ranging in depth from 0.2–0.8 m is also removed, and typically stockpiled for later re-use. The bauxite ore, consisting of approximately one to four metres of friable material and in some cases a cemented layer or duricrust, is excavated and transported along haul roads to a central crusher.

During rehabilitation, the pits are shaped to a slope compatible with the surrounding terrain, and the pit floor is ripped to a depth of 1.5 m to relieve compaction. The overburden and topsoil are replaced in sequence, with the topsoil being brought from an area that has been freshly stripped wherever possible. The area is then ripped again to a depth of 0.8 m along the contour to improve infiltration, reduce erosion and prepare the surface for applied seed. The present objective of rehabilitation is to restore a functioning jarrah forest ecosystem capable of supporting the range of pre-mining land uses. Seed of around 100 plant species, including the dominant native tree species of jarrah (*Eucalyptus marginata*) and marri (*Corymbia calophylla*), are collected from the surrounding forest within defined provenance zones and applied at the time of contour ripping. Plant species that are difficult to establish from seed are grown from cuttings or by tissue culture (Koch 2007), and planted in the winter wet season.

1.2 Aim of this study

The aim of this study was to investigate the potential effects of bauxite mining on stream flows and stream salinity into the Serpentine Reservoir, considering a long-term mine plan and a projected changing climate over a 40-year planning horizon.

2 Catchment description

2.1 Location and climate

The Serpentine Reservoir is located approximately 55 km south-east of Perth (Figure 1) within the Northern Jarrah Forest. The catchment above the reservoir covers an area of 664 km^2, with the Serpentine River and the major tributary of Big Brook extending for more than 30 km to the south-east.

The climate of the Northern Jarrah Forest is typically Mediterranean with hot dry summers and cool wet winters. Most rainfall occurs between the months of May and October. There is a strong rainfall gradient across the catchment, ranging from an annual average (1975– 2003) of 1150 mm in the west to approximately 680 mm at the eastern-most extent (Figure 1). The years that data were available for each rainfall station are shown in Figure 1 next to the station number. The model used all the daily rainfall data available.

2.2 Physiography and soils

The Upper Serpentine catchment lies within the Darling Range, the western edge of which is a well-defined escarpment rising several hundred metres above the coastal plain. The Range is an undulating lateritic plateau 280–340 m AHD containing a number of isolated peaks that rise up to 600 m AHD. Elevations in the Upper Serpentine catchment vary from 250 m AHD at the dam outlet to a maximum of 572 m AHD on Mt Solus which lies between the Serpentine River and Big Brook near the centre of the catchment. Valleys are deeply incised and associated slopes relatively steep around the reservoir where the river has cut through the surface of the plateau, and on the flanks of Mt Solus. However, the terrain becomes more gently undulating with broad flatter valley shapes to the south-east of the catchment.

The catchment is underlain by predominantly granites and granitic gneisses of the Archaean Yilgarn Block, intruded by dolerite dykes which are associated with a north-westerly trend in landscape structure. Soils have developed in response to long-term *in-situ* weathering and are usually deep (10–40 m) except on steeper slopes where granite may outcrop at the surface. In a typical laterite profile, a sandy and/or gravelly surface topsoil overlays a discontinuous cemented layer or duricrust 1–2 m in thickness (only intermittently present in the lower rainfall areas), which in turn overlay a mottled zone of friable bauxitic gravels that average 3–5 m in thickness. A thicker clay pallid zone and partially weathered saprolite lie above the parent rock. While relatively uniform across the plateau, more subtle variations in relation to upland and valley associations occur and are described in more detail by Churchward and McArthur (1980). A feature of profiles overlying granite, of hydrological significance, are roughly circular root channels filled with coarse materials that extend to depth which form preferred flow paths for infiltrated rainfall (Dell et al., 1983; Johnston, 1987).

2.3 Vegetation and land use

While around 20 per cent of the catchment is national park located in the headwaters to the east and south-east, most of the Upper Serpentine catchment is designated as state forest. The catchment is largely covered by jarrah forest with jarrah and marri as the dominant overstorey species and a diverse ground- and shrub-layer (Bell & Heddle 1989). State forest areas are subject to multiple-use management including water supply, conservation, timber harvesting and bauxite mining. Rotational fuel reduction burning is carried out in a mosaic pattern throughout the forest.

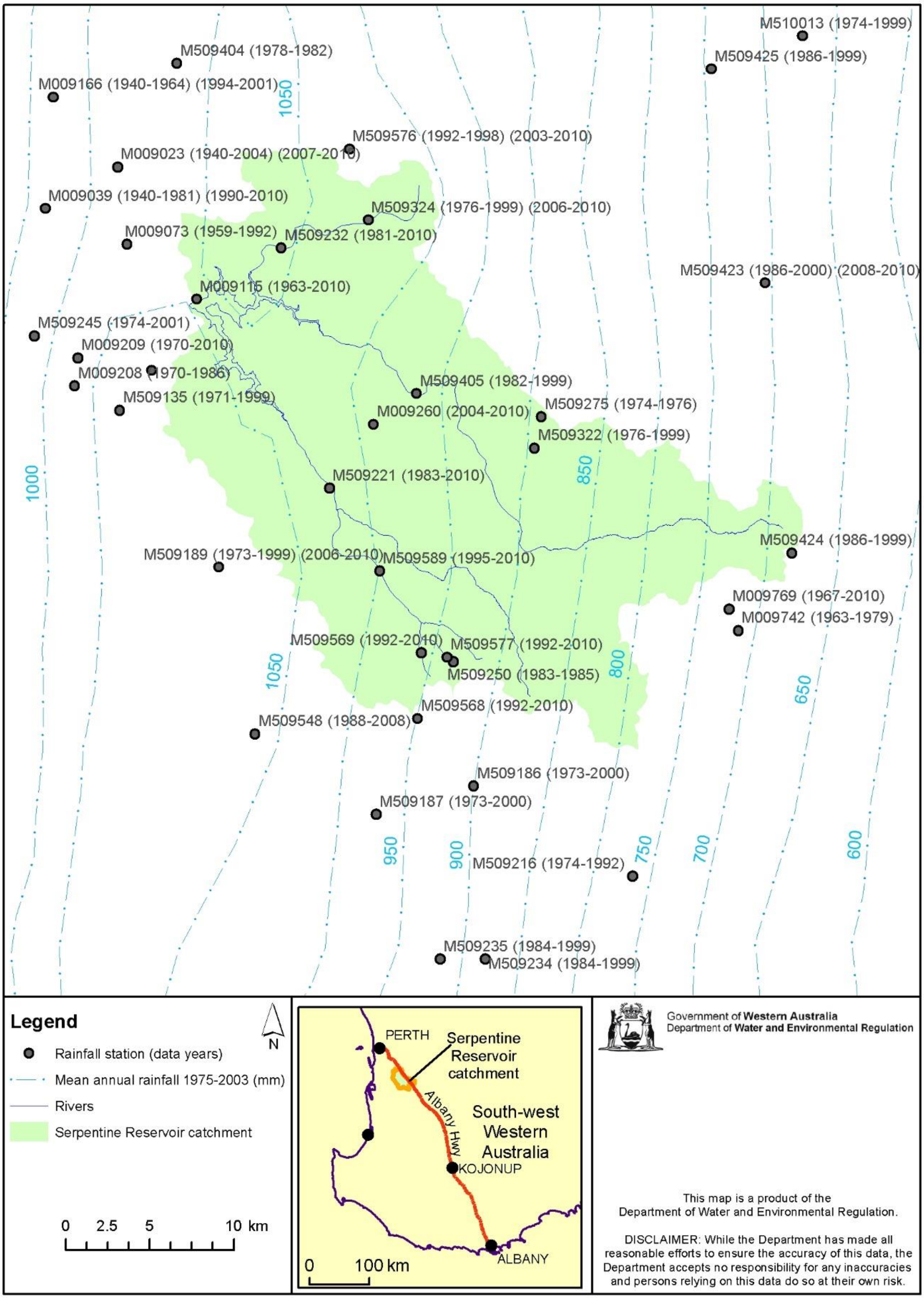

Figure 1 Location and rainfall of the Upper Serpentine catchment

3 Model setup

3.1 The LUCICAT model

LUCICAT is a semi-distributed conceptual catchment hydrology model that was developed to represent the daily salt and streamflow dynamics following land use changes in catchments of South West Western Australia (Bari & Smettem, 2003; Bari, 2005; Bari & Smettem, 2006a, b). This study utilised LUCICAT version 26.2. Catchments are divided into response units (RUs) to account for variations in climate parameters, soil, salt, storage and vegetation-cover across the catchment. The LUCICAT model is therefore suited to assessment of larger-scale catchments. Each RU can be assigned a different land use type, such as native forest, plantations, or annual or perennial pasture (Figure 2a, b). Streamflow and salt load from each RU is routed via a channel network to the catchment outlet. A total of 29 model parameters are defined, eight of which are calibrated while the remainder are set *a priori* using independently determined values (Section 4.3 & Appendix A).

The model consists of five stores: dry; wet; and subsurface stores for vertical and lateral water flow and salt flux in the unsaturated zone and near-stream dynamic saturated areas; a saturated groundwater store; and a transient stream zone store. These stores and fluxes are shown in Figure 2c.

The moisture balances of the top soil dry and wet stores are the most important components of the model and characterise the dynamically varying saturated areas responsible for surface runoff, interflow and deep percolation.

The dry store, determined by soil depth and physical properties, holds water held against gravity that is then available for evapotranspiration (interception, plant transpiration and soil evaporation).

The wet store represents moisture content in the top layer soil matrix from field capacity to saturation. Water is free to travel below or across the soil matrix. Conceptually the wet store, occupying a fraction of the catchment, is the intermittent shallow groundwater table and contributes to interflow (lateral flow) and percolation (vertical flow) to the underlying subsurface store.

The subsurface store describes the moisture balance below the dry and wet stores in the deep unsaturated soil profile. It acts as a delay function for the effects of rising groundwater levels on streamflow and salinity. Recharge from this store to the groundwater store can occur either from the soil matrix as excess flow or from preferential flow from preferred pathways. Transpiration can also occur from this store.

The groundwater store is controlled by the location of the conceptual groundwater level. If the groundwater level is at the surface, then groundwater discharge (baseflow) to the stream zone store can occur. It is a function of the catchment-average conductivity of the aquifer, slope of the groundwater system and stream length. In addition to discharge, groundwater can also be discharged to the atmosphere by transpiration from deep-rooted trees.

The stream zone store is transient and covers part of the dry and wet stores. Water can evaporate from the soil and transpire from plants from this store, and loss/gain to/from the dry store due to contraction/expansion of the saturated area. The residual (after soil evaporation and transpiration) of the baseflow becomes actual baseflow to the stream. When the groundwater level rises and the stream zone saturated areas expand, the dry store loses water to the stream zone and vice versa. All rainfall (less interception) that falls on the stream zone becomes runoff. Total streamflow is the sum of the surface runoff from pervious (surface runoff) and impervious (direct runoff) areas, interflow and baseflow components (Figure 2c).

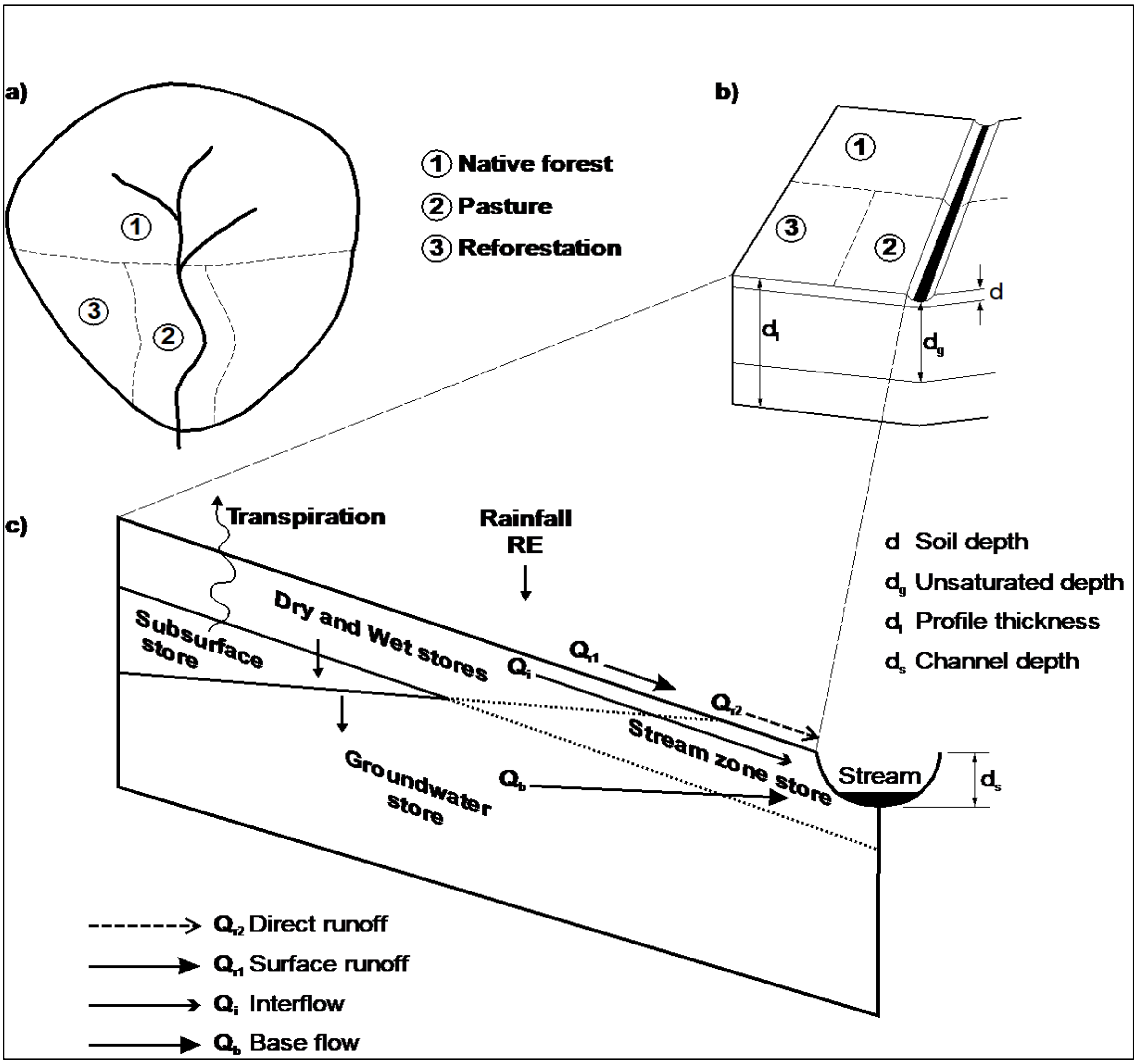

Figure 2 Schematic of the LUCICAT model showing a) a response unit or sub-catchment, b) 'open book' representation, and c) hydrological processes and sources of streamflow

Salt movement is accounted for in the five stores (Fig 2c). The dry store receives salt in rainfall and contains most of the salt held in the shallow topsoil, some of which is released to the wet store. A lumped parameter is used to represent diffusion-advection-dispersion-convection processes. If groundwater intersects the streambed and a saturated area is generated, the dry store loses salt to the stream zone store. Salt is also transported in the wet store in interflow and percolation. The subsurface store has a salt bulge which is present in the unsaturated soil profile. Salinity of the groundwater store is estimated from observed salinity or salt storage data, and applied to the baseflow.

3.2 Response units and channel networks

The catchment was divided into a total of 86 RUs with an average area of 8 km^2 (Figure 3). A separate RU was included to represent the Serpentine Reservoir which operates as a lake in the model. Each RU is described by a set of attributes including topographic, soil and salt variables and connection to surrounding RUs. A full listing of attributes is provided in Appendix A.

Streamflow and salt load are transported downstream by routing along defined stream channels (Figure 3). Flow generated in a RU is distributed to channels in proportion to their length. A node is required at the ends of a channel and where a channel crosses a RU boundary (Figure 3). Outputs from nodes at a gauging station or at the reservoir are called reporting nodes. Attributes of stream channels are provided in Appendix A, Table A2.

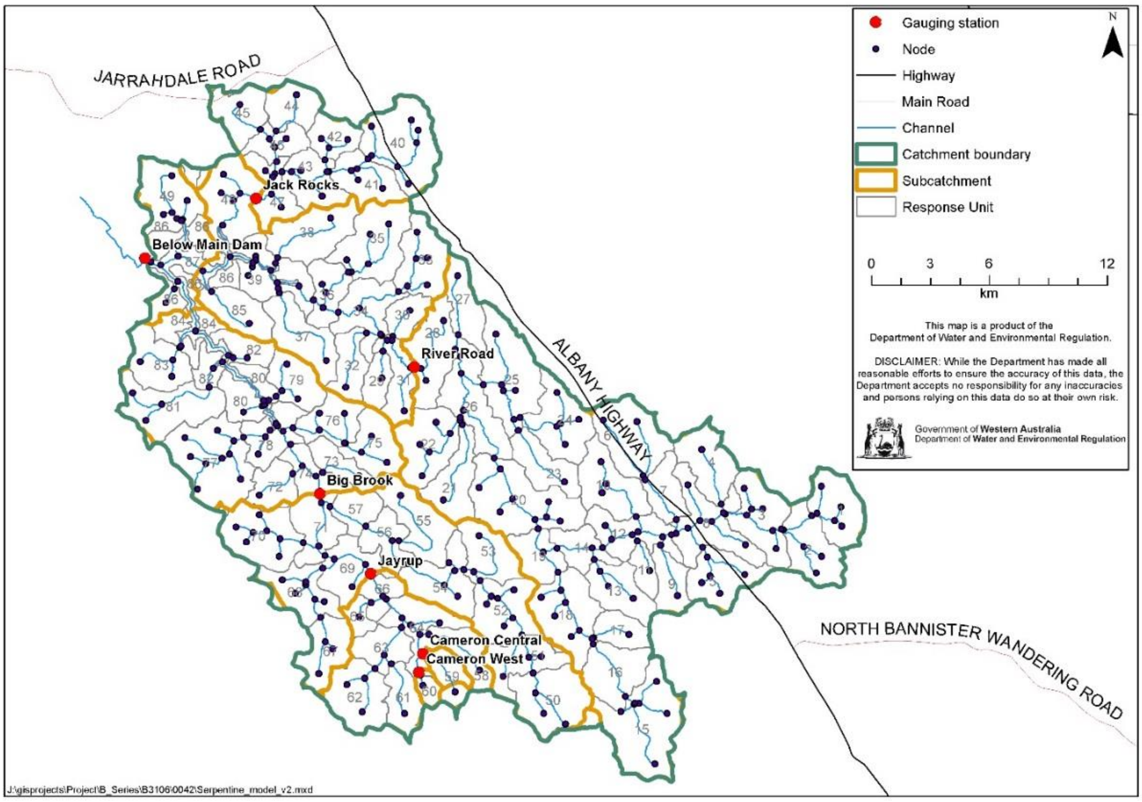

Figure 3 Response units and channels used in the LUCICAT model. Sub-catchments within the Upper Serpentine defined by gauging stations, termed reporting nodes, are also shown

3.3 Serpentine Reservoir

Total monthly inflows to the Serpentine Reservoir since opening in 1961 are estimated using a simple water balance model with the input variables being water level, monthly draw and pumpback volumes, rainfall at the Serpentine Main Dam gauge and Class A pan evaporation at Perth Airport Station 009021 (Water Corporation, 2011). For periods when draws from the main dam were unavailable, these were estimated from measured draws from a smaller pipehead dam located immediately downstream of the main dam. Flow measurement data out of the main dam (Station 614033) prior to 2011 are regarded as poor and the uncertainty related to inflow estimates was considered to be +/- 0.9 GL or approximately five per cent (Water Corporation, 2011). Estimated inflows, along with a dam capacity table, are used in this study to compare against simulated inflows and dam water levels using LUCICAT. The initial conditions of the reservoir were set by calibration (Appendix A, Table A3). The salinity of water released from the dam, measured from 30/6/2000 to 25/8/2009, was in the range 100 to 211 mg/L.

3.4 Rainfall and evaporation input

Daily rainfall at the centroid of each RU was estimated from daily rainfall of the three nearest pluviometers using an inverse-distance weighted method. A total of 42 pluviometers within and around the catchment (Figure 1) were used. On days where a station had a missing record, a station further away was used instead. Salt concentration in rainfall was calculated using distance from coast in the relationship developed by Hingston & Gailitis (1976).

FAO56 evapotranspiration data were extracted from the SILO Data Drill (www.longpaddock.qld.gov/SILO) for the Jarrahdale Bureau of Meteorology weather station (009023). Mean annual pan evaporation data at the centroid of each of the RUs was adopted from Luke et al. (1988) and converted to daily pan evaporation by scaling daily FAO56 record of Jarrahdale. The parameter Pan Mort Factor was set to 1 in the model.

3.5 Vegetation history input

A history of changes in forest cover in the catchment was developed from an annual time series (1973–2011) of spatially-averaged leaf area index (LAI) for each RU. LAI was derived from standardised and calibrated Landsat satellite imagery collected in summer of each year (Mauger et al., 2013). The pixel size of the imagery was 50 m until 1988 and 25 m subsequently. The average LAI of all RUs in the catchment over the study period was approximately 1.4, but ranged between 0.47 and 2.42 (Figure 4). LAI varied with rainfall, being relatively higher towards the west of the catchment and relatively lower to the east.

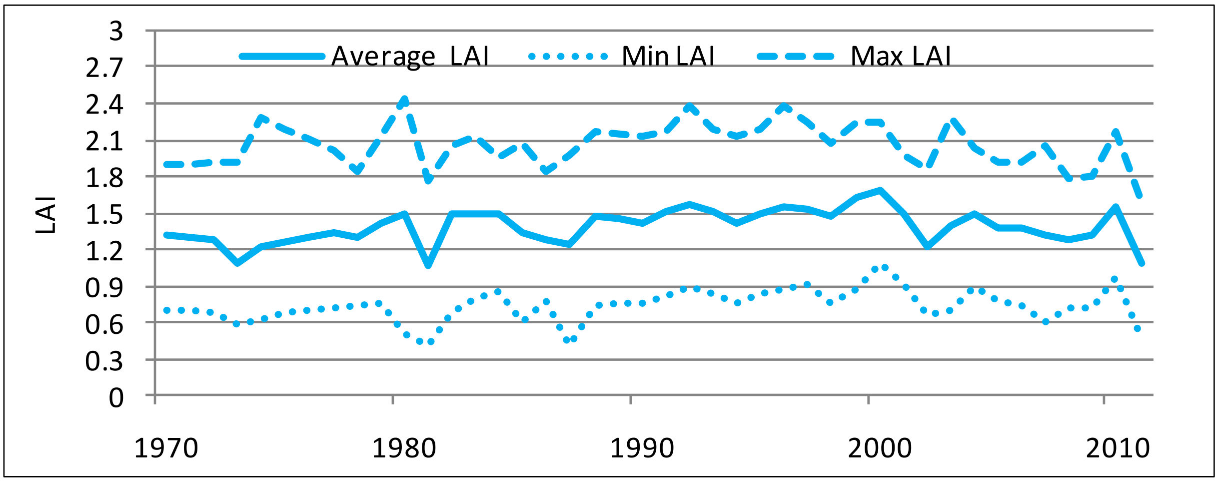

Figure 4 Average, minimum and maximum LAI of all Response Units in the Upper Serpentine catchment (1970–2011)

To enable comparison of simulated inflows to the reservoir with estimated inflows from the water balance model (Section 3.3), it was necessary to extend the LAI time series prior to the first available Landsat scenes in 1972 back to 1963. For this study, an LAI map for the catchment in 1963 was generated based on the average values for the full series 1973– 2011, with LAI in the following years 1964– 1972 linearly interpolated between 1963 and 1973.

3.6 Stream records

Streamflow and stream-salinity data were available for seven sites in the Upper Serpentine catchment for the periods indicated (Table 1; Figure. 3).

Table 1 Gauging sites and records in the Upper Serpentine catchment

Site no.	Site name	Flow record (years)	Salinity record (years)	Catchment area (km²)
614033	Below Main Dam	1980–2006	2000–2009	664
614031	Jack Rocks	1981–1999, 2006-2010	1985–1998	54
614035	River Road	1982–1999	1982–1998	243
614037	Big Brook	1983–2010	1995–2010	149
614093	Jayrup	1995–2010	1995–2010	45
614064	Cameron West	1991–2010	1991–2010	1.6
614066	Cameron Central	1992–2010	1992–2010	4.6

4 Model calibration

4.1 Model objectives

The model objectives specify the requirements of the LUCICAT model to satisfy the aims of the study. The main objective was to develop a calibrated model that could replicate the change in annual volume of flow and stream salinity into the Serpentine Reservoir with differing projected series of rainfall and land use changes due to bauxite mining.

The main objectives are met if it were possible to replicate the:

- monthly storage volumes of the Serpentine Reservoir (1975–2000)
- annual inflows to the Serpentine Reservoir (1975–2010)
- annual streamflow over an average rainfall period (1975–2010) for Big Brook, River Road, Jayrup and Jack Rocks gauging stations
- annual streamflow over the recent lower rainfall period (2001–2010) for the inflows to Serpentine Reservoir, Big Brook, and Jack Rocks gauging stations
- annual salinity for Serpentine Reservoir outflow, Big Brook, Jack Rocks, River Road and Jayrup gauging stations.

River Road and Big Brook gauging stations monitor 36 per cent and 22 per cent respectively of the catchment area upstream of Serpentine Reservoir. Jack Rocks gauging station monitors 8 per cent of the area upstream of the reservoir, but it has the highest annual rainfall of 932 mm (2000–2010). Replicating the flow and salt load at these gauging stations indicates the model is suitable to simulate inflow and salt load inputs to the Serpentine Reservoir. Cameron West and Cameron Central were not considered for the modelling objectives, since these two catchments were each less than one per cent of the total Upper Serpentine catchment.

While there was some minor mining in the Upper Serpentine Catchment from 1996, it was decided to put more emphasis on later years in assessing the model's performance when mining occurred. These later years (2001–2010) did not include many wet years, so two periods were required to assess the model properly. Another medium period was used (1975–2010) to include wetter years.

Replicating streamflow and salt load over the recent low rainfall period will show that the model is suitable for simulating streamflow and salt load under a drier climate. Salinity is highly variable and dependant on the rainfall, being lower in wetter years and higher in dry years. Checking the daily streamflow and salinity for a dry, medium and wet year give an indication of the model's performance for varying conditions.

4.2 Measures of model performance

Annual simulation results were assessed against two objective functions which address different behavioural errors in a model. The coefficient of determination R^2 is calculated as (Equation 1):

$$R^2 = \left(\frac{\sum_{i=1}^{n} (O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n} (O_i - \bar{O})^2} \sqrt{\sum_{i=1}^{n} (P_i - \bar{P})^2}} \right)^2$$

Equation 1

where O is the observed value and P is the simulated value. An R^2 value of 1 means that the dispersion of the prediction is equal to that of the observation; a value of 0 means no correlation. A model that systematically over-predicts or under-predicts (bias) can still result in a value of R^2 close to 1. The gradient of the regression between observed and simulated values should be close to 1 for a good model fit. In this study, the intercept term was forced through the origin. Bias in the results is observed if the regression slope is either greater or less than 1.

The second objective function used in the study was the Nash Sutcliffe Efficiency (NSE) term (Equation 2, Nash & Sutcliffe, 1970). This efficiency criterion normalises the variance of the observation series during the period of investigation:

$$NSE = 1 - \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} (O_i - \bar{O})^2}$$

Equation 2

where O is the observed value and P is the simulated value. This results in a relatively higher value of NSE for catchments with large variations in flow and lower values of NSE for catchments with lower variations in flow.

The NSE is sensitive to over- or under-prediction especially during low flow periods (Krause et al., 2005). A perfect fit of simulated and observed values results in an NSE = 1. A value of 0 means that the mean of the data would have been better than the model's prediction. For models that are worse than this, NSE can have negative values.

To meet the modelling objectives, the following criteria were set for the reservoir inflows and major gauging stations of Big Brook, Jack Rocks, River Road and Jayrup:

- bias in annual streamflow < ± 25%
- annual streamflow Nash Sutcliffe Efficiency (NSE) > 0.7
- annual streamflow coefficient of determination (R^2) > 0.8
- annual modelled outflow salinity of the reservoir to be within 50 mg/L of the observed values.

4.3 Calibration approach

Global parameters controlling the catchment water and salt balances were supplied in a global parameter input file (Appendix A, Table B1). The interflow exponent, the relationship between RU lateral hydraulic conductivity of topsoil and moisture content, is the most influential parameter among all global parameters and was the target for initial calibration. The second most sensitive parameter is the vertical conductivity of the wet store which controls the percolation to the deep unsaturated profile. Together with the spatial distribution of water-holding capacity, these parameters control the degree of homogeneity of soil characteristics across the whole catchment. For salinity calibration, focus was placed on two global parameters which have the greatest influence on salinity: lateral hydraulic conductivity of the aquifer controls the salt load transportation to the stream, and a second parameter which controls the salt releases from the dry store to the wet store.

Local parameter values (Appendix A, Table A1) were refined iteratively by comparing nodal daily and yearly flow model outputs with the relevant observed data. At this stage, the parameters controlling evapotranspiration and interflow were targeted. Both these vary with rainfall; the interflow generation process in a high rainfall zone is larger than in a low rainfall zone, therefore smaller values are considered in RUs in higher rainfall zones and vice versa.

Iterative checks of model fits used two measures of model performance, described in the following section. An additional check was performed by comparing the general trend of groundwater levels using LUCICAT simulations, with the general trend in groundwater levels observed in catchment bores. Observed groundwater levels were not directly compared since simulated groundwater levels applied to an entire RU, however, the trend in groundwater levels was a useful check.

A warm-up period of five to ten years was used in the model to account for the antecedent conditions of the catchment.

4.4 Comparison with observed data

Annual flows

LUCICAT produced satisfactory predictions of annual flow at the reservoir and at the major gauging stations within the Upper Serpentine catchment, with R^2 in the range 0.70 to 0.98, NSE in the range 0.73 to 0.89 and bias between observed and modelled flows across the available record mostly within seven per cent of the 1:1 line (Figure 5). The model was therefore considered fit for purpose since it satisfied the model objectives. Relatively poorer fits were obtained for Cameron West catchment, and particularly Cameron Central catchment where flow was over-predicted by more than 50 per cent on average. Both these catchments are small (Table 1) and were each represented by a single RU in the LUCICAT model (Figure 3). Annual flows were also small and runoff coefficients in both catchments were < 1 % on average across all years, the least of all sites (Figure 6).

Bias in Cameron West and Cameron Central was largest after 2006 when disturbance from mining was greatest (Figure 6e, f). Bias was apparent for the Jack Rocks site after 2006 when the station was reopened (Figure 6a). In this period, predicted runoff coefficients were almost double those observed, except for the record dry year of 2010. Mining in Jack Rocks was limited to approximately two per cent of the total catchment area and all areas had been fully rehabilitated many years before. The issue affecting Jack Rocks therefore appears to be different to the Cameron West and Cameron Central catchments. Better model fits were obtained for the larger catchments of River Road, Big Brook and Jayrup (Figure 6b, c, d).

Modelled annual reservoir inflows were, on average, within three per cent of those estimated from the water balance model, with a reasonably good fit for all years (Figure 5a). However, annual inflows were consistently over-predicted after 2001 (Figure 7a). This is clearly visible in the monthly reservoir storage volumes (Figure7b) and annual runoff coefficients (Figure 7c). For the period 2001–10, actual annual average inflows were 17.5 GL while modelled annual inflows averaged 26.2 GL an overestimate of 50 per cent. Mining in the catchment (Figure 7c), occurred in parts of the Jarrahdale mine in the late 1990s followed by the Huntly mine from 2004. The LUCICAT model under-predicted the inflows to the reservoir before 2001 and over-predicted the inflows after 2001. This divergence in bias after 2001 did not coincide with the commencement of mining in the catchment. Altogether, less than two per cent of the catchment was mined by 2010, which is as far as the records go. The pattern of bias therefore more closely resembles the Jack Rocks catchment rather than the Cameron West and Cameron Central catchments. These observations are discussed further below.

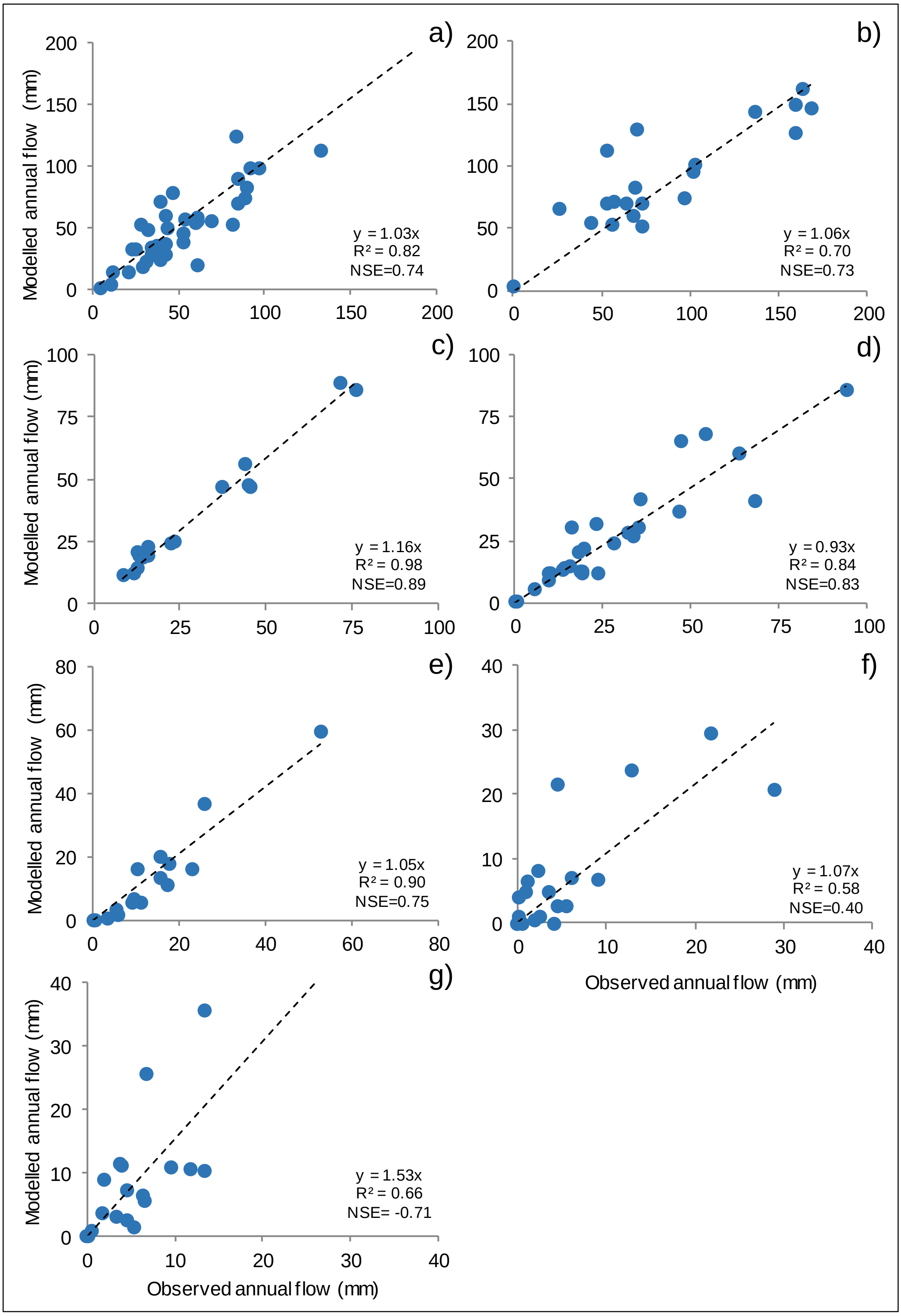

Figure 5 Regression plots and objective function statistics for comparisons of observed and LUCICAT-modelled annual flows for a) Serpentine reservoir, b) Jack Rocks, c) River Road, d) Big Brook, e) Jayrup, f) Cameron West and g) Cameron Central gauging stations

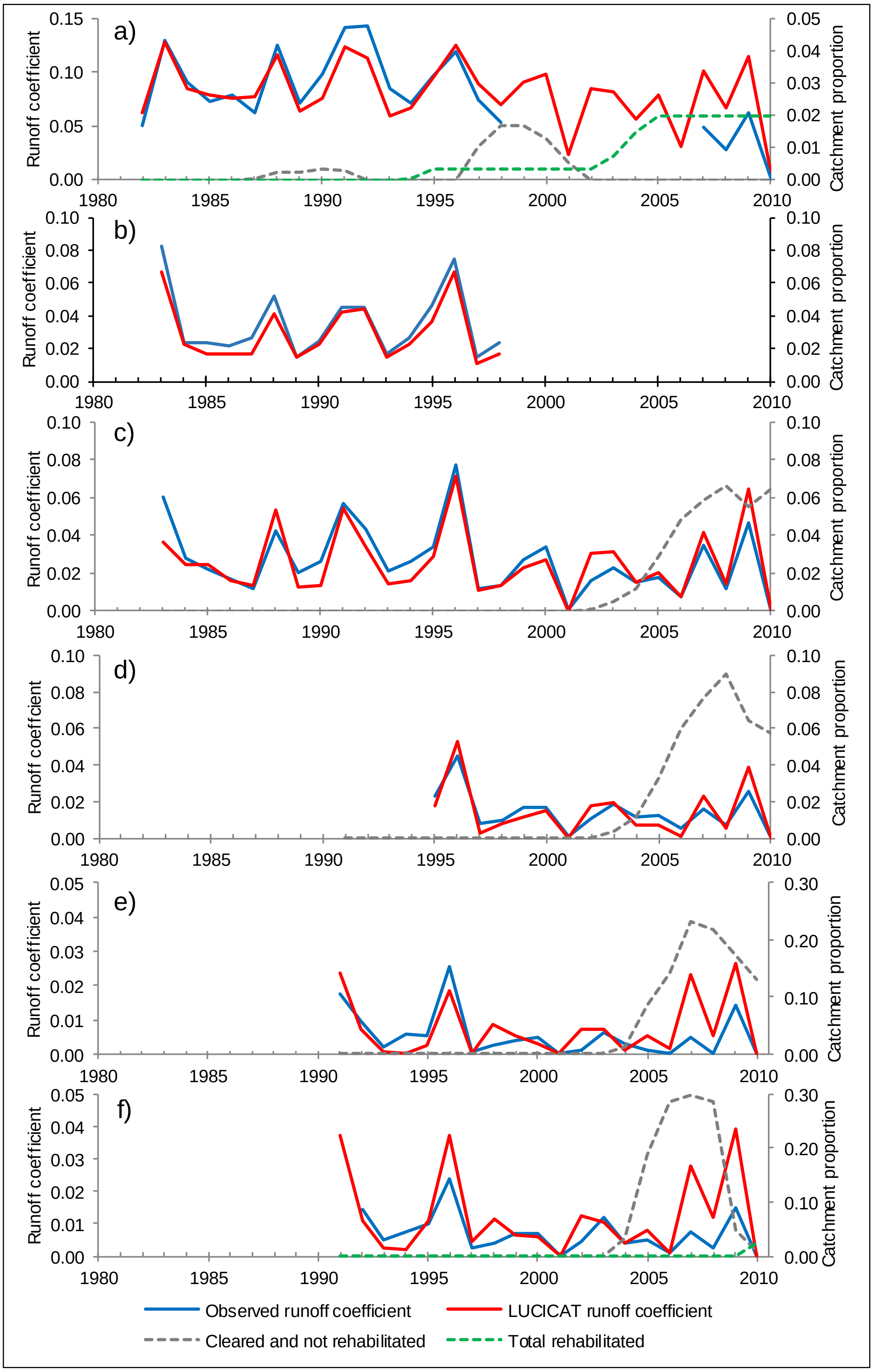

Figure 6 Comparison of LUCICAT-modelled and observed runoff coefficients at a) Jack Rocks, b) River Road, c) Big Brook, d) Jayrup, e) Cameron West and f) Cameron Central. Also shown is the proportion of the catchment affected by clearing for mining and not yet rehabilitated and the proportion of the catchment rehabilitated after mining

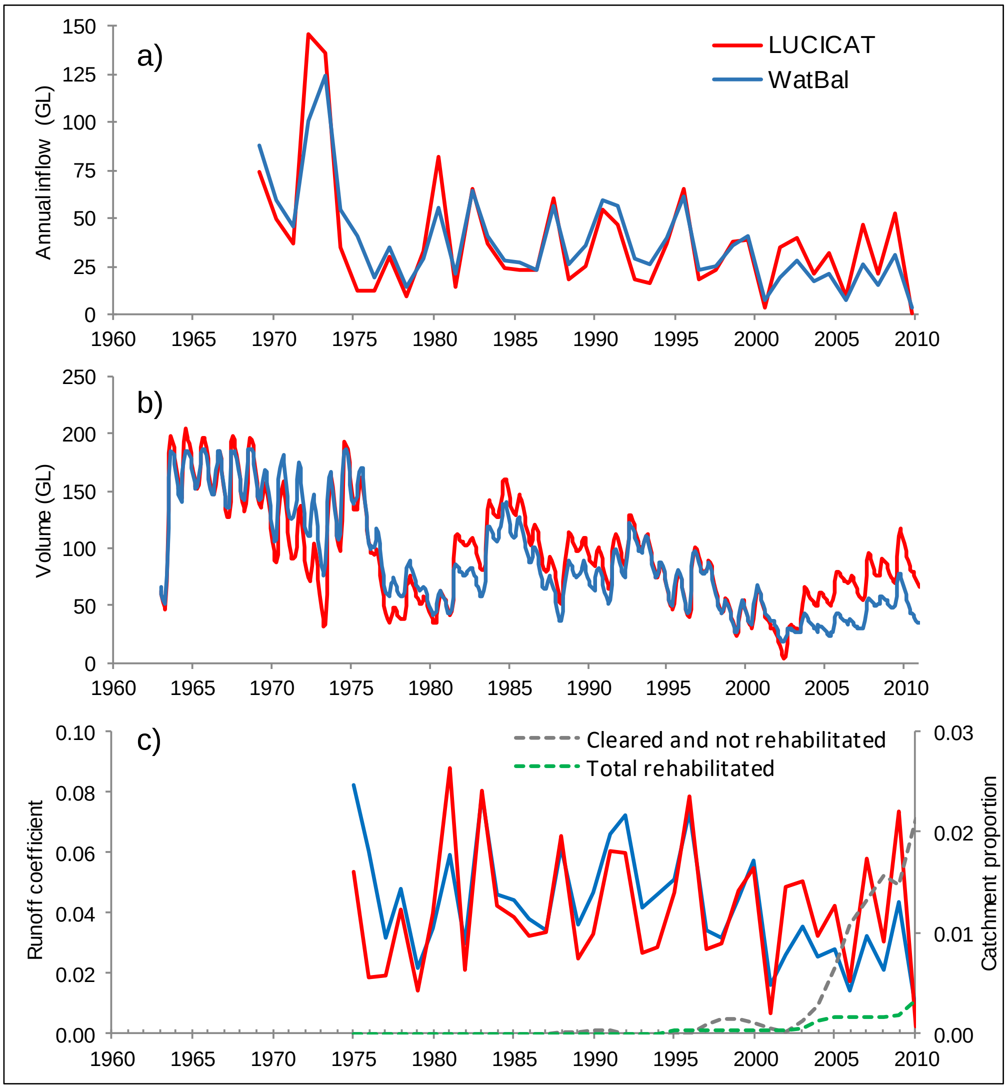

Figure 7 Comparison of a) annual inflows, b) monthly storage volumes and c) runoff coefficients from LUCICAT modelling and a dam water balance model estimate (WatBal) for the Serpentine Reservoir. Also shown in c) is the proportion of the catchment affected by clearing for mining and the proportion of the catchment rehabilitated after mining

Annual salinity

Estimated annual flow-weighted salinity of the Serpentine Reservoir from LUCICAT agreed within 40 mg/L of measured salinity in the main dam outflow (station 614033; Table 1) for the years in which records were complete (2001–05, Table 2).

Good model fits were obtained for the larger catchments of Jack Rocks, River Road, Big Brook and Jayrup (Figure 8a–d), although salinity at Jack Rocks was over-estimated by 16 per cent on average and salinity at River Road tended to fall below the 1:1 line.

Particularly good fits were obtained for Big Brook and Jayrup catchments (Figure 8c, d) where the model under-estimated salinity in only the high flow years of 1996 and 2009. Poorer fits were obtained for the small headwater catchments of Cameron

West and Cameron Central, reflecting the poorer fit for flows. Modelled annual estimates of salinity for all catchments tended to be lower in the years where flow had been over-estimated and *vice versa*. Annual salinity in the years 2005–09 tended to be under-estimated for both catchments. Larger discrepancies in salinity (Figure 8e, f) were usually associated with years such as 2006 when observed flow was minimal but modelled flows were higher.

Table 2 Comparison of LUCICAT-modelled and observed annual salinity in the Serpentine Reservoir

Year	Observed salinity (mg/L)	Modelled salinity (mg/L)
2001	154.2	170.7
2002	155.9	193.6
2003	170.1	159.8
2004	164.6	160.1
2005	161.0	168.7

Daily flows and salinity

Model results for daily time scales provided further insight into the patterns observed for annual data. Good model fit for Big Brook catchment is demonstrated in 2007 where there is good correspondence between the start of season flow, peaks and recession curves (Figure 9a). Likewise, modelled salinity tracked reasonably well (Figure 9b). Good model fit is also evident for the River Road site, exemplified by the higher flow year 1988 (Figure 9c, d). Again, the start of season flow and general seasonal form of the hydrograph track well, but the overestimation of annual flows identified in Section 4.3.1 can be seen in the higher estimates of peak flows.

Two years (1989, 2008) are shown for the Jack Rocks site in Figs 9e-h to demonstrate the overestimation of flow in the latter part of the record. Both years had similar rainfall (approx. 950 mm) but flow in 1989 (68 mm) was nearly three times greater than in 2008 (28 mm; Figure 9e, g). In 2008, modelled flow commenced strongly a month prior to significant observed flows. Peak flows were also strongly overestimated, and recessions were higher. In 1989, modelled salinity followed actual salinity for the majority of the season. Modelled salinity at the start and end of the flow season were much greater (Figure 9f), which was most likely responsible for the overestimation of annual salinity (Figure 8a). There were no observed salinity readings in 2008 to compare with modelled values (Figure 9h).

While annual flows in Jayrup catchment were well represented by LUCICAT, there was a tendency for modelled flows to commence later than actual flows and have higher peak flows later in the season (Figure 10a). However, modelled salinity followed actual salinity well (Figure 10b). Modelled flows in both Cameron West and Cameron Central catchments also displayed a pattern of a delayed start to the flow season, similar to Jayrup. For example, in 2000 prior to mining in Cameron Central catchment (Figure 10c), observed flow commenced almost a month before modelled flow. While modelled salinity tracked actual salinity reasonably well, modelled salinity tended to be lower than observed late in the season (Figure 10d), reflecting higher modelled peak flows in this latter part of the season. Figure 10e shows that for the years when mining disturbance was greatest in Cameron Central catchment, the overestimation of annual flows identified during this period (Section 4.3.1) manifest in a closer match of the start of season flow rather than the delayed start, higher peak flows and less rapid recessions. Consequently, modelled salinity are much lower than actual (Figure 10f). Elevated salinity at the start and end of the flow season are also characteristic of LUCICAT output, however, observed salinity in both Cameron West and Central catchments, and Jayrup catchment, are consistently low.

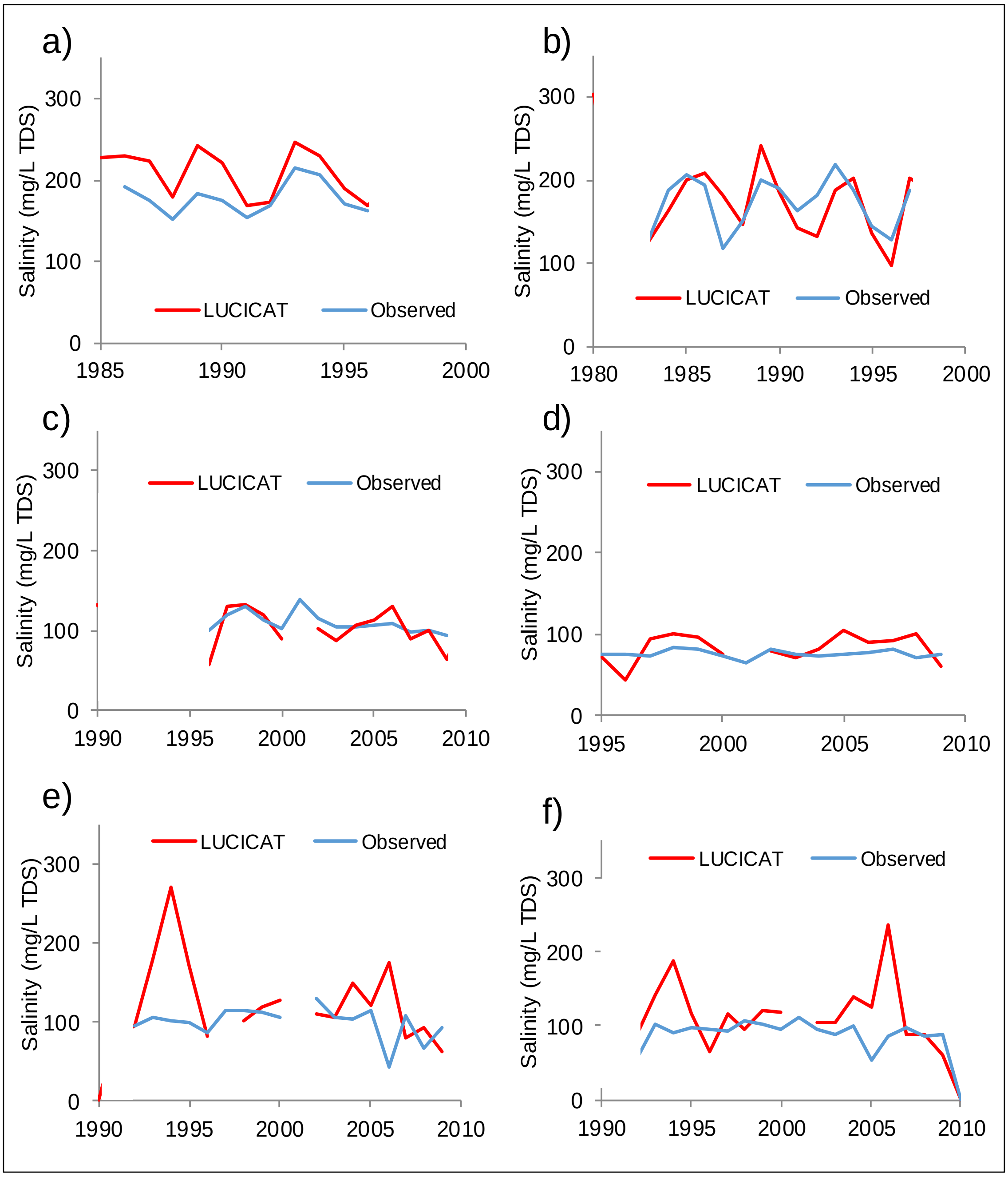

Figure 8 Annual salinity comparisons for a) Jack Rocks, b) River Road, c) Big Brook, d) Jayrup, e) Cameron West and f) Cameron Central

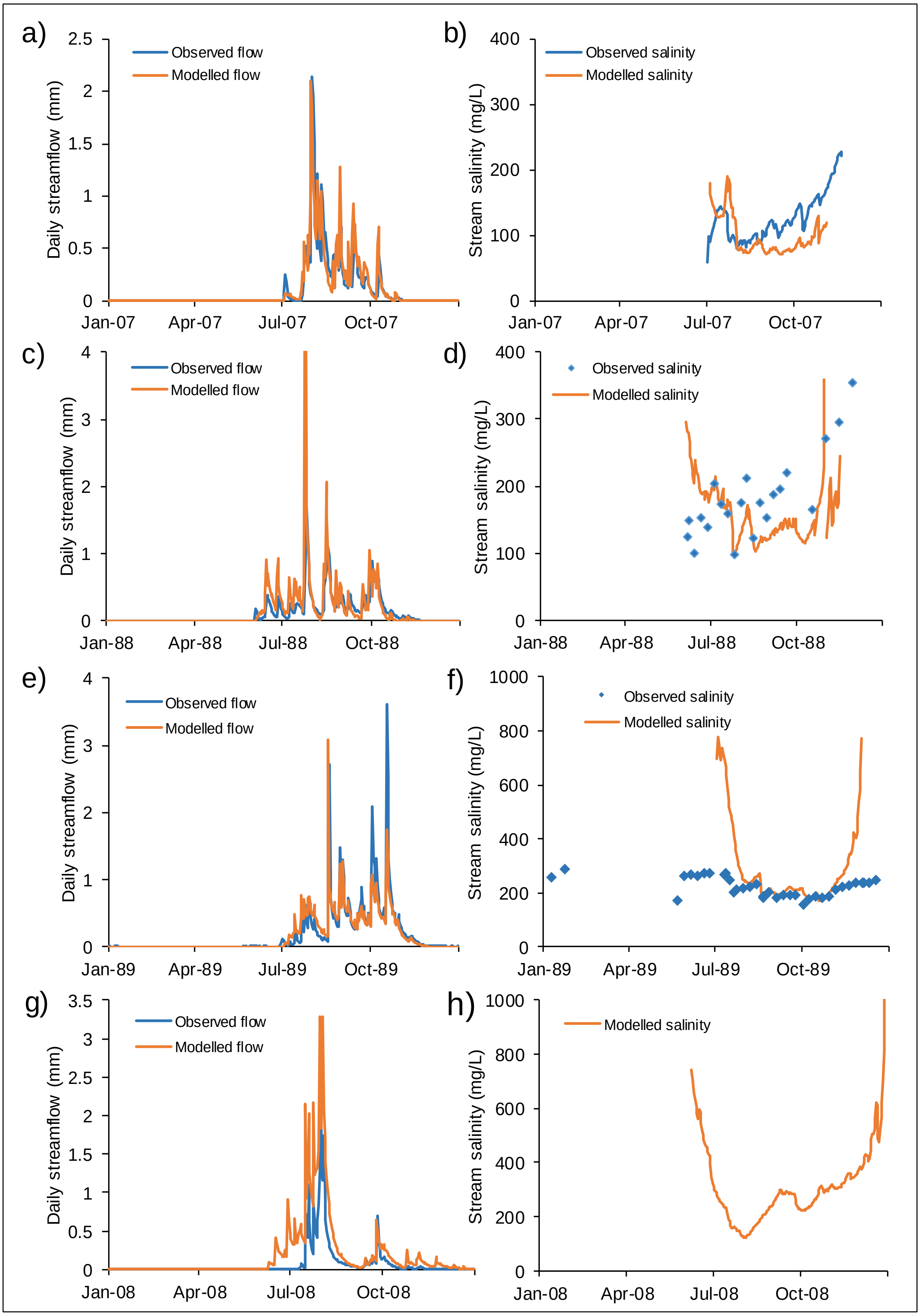

Figure 9 Daily flow and stream salinity hydrographs for (a, b) Big Brook in 2007, (c, d) River Road in 1988, (e, f) Jack Rocks in 1989 and (g, h) Jack Rocks in 2008

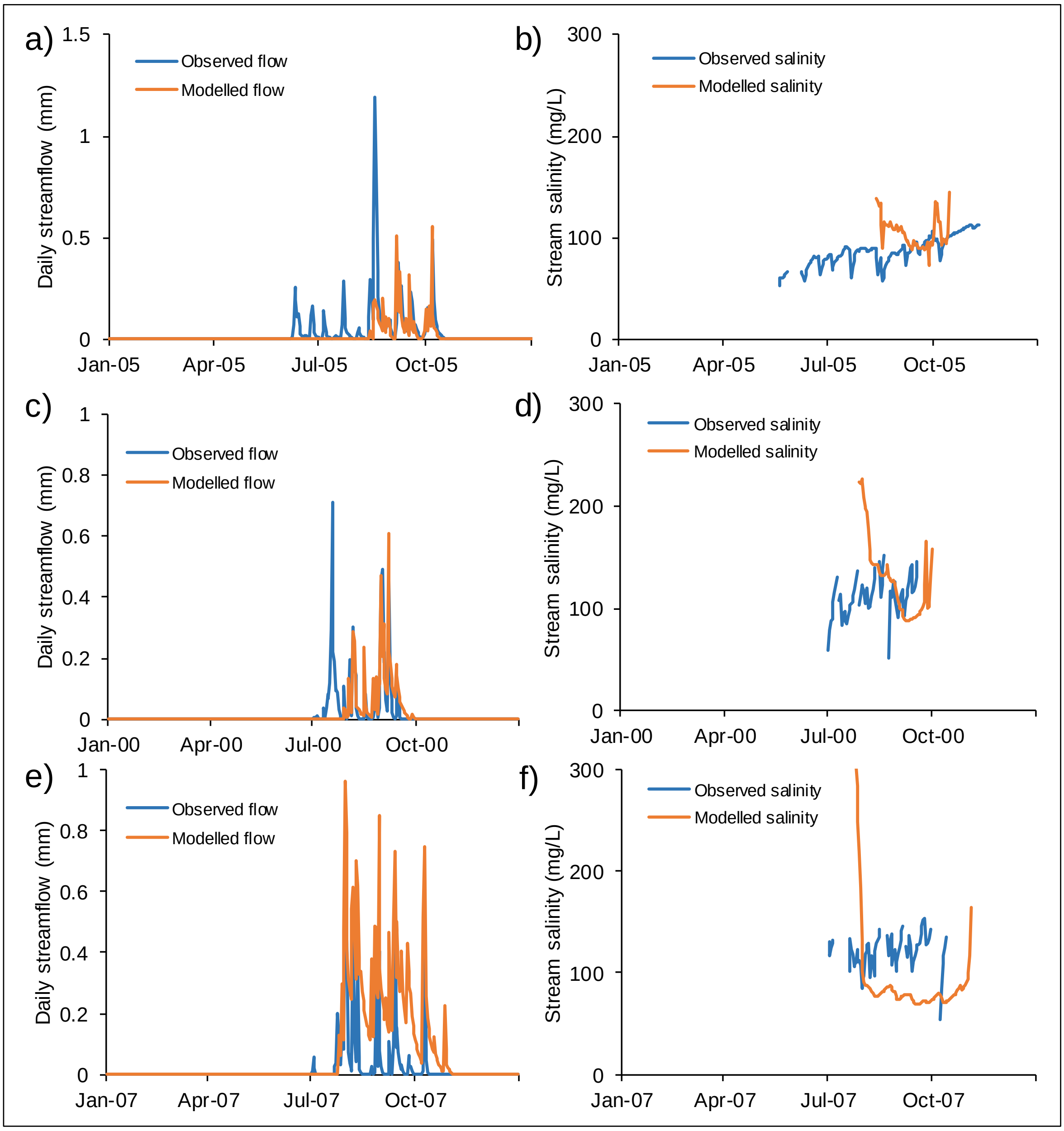

Figure 10 Daily flow and stream salinity hydrographs for (a, b) Jayrup in 2005, (c, d) Cameron Central in 2000 and (e, f) Cameron Central in 2007

Discussion on calibration

Comparison of modelled and observed flows above highlighted bias in modelled flows after 2001 for Serpentine Reservoir (Figure 7). Reduced runoff relative to rainfall was observed from 2001 onwards (Figure 11a) while modelled flows were notably higher. Petrone et al. (2010) similarly identified a statistically significant change point in inflows to the Serpentine Reservoir in 2001, together with several other smaller catchments in the region with change points in either 1998 or 2001. Hughes et al. (2012) showed that decreases in runoff coefficients were associated with step declines in groundwater levels following strong drought years that were not followed by wetter years. Therefore, it is likely that a step decline in catchment groundwater storage, and more importantly reduced connectivity of deep groundwater with valley floors (Hughes et al., 2012; Kinal and Stoneman, 2012) occurred in parts of the Upper Serpentine where groundwater has historically been closer to the surface (Schofield et al., 1989). While it is not possible to determine the year of change for Jack Rocks catchment due to the closure of the station between 1999 and 2006, lower flows for the period after reopening (Figure 11b) are consistent with a change point in 2001. Data recently presented by Grigg (2017) and Grigg and Hughes (2018) on the relationship between runoff coefficient and the size of the groundwater discharge area in jarrah forest catchments, suggests that the degree of groundwater connection in Jack Rocks fell from a range of four to seven percent of the catchment area prior to 1999, when the station closed, to less than two per cent subsequently.

Of note is the apparent absence or possibly more subdued change in the runoff coefficient for Big Brook catchment (Figure 11c). Most of Big Brook catchment spans the IRZ that has been historically associated with disconnected deep groundwater (Croton et al., 2011). Petrone et al. (2010) also identified a statistically significant change point in runoff for the Upper Serpentine in 1975, which was adequately captured by the model (Figure 7). The change point in 1975 was accompanied by a statistically significant reduction in rainfall around the same year, a feature that is missing from 2001. These authors noted that the change point in 2001 was associated with an individual dry year rather an overall rainfall trend, a distinction that modelled groundwater storage may not be reflecting well (Hughes and Vaze, 2015; Grigg and Hughes, 2018).

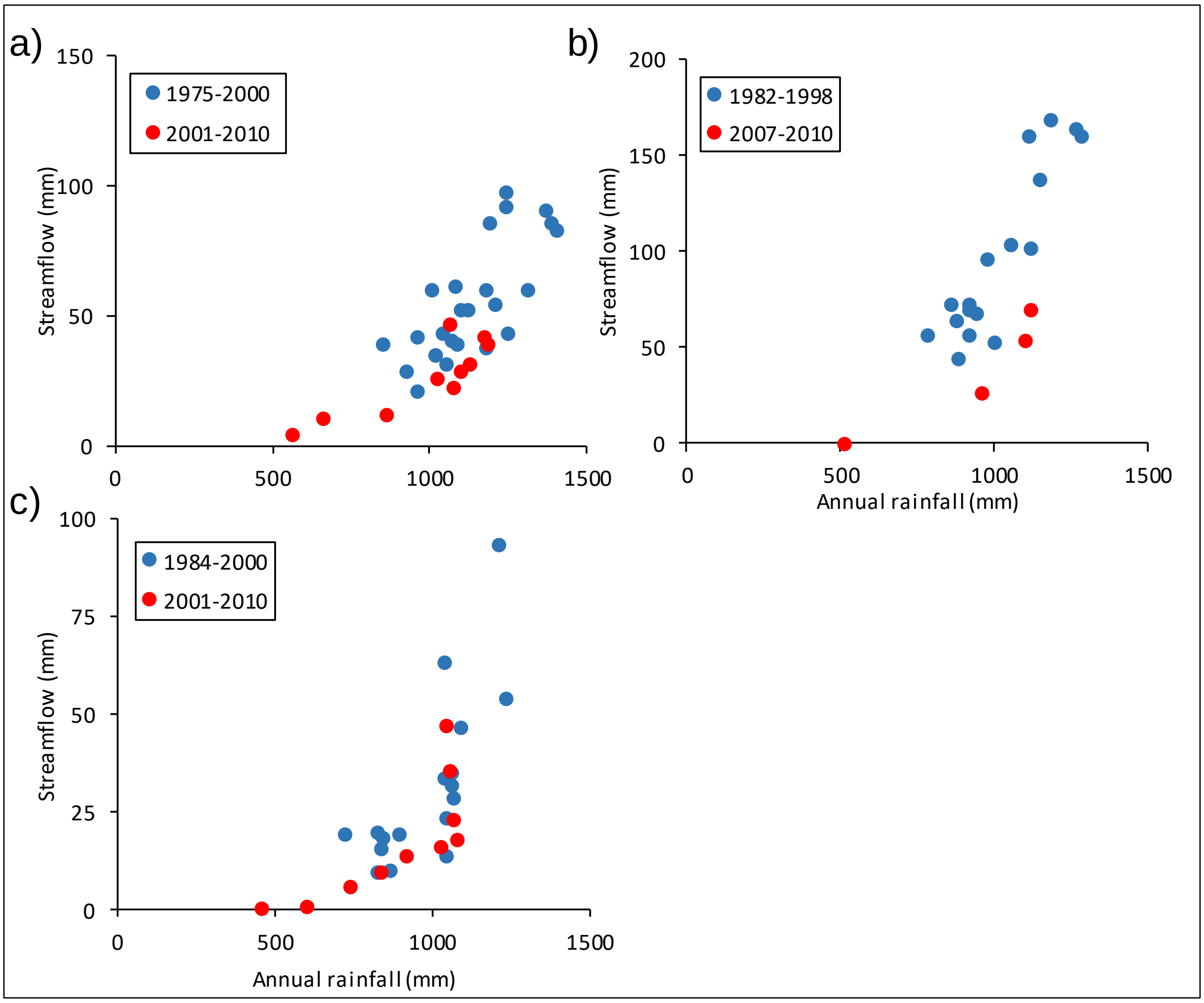

Figure 11 Relationship between annual rainfall and streamflow for a) Serpentine Reservoir, b) Jack Rocks and c) Big Brook catchment. Note that in b) complete annual flow was not recorded for the years 1999-2006

Deep groundwater has been well below the valley floor throughout the period of records in Cameron West and Cameron Central catchments (Croton et al., 2011). Model overestimation of flows during the period of mining since 2003 (Figs. 6e, f, 10e) is not related to a step-decline in groundwater connection. Rather, model overestimation is more likely associated with routing of infiltrated rainfall through the wet store to the stream zone, possibly as lateral interflow. Modelled additional recharge as a result of clearing for mining within the RU may be preferentially directed as downslope lateral flows rather than into the subsurface and groundwater stores by deep percolation, in turn creating a larger saturated area in the stream zone. Direct runoff is also increased as a consequence. Croton et al. (2011) found that there was no streamflow response to mining in either of these catchments, indicating that downslope interflow is insignificant as a pathway for infiltrated rainfall and streamflow generation. Similarly, Grigg (2017) concluded from a comparison of streamflow response to mining and to heavy thinning (in which the surface soil horizons remained intact) that shallow interflow must be limited to the valley floor and immediately adjacent slopes. In the wide and relatively flat valley floors more typical of the eastern parts of the jarrah forest and of the south-east of the Upper Serpentine, shallow perched aquifers can be present in the valley floor (Fordyce et al., 2007) that fill during the winter wet season and are the main source of streamflow, but are dry throughout the remainder of the year. These perched aquifers may fill and generate streamflow causing modelled flows to start and finish later than observed flows in Jayrup, Cameron Central and, to a lesser extent, Cameron West catchments (Figs. 10a, c). A closer examination of model store dynamics is warranted in future work to improve model's effectiveness under these circumstances.

5 Bauxite mining and climate scenarios

5.1 Description of scenarios

Two possible mine plans together with a no-mining comparison were considered in conjunction with two future climates to give a total of six future (2011–50) scenarios. These are summarised in Table 3 and are described in more detail in the sections that follow.

Table 3 Summary of modelled bauxite mining and climate scenarios

Scenario	Bauxite mining (existing and proposed)	Daily future rainfall & PET for 2011–50 based on
Unmined – Average	No existing or future mining	1975–2010
Unmined – Dry	No existing or future mining	2001–2010
Mined A – Average	12% of Upper Serpentine	1975–2010
Mined A – Dry	12% of Upper Serpentine	2001–2010
Mined B – Average	9% of Upper Serpentine catchment	1975–2010
Mined B – Dry	9% of Upper Serpentine catchment	2001–2010

Bauxite mining

To assess the hydrological impacts of bauxite mining and rehabilitation for existing and proposed future mining, an unmined case and two mined scenarios (Case A and Case B) were considered.

In the unmined case, the LAI for all areas mined prior to 2011 (Figure 12, Table 4) was replaced for each RU with an estimate of what the native forest LAI would have been if no mining had occurred. This was assumed to be the average LAI of all forest areas within the response unit not disturbed by mining for the period 1975–2010. From 2011 to the end of simulations, an average forest LAI for all areas was assumed, which varied depending on the RU. One of two sets of LAI values was used depending on the future climate scenario (see following section): the average forest LAI for the period 1975–2010 for the future average climate, and the average forest LAI for the period 2002–2010 for the future dry climate (the latter being 1.5 per cent less, on a whole catchment basis).

The Case A mining proposal included existing mined areas in the south west of the Upper Serpentine catchment and a proposed northward extension into the Jack Rocks sub-catchment (Figure 12a) totalling 77 km^2 (Table 4) or 12 per cent of the total catchment. A smaller footprint of 62 km^2 (Table 4) or nine per cent of the total catchment under an alternative Case B was included whereby mining did not extend north of the Serpentine River (Figure 12b). For both cases, no mining was planned for the eastern parts of the Upper Serpentine. Each mine pit was assigned a year of mining according to a conceptual mine plan up until the final year in 2030, or sooner under Case B (Figure 12 shows the schedule broken into only two periods for the purposes of illustration). It is important to note that the extent of each mine area becomes less certain for later mine areas due to the progression of exploration drilling. Therefore, many of these areas are an overestimate of the final mined pits, and the effects of mining and rehabilitation will likely be less than predicted, all else being equal.

In the LUCICAT model, mined areas from 2011 onwards were assigned an LAI value of zero one year prior to the planned mining year. The forest is cleared one year prior to mining. Two years after the planned mining year, an LAI growth curve shown in Figure 13 was applied. The growth curve reflected standard current establishment prescriptions for rehabilitation, with a target combined stocking of jarrah and marri trees of 1300 trees per hectare, and a diverse native understorey mix featuring a prominent quick- growing shrub layer. Importantly, prescribed burns or wildfire events that cause both transient and longer-term reductions in understorey cover over the scenario period were ignored. Similarly, no disturbance was assumed for the over-storey through fire or timber harvesting, even though these are likely to occur at some point over the course of the time series. Consequently, the LAI trajectory of rehabilitated forest eventually exceeds the LAI of typical unmined multiple-use forest (Figure 13).

For both Cases A and B, the LAI of unmined areas from 2011 onwards was assumed to be the same as that adopted for the no-mining scenario described above.

Table 4 Existing and proposed future mining in the Upper Serpentine and sub-catchments under two different mining scenarios

Catchment	Existing mining		Proposed mining (km^2)		Total mining (km^2)	
	Years	Area (km^2)	Case A	Case B	Case A	Case B
Serpentine Main Dam	1987–2010	24.00	53.57	37.80	77.57	61.81
Jack Rocks	1987–1999	1.09	7.13	0	8.21	1.09
River Road	2010–2010	0.50	4.99	4.10	5.49	4.60
Big Brook	2002–2010	18.30	4.55	4.55	22.85	22.85
Jayrup	2004–2010	5.53	0.62	0.62	6.15	6.15
Cameron West	2004–2008	1.24	0	0	1.24	1.24
Cameron Central	2004–2008	0.52	0	0	0.52	0.52

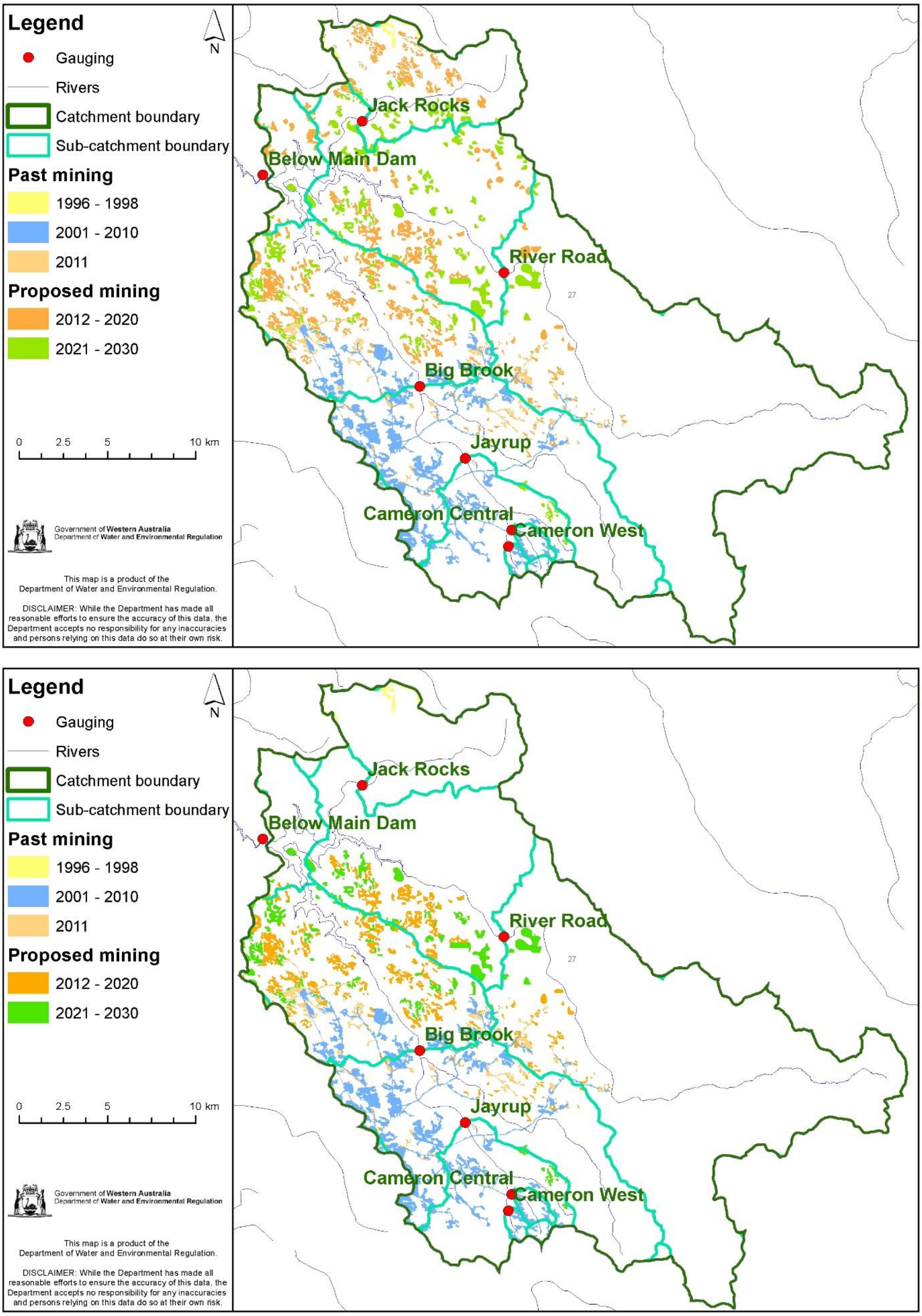

Figure 12 Existing (pre-2011) and proposed future mining areas in the Upper Serpentine catchment for a) Case A and b) Case B

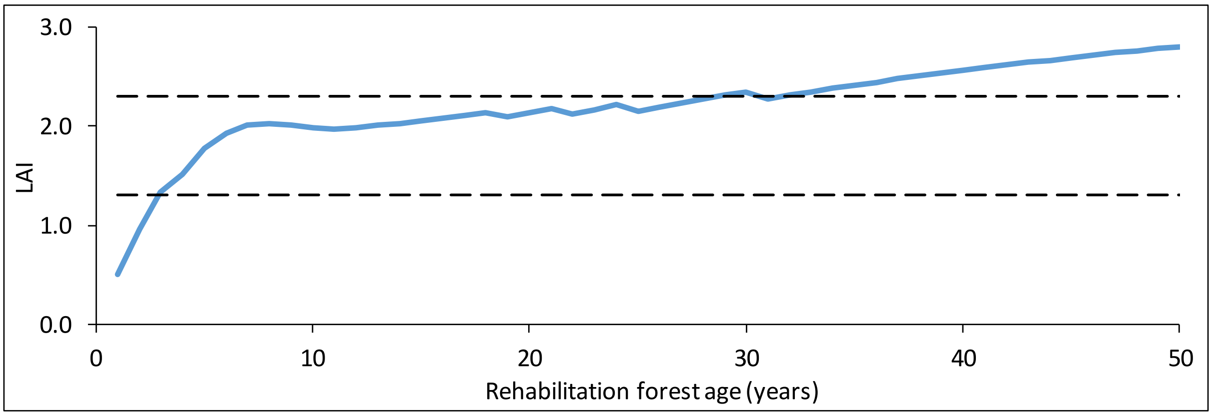

Figure 13 Assumed growth curve for rehabilitated jarrah forest. The dotted lines indicate the range in LAI of typical unmined jarrah forest at the plot scale

Climate

Two future climate scenarios were considered, reflecting projections for continued decline in rainfall for South West Western Australia (Silberstein et al., 2012). The 'average' future annual rainfall and derived potential FAO evapotranspiration (PET) for the period 2011–50 were constructed by repeating the respective series recorded across the catchment during the period 1975–2010. Hence the rainfall and PET for 2011 was assumed to be equal to that of 1975, the rainfall for 2012 was assumed to be equal to that of 1976 and so on. The 'dry' future annual rainfall and PET were constructed by repeating the respective series recorded across the catchment during the period 2001–10 (Figure 14). Hence the rainfall and PET for 2011 was assumed to be equal to that of 2001, the rainfall and PET for 2012 was assumed to be equal to that of 2002, and so on, until 2020. The pattern was repeated three times with the rainfall for the final year in 2050 being equal to that of 2010. The average rainfall at the centroid of the Upper Serpentine catchment for the period 1975–2010 was 914 mm, and 841 mm for the period 2001–10. The period 2001–10 contained three very dry years in 2001, 2006 and 2010 and was characterised by an absence of very wet years (Figure 14).

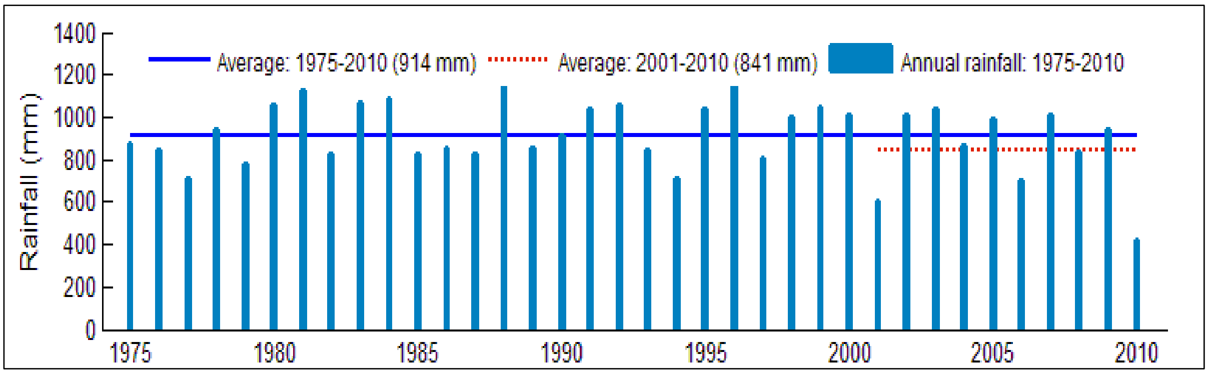

Figure 14 Time series of estimated annual rainfall at the centroid of the Upper Serpentine catchment

5.2 Scenario results and discussion

Projected inflows to Serpentine Reservoir to 2050 were divided into two periods 2011–30 and 2031–50 (Table 5). The first period was characterised by mining and rehabilitation activities taking place concurrently, while in the second period there was no further clearing for mining, and rehabilitated vegetation on all previously mined areas was in various stages of regrowth.

For the no-mining scenario, there was little difference in inflows between the two periods (Table 5), and the average annual inflow of about 29 GL for the average future climate was close to that observed in the period 1975–2010 (data not shown). Inflows under the dry future climate were lower than the average future climate as expected (Table 5). However, inflows were higher than the observed inflows for the period 2001–10. This reflected the overestimation of inflows in this period during the calibration of the model. Inspection of the plot of annual inflows (Figure 15b) reveals that the sequence of inflows essentially reset for each of the repeated sequence of rainfall years, suggesting that the model may not be capturing step declines in groundwater and connectivity as previously discussed. Such step declines might be expected to result in declining flows over the period due to increasing groundwater disconnection in the higher rainfall parts of the catchment, and the estimates of both inflows and responses to mining may therefore be overestimated.

The key finding for both mining scenarios was the relatively minor inflow-response on an average annual basis. Regardless of the mining case or future climate, the change in inflows due to mining was no greater than five per cent of flow (Table 5) and is barely visible in the plots of annual flows (Figure 15a, b).

When inflow differences are viewed in more detail (Figure 15c), relatively greater inflows were simulated for the first period, coincident with the greatest proportion of the catchment cleared for mining, before declining to below pre-mining levels in the second period when all mine rehabilitation had been established. In this second period, simulated forest density or LAI in rehabilitated areas was in the upper range of, or exceeded, that of unmined forest (Figure 13).

Increased streamflow arising from reductions in forest cover has been documented for several catchments in South West Western Australia, with the magnitude of response increasing with greater vegetation reductions, and the response-duration being shorter where forest recovery is faster (Bari and Ruprecht, 2003). The relatively minor responses simulated in this study are likely to be partly associated with the relatively small proportion of the catchment subject to clearing and mining at the scale of the Upper Serpentine catchment. Even under the Mining Case A scenario, only 12 per cent of the catchment overall was subject to mining, and less than three per cent of the catchment was cleared but not rehabilitated in any one year (Figure 15c). This compares with approximately 30 per cent cleared for mining in the smaller Cameron West and Cameron Central catchments in this study, and 50 per cent in a small jarrah forest headwater catchment (with associated larger streamflow responses) reported by Grigg (2017).

Table 5 Projected inflow to Serpentine Reservoir for mining and climate scenarios

Scenario	Average inflow 2011–30 (GL)	Average inflow 2031–50 (GL)	Difference 2011–30 GL (%)[a]	Difference 2031–50 GL (%)[a]
Unmined – Average	28.9	28.0	-	-
Unmined – Dry	24.9	24.9	-	-
Mined A – Average	30.0	26.6	1.1 (4)	-1.4 (-5)
Mined A – Dry	25.8	23.7	0.9 (4)	-1.2 (-5)
Mined B – Average	29.7	26.9	0.8 (3)	-1.1 (-4)
Mined B – Dry	25.6	23.9	0.7 (3)	-1.0 (-4)

[a] Percentage of total average flows compared to the 'no mining' case

The rehabilitation growth curve adopted for the study, in which LAI recovers rapidly in the first five to ten years after establishment, may also be responsible for the minor overall inflow response. Evapotranspiration is closely correlated with LAI in jarrah forest stands (Macfarlane et al., 2018), hence a rapidly increasing LAI in the LUCICAT model would have considerably reduced the amount of infiltrated rainfall available for streamflow generation. The adopted growth curve is also the main factor responsible for the decline below simulated no-mining inflows since, in the absence of typical forest disturbances such as prescribed burns or timber harvesting, simulated LAI eventually exceeds that of the unmined forest. For the purposes of this study, the results therefore provide a more conservative estimate of the effect of mining.

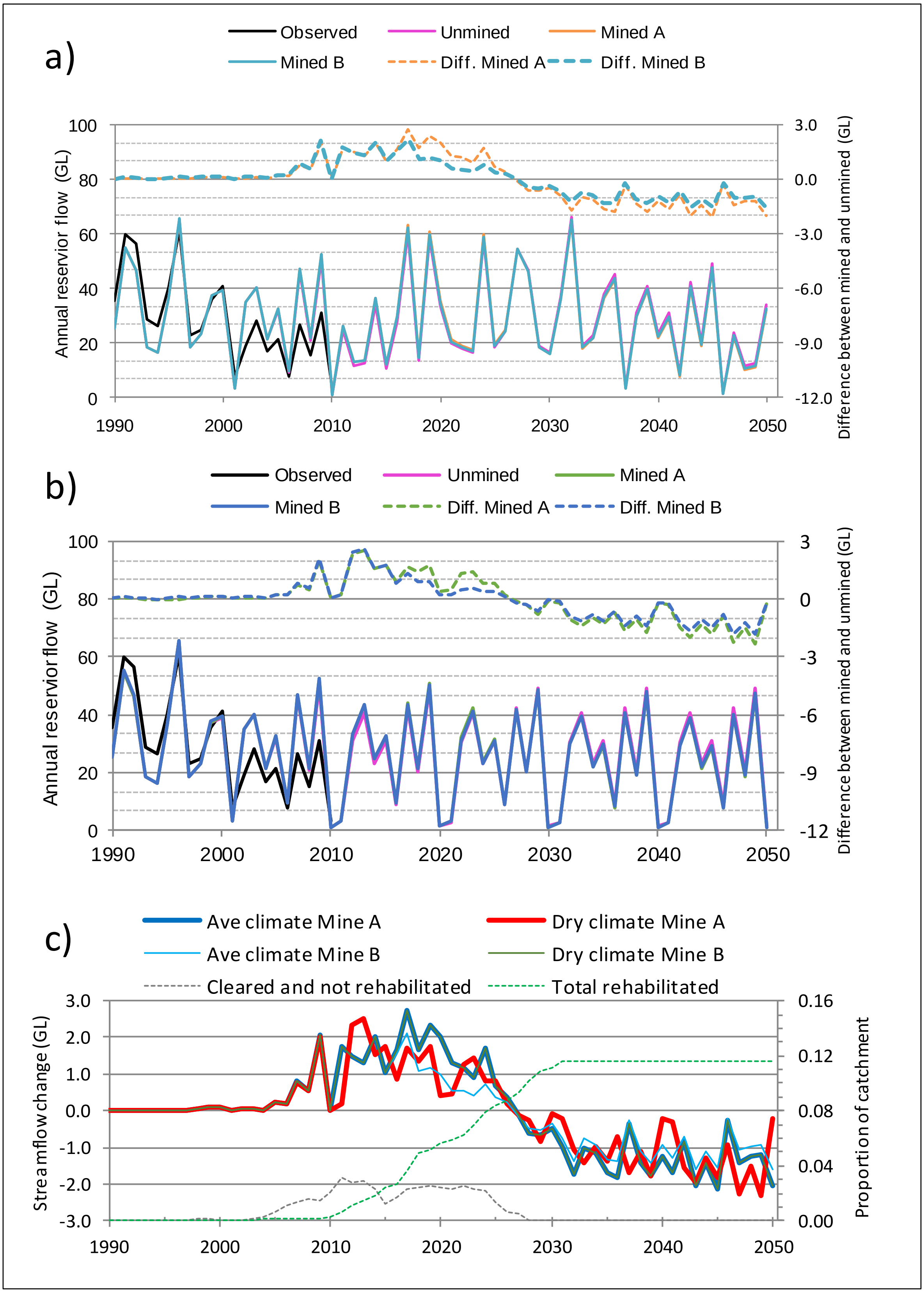

Figure 15 Projected annual inflows to the Serpentine Reservoir and inflow differences for two mining scenarios relative to an unmined case for a) a future 'average' climate, b) a future 'dry' climate and c) inflow differences between scenarios showing mining and rehabilitation in the catchment

For the no-mining scenario and average future climate, average annual inflow salinity to the reservoir of 155–166 mg/L (Table 6) remained within the range of measured salinity of 154–170 mg/L (Table 2). Average annual salinity for the no-mining case was projected to be slightly higher under the dry future climate scenario due to higher peaks in salinity of up to 370 mg/L in strong drought years with very low flows, however, salt loads and therefore impacts upon reservoir salinity would be limited. In all cases and years, however, simulated average annual inflow salinity were well within drinking water standards (<500 mg/L).

Simulated average annual salt loads for all mining and climate scenarios were higher in the first period to 2030 (Table 6) due to increased mobilisation of salts to the streams with simulated clearing, then relatively reduced salt loads in the subsequent period to 2050 as the growing vegetation reduced soil moisture levels and salt mobilisation to streams. Salt loads declined more rapidly than reductions in flow leading to slightly lower average salinity in this second period (Table 6).

Table 6 Projected inflow salinity and salt load [in brackets] to Serpentine Main Dam for mining and climate scenarios

Scenario	Average salinity [saltload] 2011–30 (mg/L) [kT]	Average salinity [saltload] 2031–50 (mg/L) [kT]	Difference 2011–30 mg/L (%)[a]	Difference 2031–50 mg/L (%)[a]
Unmined – Average	166 [4.35]	155 [3.72]		
Unmined – Dry	195 [3.80]	178 [3.47]		
Mined A – Average	163 [4.44]	160 [3.61]	-3.9 (-2)	4.8 (3)
Mined A – Dry	191 [3.88]	184 [3.36]	-4.7 (-2)	5.4 (3)
Mined B – Average	163 [4.41]	158 [3.63]	-3.1 (-2)	3.8 (2)
Mined B – Dry	195 [3.88]	181 [3.36]	0 (0)	2.6 (1)

[a] Percentage of average salinity compared to the ‘no mining’ case

Simulation results for the difference in stream salinity for mining compared to the no-mining scenario followed similar patterns to those seen for stream flows, except that differences were reversed over the course of mining and rehabilitation. Hence, salinity differences were relatively lower with mining during the first period to 2030 and relatively higher in the subsequent period to 2050 (Table 6; Figure 16). On an annual average basis, the maximum increase in salinity was projected to be 5.4 mg/L or three per cent compared to the no-mining case, which is within the range of measured salinity. Even when considered on an individual year basis where a maximum change of 20 mg/L was simulated (Figure 16), these differences are within the range of data collection and model errors. Therefore, it is concluded that the effects on the salinity of inflows to the reservoir by mining in the Upper Serpentine catchment will be minimal, even over the longer term.

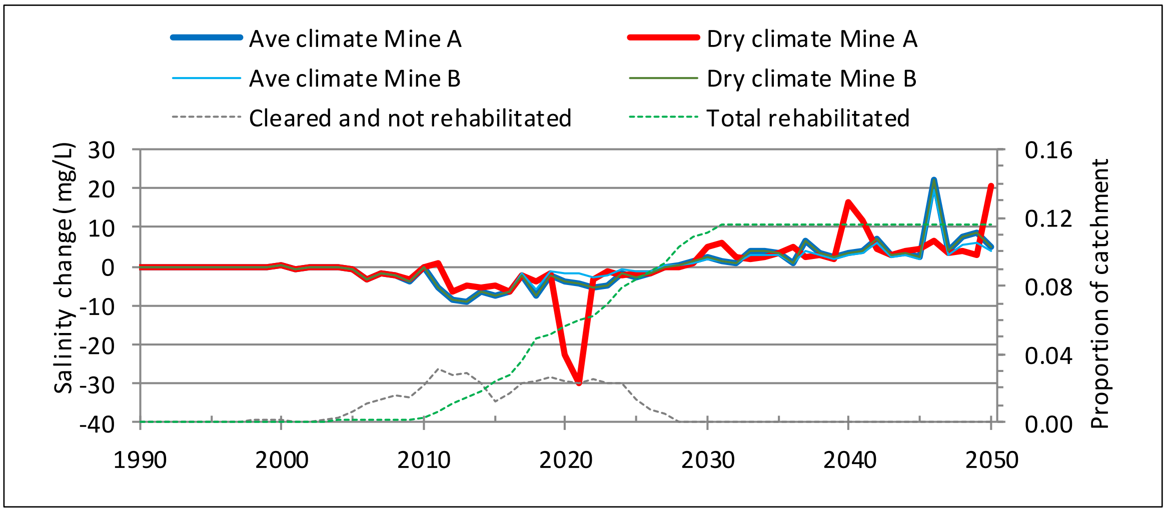

Figure 16 Changes in salinity inflow to the Serpentine Reservoir between unmined and mined scenarios

6 Conclusion and recommendations

The LUCICAT model was successfully applied to the Upper Serpentine catchment, a large (664 km^2) catchment in the Northern Jarrah Forest that forms part of the Integrated Water Supply Scheme supplying water to metropolitan Perth and regional centres. The model was used to assess the inflow and salinity responses to bauxite mining and rehabilitation, in combination with different future climate scenarios over an extended period from 2011 to 2050.

Annual inflows to the Serpentine Reservoir were satisfactorily calibrated, with a coefficient of determination of 0.82 and an NSE of 0.74. LUCICAT's modelled annual inflows agreed within three per cent of the Water Corporation's water balance inflow estimates for the reservoir, and annual flows for most internal sub-catchments were on average within seven per cent of observed flows for the complete period of records. Modelled annual flow-weighted salinity of inflows to the Serpentine Reservoir agreed within 40 mg/L of measured salinity at the main dam outflow (154–170 mg/L).

Two possible mining scenarios covering nine per cent or twelve per cent of the catchment, together with a no-mining comparison, were considered in the context of two future climates (average 914 mm/year and dry 841 mm/year at the catchment centroid) to give a total of six future (2011–50) scenarios. Model results showed that regardless of the mining case or future climate the projected change in inflows due to mining was no greater than approximately 2 GL/year in any one year, or five per cent of flow on an annual average basis. Both increases and decreases in flow were observed over the time series relative to the unmined alternative. On an annual average basis, the maximum increase in salinity was projected to be 5.4 mg/L or three per cent of reservoir salinity compared to the no-mining case. The maximum increase in salinity during very dry years was projected to be 30 mg/L. The effects of mining within the Upper Serpentine on reservoir salinity were therefore considered to be minimal.

LUCICAT appeared to overestimate flows subsequent to strong drought years that are not followed by wetter years, which are known to cause step-declines in groundwater connection and associated flow. It is recommended that the LUCICAT model be investigated in more detail to understand the dynamics of simulated groundwater levels in the context of these single strong drought years.

Appendices

Appendix A — Additional information for model setup and calibration

Table A1 Attributes of Response Units contained in input file Serpentine_atr_in.dbf. Attributes in bold are obtained by calibration

Field name	Typical value/s	Units	Meaning
ID_SUBCAT	44		RU identifier
EAST	*422540.41035*	m	MGA Easting of RU centroid
NORTH	6422349.64831	m	MGA Northing of RU centroid
FLOW_TO_SC	Not used in this study		
AREA	5.48688	km^2	RU area
PRINT	0.00000		= 1.0 when output files required, otherwise 0
IMP_AREA	0.00000	fraction	Portion of RU area that is impervious including lake area
DPTH_UPPER	2400.00000	mm	Thickness of upper soil layer
DPTH_STRM	2600.00000	mm	Depth of stream channel
DPTH_ROCK	21800.00000	mm	Depth to bedrock
AV_SLOPE	0.07879	fraction	Average ground slope
ELEV_DIFF	160.00000	m	Maximum elevation difference
UZFWC	**0.0006-0.012**	**fraction**	**Initial upper zone free water content**
RAINSALT	11.5	mg/L	Salt concentration in rainfall
UZTWC_SALT	**0.15-1.64**	**kg/ha**	**Initial upper zone salt stored in soil**
LTWC_SALT	**0.06-1.46**	**kg/ha**	**Initial lower zone salt stored in soil**
GWST_SALT	**0.06-1.36**	**kg/ha**	**Initial salt stored in groundwater**
UZFWC_SALT	**500-1000**	**mg/L**	**Initial salt concentration upper zone free water**
DPTH_GL_S1	3094.39000	mm	Initial depth to groundwater in fraction 1
DEPR_MAX1	0.00000		Depression storage in fraction 1
ANN_RAIN	1062.42312	mm	Average annual rainfall at centroid

Table A2 Attributes of Response Units contained in input file Serpentine_atr_in.dbf. Attributes in bold are obtained by calibration

Field name	Typical value/s	Units	Meaning
TOPNODE	181		Identifier of upstream node
EASTING	422737.50000	m	MGA easting of top node location
NORTHING	6422937.50000	m	MGA northing of top node location
BOTNODE	183.00000		Identifier of downstream node
MANCOEFF	0.08000	fraction	Manning's roughness coefficient
WIDTH	**4.00000**	**m**	**Channel width**
LENGTH	2734.40386	m	Channel length
TOPELEV	289.82324	m AHD	Ground elevation of top node
UPSUB	0.00000		Identifier of upstream RU which is not joined to the top node in this RU
LAKENODE	0.00000		Identifier of lake if it exists at this node
RESUNIT	44.00000		RU that contains this channel
DELEV	270.11987	m AHD	Ground elevation of the bottom node
PRINT	0.00000		=1 when output files required for the top node

Table A3 Attributes of the Serpentine Reservoir Response Unit used to calibrate initial conditions in Lake_initial.par

Field name	Value/s	Units	Meaning
GW_SALINITY	300.000	mg/L	Salinity of the groundwater system beneath the lake
SALINITY_MAX	1000.000	mg/L	Maximum salinity of the lake
EVAP_FACTOR	8.600E-07		Lake salinity evaporation factor
PAN_FACTOR	0.85		Pan evaporation factor
BED_CONDUCT	0.000E-00	mm/day	Lake bed conductance
SALT_DEPOSIT	0.000	g/m^2	Salt deposition on soil surface
SALT_INITIAL	2.318E+10	G	Initial salt storage in lake
WATER_INITIAL	65.3E+06	m^3	Minimum lake volume
HEAD_AQ_INI	0.000		Initial aquifer head beneath the lake
HEAD_AQ_AMP	1.000		Average amplitude of aquifer head beneath the lake
HEAD_AQ_LAG	0.000		Phase lag of aquifer head beneath the lake
HEAD_AQ_DEL	0.000		Long-term change of aquifer head beneath the lake

Table B1 Global parameter input set. Attributes in bold are obtained by calibration

Field name	Value	Units	Meaning
SAT_COND	**900.000000**	**mm/day**	**Saturated hydraulic conductivity (K_{ll})**
CINT	**0.700000**		**Interception store coefficient**
CINTER_A	0.500000		Throughfall constant
CINTER_A1	0.130000		Throughfall intercept
CSOIL	1.600000		Soil evaporation constant exponent
CSOIL_A	1.000000		Soil evaporation constant multiplier
LAI_MAX	2.000000		Leaf area index - maximum
ATUZ	0.356000		Dry water store soil moisture exponent for top soil (b)
AFUZ	0.356000		Wet Water Store soil moisture exponent for top soil (c)
ALZ	1.320000		Subsurface Store soil moisture exponent (a)
UZTWMI	0.080000	mm/mm	Dry Store water content threshold
UZTWM_IN	0.300000	mm/mm	Dry store maximum initial water content
UZTWC	**0.090000**	**mm/mm**	**Dry store initial water content**
UZFWM	0.300000	mm/mm	Wet store maximum water content
LZSWM_INT	0.550000	mm/mm	Subsurface Store maximum water content
LZSWC	0.025000	mm/mm	Subsurface Store initial water content
LZTWM	0.300000	mm/mm	Subsurface Store maximum water content
A_INTERF	395.000000	mm/day	Lateral conductivity of the Wet Store
EXP_INTERF	2.300000		Interflow exponent ia (-)
PERC_BAS	27.185000	mm/day	Conductivity - Wet and Subsurface Stores (K_{uv})
PERC_S	0.500000		Percolation coefficient - seasonal variability (-)
PERC_BAS1	3.353900	mm/day	Vertical conductivity of the Subsurface Store
PERC_S1	1.000000		Percolation coefficient - seasonal variability (-)
PERC_EXP	1.500000		Percolation exponent (-)
SALT_RELEASE	**0.010700**		**Salt release from Dry to Wet Stores (-)**
GW_LOSS_COEFF	0.000000125		Loss of groundwater (-)
EXP_TRAN	1.350000		Transpiration exponent (-)
ALPHATRAN_MX	1.000000		The biological factor for maximum rainfall (at) (-)
ALPHATRAN_MN	**2.700000**		**The biological factor for minimum rainfall (at) (-)**
SZONE_DEPTH	1000.	mm	Depth of water in stream zone at capacity
SZONE_WIDTH	0.1	m	Width of stream zone each side of channel
CRIT_DEPTH_MX	100000.0	mm	Upper limit for calculated critical depth

Field name	Value	Units	Meaning
CRIT_DEPTH_MN	00000.0	mm	Lower limit for calculated critical depth
ELEV_DIFF_MULT	0.50000		Multiplier to all elevation differences (-)
AVSLOPE_MULT	0.60000		Multiplier to all average slopes (-)
EXP_INTERF_MX*	2.000000		Interflow exponent_maximum
FARMDAM_USE_FACTOR	0.00000		Multiplier of farm dam capacity for annual demand (-)
PAN_MORT_FACTOR**	1.0000		Factor converting pan evap. to potential evap. (-)

Notes:

* Parameter set to default value.

** In this model, potential evapotranspiration was used in place of pan evaporation, therefore this factor was set to 1.

Shortened forms

AHD	Australian Height Datum
IRZ	Intermediate Rainfall Zone
JIRZRP	Joint Intermediate Rainfall Zone Research Program
GL	gigalitres
km	kilometres
km^2	square kilometres
LAI	leaf area index
m	metres
mg/L	milligrams per litre
mm	millimetres
NSE	Nash Sutcliffe Efficiency
PET	potential evapotranspiration
RU	response unit

Glossary

baseflow	That portion of a river and streamflow coming from groundwater discharge
bauxite	A mining ore used to produce aluminium. It consists largely of hydrated alumina with varying portions of iron oxides.
impervious	Not allowing fluid (water) to pass through
IRZ	Intermediate Rainfall Zone
interflow	Water that infiltrates the soil surface and travels by means of gravity toward a stream channel
Jarrah Forest	Forest that exists on the western edge of the Darling Plateau in the South West Division of Western Australia. The predominate tree species is Jarrah (Eucalyptus marginata)
LAI	Leaf Area Index. A dimensionless quantity that is the one-sided green leaf area per unit ground surface area in broadleaf canopies
Mg/L	milligrams per litre. A unit measurement of mass per unit volume of water
ML	Megalitre. A metric volumetric unit comprising of one million litres
NSE	Nash Sutcliffe Efficiency coefficient. A statistical criteria for measuring the predictive power of hydrological models
pervious	Allowing fluid (water) to pass through
Response Unit	In this study it is a spatial unit of a model with similar land uses, slopes and soils
Salinity	The concentration of dissolved salts in water

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Drinking Water Risk Assessment

Serpentine, Serpentine Pipehead, South Dandalup, and Wungong Brook Catchments

Alcoa of Australia Limited

14 January 2022

The Power of Commitment

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Executive summary

Background

Alcoa of Australia Limited (Alcoa) is proposing to increase production at the Pinjarra Alumina Refinery (Refinery) by 5 per cent from 5.0 million tonnes per annum (Mtpa) to 5.25 Mtpa by transitioning the Huntly Bauxite Mine into the proposed Myara North and Holyoake mine regions (the Proposal). The Proposal is located in the Peel region of Western Australia (WA), approximately 100 km south-east of Perth.

The Huntly Mine operations will transition into the Myara North and Holyoake regions, which primarily lie within the Serpentine Main Dam and South Dandalup Dam Public Drinking Water Source Areas (PDWSAs). A small portion of the Myara North region lies within the Serpentine Pipehead Dam (herein referred to as Pipehead Dam) PDWSA and in the upper catchments of the Canning River and Wungong Brook PDWSAs. The Huntly Mine currently operates within the Serpentine Main Dam, Pipehead Dam and North Dandalup Dam PDWSAs.

The Proposal will be subject to environmental impact assessment under under Part IV of the WA *Environmental Protection Act 1986* (EP Act), and the *Environmental Protection Biodiversity and Conservation Act 1999* (EPBC Act). The environmental impact assessment will be via a Public Environmental Review (PER) and have identified Inland Waters as a preliminary key environmental factor. The assessment of the Inland Waters factor is to include a public drinking water risk assessment in accordance with contemporary standards and guidance. The risk assessment should consider potential contaminants arising from mining activities and infrastructure, as well as mobilisation of existing contaminants from past catchment activities. Where high risks to public drinking water beneficial uses are identified, the assessment is required to detail potential impacts to human health.

Contemporary guidance regarding the human health aspects of drinking water has been used throughout this report. The primary sources included the Australian Drinking Water Guidelines (ADWG), the World Health Organisation guidelines for drinking water quality, the Australian and New Zealand Guidelines for Fresh and Marine Water Quality, and the Water Services Association of Australia (WSAA) Health Based Targets (HBT) Manual.

The Serpentine, South Dandalup and Pipehead Dam PDWSAs constitute a single “source water”, culminating at the point of supply to the Pipehead Dam Water Treatment Plant (WTP). Desalination inputs from the Integrated Water Supply Scheme (IWSS) to Pipehead Dam are substantial, and are projected to make up an increasing proportion of the source water in the future. Catchment access is restricted, with permissible activities listed in Source Water Protection plans for each PDWSA. The PDWSAs are predominantly managed as priority 1 with small areas of private land managed as priority 2. The source water is treated with chlorine, and then transferred to the IWSS for distribution to downstream customers.

The potential hazards from the Proposal to water quality were identified, based on proposed land uses. Those uses included:

– construction
– mine development, mining and rehabilitation stages of the Huntly Mine operations
– associated mine facilities and infrastructure.

The identified potential hazards from the Proposal included:

– generation and discharge of pathogenic microorganisms from increased human activity;
– increases in sediment, suspended solids and turbidity from erosion during mining activities;
– increases in stream salinity as a result of mining-induced saline groundwater discharge; and
– contamination from spills, leaks, and/or emissions from the storage, handling and use of hazardous materials and waste.

Long term hazards (following the completion of Proposal activities) were identified, associated with mine rehabilitation and climate change, including:

– potential increase in large scale wildfires that generate sediment, suspended solids, turbidity, organic matter and nutrients

– long term resilience of mine rehabilitation and un-mined vegetation and erosion of rehabilitation areas that generate sediment, suspended solids and turbidity
– remobilisation of sediment from deposition areas on slopes, streams and reservoir floors.

Pathogen risks during mining

Examination of pathogen hazards included a source vulnerability assessment for the three PDWSAs, using the methodology described in the WSAA HBT Manual (2015). The source vulnerability assessment of human settlement and stock animal challenges of microbial risk aligned well with category 1 source waters. Some challenges presented from itinerant human activity could be regarded as category 1 or 2, however with the consideration of existing mitigation factors, the source water could be considered as a category 1 source. This was consistent with the current treatment applied to the source water. The assessment was verified with a desktop sanitary survey using the methodology described in Baker et al (2016), applied to sewage treatment systems and mobile work teams typically associated with construction, mining and rehabilitation activities. The worst-case outputs from this survey assessment produced medium or low-risk results, in line with the outcomes of the vulnerability assessment.

Further examination of pathogen hazards included a quantitative microbial risk assessment (QMRA), conducted to estimate the impacts of pathogen inputs from the Proposal and other sources in the three PDWSAs that will sometimes be entrained in the source waters for drinking water supply. This examined the concentration of the reference pathogen *Cryptosporidium* through to potential exposure to the local population, estimated the risk of illness from such exposure, and expressed this risk as Disability Adjusted Life Years (DALYs). Pathogen inputs to the catchment were examined as hazardous events, including:

– sewage overflow during on-site treatment
– washout of treated effluent from an irrigation area
– subsurface leaching of treated effluent
– direct faecal deposition in a riparian zone by a staff member with asymptomatic cryptosporidiosis.

A reasonable design worst case of each of these events was considered, with the assumption of steep terrain, little vegetation coverage, and heavy rainfall resulting in high rates of transport of contamination into the receiving reservoir. Hydrological modelling described in GHD (2021) examined subsequent pathogen transport and survival through the reservoirs, and pathogen exposure and dose response estimates (AGWR, 2020) were applied to calculate the risk from the use of each dam as a source water. The risk was then compared with an acceptance threshold of
10^{-6} DALYs/ person/ year.

The QMRA outputs identified that the risk from the most hazardous tested event, of direct faecal deposition in the Pipehead Dam catchment, was elevated above the threshold of acceptable risk. As an elevated risk, this hazard requires attention through additional preventative barriers to reduce the risk to an acceptable level. In addition to the averaged annual concentration of *Cryptosporidium* resulting from the examined hazards, GHD (2021) predicted the peak concentrations of this organism resulting the hazards. For the highest risk hazards presented in the Pipehead Dam PDWSA, these included concentrations of ~0.00001 oocysts/L and ~0.01 oocysts/L, based on the location of faecal deposition within that PDWSA. From these calculated concentrations, the latter hazard presents an unacceptable short-term high risk of cryptosporidiosis, in addition to the annualized risk. This observation supports the conclusion that the mitigation of this hazard to a level of acceptable risk requires attention through additional preventative barriers.

Turbidity risks during mining

Erosion risks were examined in an assessment of turbidity as a water quality parameter in the Serpentine, South Dandalup and Pipehead PDWSAs. While not hazardous in itself, turbidity is able to reduce the efficacy of treatment processes in inactivating or removing pathogens, and the existing water treatment processes at the Pipehead Dam WTP do not include a mechanism to reduce turbidity in the raw water. The ADWG notes that where the turbidity of a source exceeds 1 nephelometric turbidity units (NTU), adequate disinfection may be more difficult to maintain, but may still be achievable. Generally, the lower the turbidity of a source water, the more effective chlorination will be, and validation is required to demonstrate that disinfection of higher turbidity water is effective. The literature basis for turbidity as an indicator of disinfection efficacy was examined, including the demonstrated finding that turbidity-generating compounds such as clays, humic acids and fulvic acids have no effect on disinfection. Where high turbidity (20 NTU) waters containing organic particles generated from wastewater were examined, these waters could still be effectively disinfected for chlorine-resistant viruses, but required longer chlorine contact times to factor in the chlorine demand from wastewater particulates. In practice, challenge testing can be performed to validate and optimise virus disinfection, where a source water is outside the tested range for disinfection parameters such as turbidity.

In the case of the Serpentine, South Dandalup and Pipehead PDWSAs, turbidity challenges were modelled in GHD (2021) in the form of inorganic clay and silt particles, simulating turbidity inputs associated with natural waterways and mining sumps. It is noted that these inorganic particles would not be expected to affect disinfection efficacy. The key results and conclusions regarding turbidity challenges from GHD (2021) were that Serpentine Main Dam turbidity concentrations were sensitive to changes in sump failure suspended solids concentrations, as mining comprises a sufficient proportion of the catchment landscape to do so. This contrasted with South Dandalup Dam sump failure suspended solids concentrations, as the proposed mining area is a small proportion of the overall catchment area, and there is no existing mining in that catchment and previous mining areas are assumed to be fully rehabilitated.

Fuel spill risks during mining

The Huntly Mine is a diesel only fuel site, with no storage or handling of unleaded petrol. Diesel is predominantly used for haul trucks, excavators and other large earthmoving equipment, and to a lesser extent for light vehicles. The storage and handling of diesel creates a potential hazard for spillage of diesel that may enter reservoirs. GHD (2021) examined the effect of mining activity-related diesel spill incidents in the catchments, with the assumption that a 15 m^3 fuel tanker load was directly discharged into a stream at a haul road crossing. The modelled processes leading to decreased diesel concentrations were river dilution, reservoir mixing and dispersion, and withdrawals from the dams. The modelled diesel spill incidents in Serpentine Main Dam and South Dandalup Dam were predicted to result in peak concentrations at the dam offtakes at up to 1 µg/L, whilst a mid-reservoir spill in Pipehead Dam was predicted to result in peak concentrations at the dam offtake at up to 5 µg/L. These concentrations did not exceed the ADWG health based guideline limits for components of diesel fuel. The ADWG notes that diesel contamination in drinking water has a taste and odour threshold of 5 µg/L. This could be reached, with the largest predicted peak diesel concentration of up to 5 µg/L for the Pipehead Dam.

PFAS risks

Alcoa have committed to using PFAS-free firefighting foams for the Myara North and Holyoake regions. All water supplies to construction and operations in the Myara North and Holyoake regions will be sourced from public water supply reservoirs or borefields that are tested and verified as free of detectable PFAS. PFAS would be limited to minor quantities in materials such as workforce clothing, paper packaging, carpets or wire insulation, which are unlikely to be discharged to the environment as all wastes will be recycled or disposed off-site at licensed waste facilities. Accordingly, the direct discharge of PFAS from construction and mining is expected to pose a low risk to drinking water quality.

The existing land uses and baseline monitoring program (GHD 2021) do not indicate the presence of substantial PFAS contamination within the Myara North or Holyoake regions. PFAS are relatively persistent and water-soluble compounds which readily mobilise through the unsaturated zone and into groundwater, which discharges into streams. It is therefore expected that any existing substantial PFAS contamination of the catchments would be detectable in stream flows. Due to the absence of existing substantial contamination, any hydrological changes from construction and mining (i.e. the clearing of vegetation causing groundwater mounding and increased stream flows) are not expected to mobilise substantial quantities of PFAS into reservoirs. Accordingly, the indirect mobilisation of historical PFAS from catchments due to construction and mining is expected to pose a low risk to drinking water quality.

Other hazardous materials

Diesel is the predominant hazardous material used at the Huntly Mine, and to a lesser extent hydraulic and lubricating oils. Minor quantities of other hazardous materials include solvents, adhesives and other chemicals are used for vehicle and equipment maintenance or water treatment.

Haul trucks, some wheeled earthmoving equipment and light vehicles are refuelled at fuel bays. Planned maintenance of haul trucks, light vehicles and some earthmoving equipment is undertaken at workshops. The fuel bay and workshop buildings are located at mine facilities and have roofs and sealed floors, which are expected to capture spills or leaks during refuelling or maintenance. Diesel and oil storage tanks are located at mine facilities and are double-lined and above ground to minimise and detect leaks. Smaller quantities of hazardous materials stored at mine facilities inside buildings or on sealed floors.

Excavators, bulldozers and other earthmoving equipment are refuelled and maintained in the field. Refuelling and maintenance in the field have potential to cause spills and leaks that contaminate soils. There is also potential for ongoing, low level oil leaks from vehicles and equipment, and rare collisions that result in fuel or oil spills.

The majority of spills and leaks, particularly those from major incidents and involving large volumes, are expected to be identified quickly and the contaminated soils excavated and disposed off-site at a licensed waste facility. Smaller spills and leaks may potentially be missed and the contaminants leach through the unsaturated zone. The smaller spills and leaks are expected to remain predominantly adsorbed to soil particles beneath the spill site. Diesel and particularly oil contain larger chain hydrocarbons that are weakly water soluble and readily adsorb to soils with organic matter and clay content. Accordingly small volumes of diesel and oil that escape detection and remediation are unlikely to result in substantial migration of hydrocarbons that reach streams and can be transported into the reservoirs. This is verified by site investigation at the Huntly Mine, which did not detect hydrocarbons in stream flows downstream of existing mine pits, haul roads and mine facilities. Accordingly, the storage and handling of hazardous materials during construction or operations is expected to pose a low risk to drinking water quality.

Long term fire risks

The evidence reviewed by Australian authors and the impact of 2005 Perth Hills and 2016 Waroona-Yarloop fires suggest that the Serpentine Main Dam, South Dandalup Dam and Wungong Dam reservoirs may be susceptible to water quality impacts from bushfires. Such an event may include a high intensity wildfire that covers a large proportion of a catchment, occurs over steep terrain and in the year prior to heavy rainfall events.

A major wildfire and heavy rainfall sequence may result in widespread ash deposition, runoff and erosion that generate substantial discharges of ash and sediment into the catchment's reservoir. Depending on the severity and location of fire and rainfall, there is potential for the scale of discharges to exceed the attenuating capacity of the reservoir and cause elevated contaminant levels at the offtake that exceed drinking water quality criteria.

It is expected that the transition of mining into the Myara North and Holyoake regions will continue to enable DBCA's prescribed burning program to be effectively planned, funded and implemented, as has been demonstrated within the Huntly Mine to date. Accordingly, the Proposal is expected to maintain and support the State Government's program to limit fuel accumulation in the Northern Jarrah Forest, thereby reducing the likelihood of large wildfires occurring in the Serpentine Main Dam, South Dandalup Dam or Wungong Brook PDWSAs.

Long term erosion of rehabilitation

The net effect of bauxite mining of Jarrah forest soils is the removal of an approximately 4-6 m thick layer of caprock and friable fragmental material, and replacement of the seed rich topsoil and overburden over a ripped, friable substrate of sandy loams and clays. The total depth of friable material created is about 1.5 m, including topsoil, overburden and ripped substrate.

The establishment of a 1.5 m thick friable stratum provides a comparable, though generally thicker, stratum than the topsoil and overburden present above the caprock prior to mining. The friable layer enables development of a dense root structure of Jarrah forest vegetation as occurs in the topsoil and overburden present prior to mining. Deeper rooted vegetation establishing within the friable layer is expected to re-colonise ancient root channels present in the underlying regolith materials, as have been used by successive generations of trees prior to mining. There is expected to be a partial loss of soil water capacity due to the removal of the bauxite friable fragmental layer, which represents approximately 10 per cent of the regolith thickness.

Loss of the bauxite friable fragmental layer has not been observed to result in impaired growth or health of rehabilitation. Monitoring of rehabilitation has demonstrated the successful establishment and persistence of overstorey, floristic diversity and understorey coverage, including during drought periods such as 2010/11. The results of monitoring collectively demonstrate that Alcoa's rehabilitation establishes and persists, including during drought and heat wave events, indicating that the 1.5 m thick friable substrate over regolith containing ancient root channels is an effective growth medium.

Accordingly, mine rehabilitation vegetation is expected to be sustained over the long term with resilience to climate change comparable to that of un-mined Jarrah forest. Mine rehabilitation is therefore expected to provide long term protection of soils from erosion and associated sediment discharge to streams and reservoirs.

Preventative risk management

Alcoa implements preventative risk management at the Huntly Mine, which incorporates multiple barriers to prevent hazards to drinking water from occurring or reduce them to acceptable levels. The multiple barriers are established to control hazards relating to pathogens, sediment discharge and hydrocarbons. The barriers act to prevent and minimise the discharge of pathogens, sediment and hydrocarbons into downstream reservoirs, which are themselves barriers to contaminant transport to the offtakes.

Review of the existing barrier network at the Huntly Mine indicates that some barriers are likely to fail under certain conditions and with multiple barrier failures result in varying quantities of contaminants reaching the downstream reservoirs. Key conditions that can cause barrier failure include workforce behaviour in the case of discharge of pathogens, and major storm events during wet catchment conditions in the case of sediment and hydrocarbons. Additional barriers and improvements to existing barriers are proposed to reduce the likelihood of barrier failure and potential for discharge of contaminants into reservoirs. Key improvements proposed include:

- Avoidance of mining in the Serpentine Pipehead PDWSA
- Workforce education and monitoring
- Incident reporting / response
- Application of risk-based Mine drainage controls in all disturbed areas, in accordance with Alcoa Drainage Manual and Haul road Sump Design Manual
- Rehabilitated mine pits to be designed and executed to prevent overflow during a 1 per cent 24hr AEP event.

Residual risk assessment

The Proposal will result in an increase in the mine workforce, area open and mine fleet operations at the Huntly Mine compared to current operations in the Myara mine region. These increases have the potential to increase the risk of pathogen, sediment and hydrocarbon discharge into downstream reservoirs and the IWSS.

Subject to the improvements proposed, the residual risk from the proposed Huntly Mine operations at the Myara North and Holyoake regions is expected to reduce from the risk posed by the existing Huntly Mine operations to the IWSS.

Limitations

This report is subject to, and must be read in conjunction with, the limitations set out in section 1.2 and the assumptions and qualifications contained throughout the Report.

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Appendices

Terminology

Terminology	Definition
Alcoa of Australia Limited (Alcoa)	The proponent of the Proposal.
GHD Pty Ltd (GHD)	Consultant engaged by Alcoa to prepare environmental approvals documentation and supporting technical studies for the Proposal.
Myara North Development Envelope	Myara North mine region and associated infrastructure corridor within the Huntly mine region. 22,703 ha total
Myara North Infrastructure Corridor	Corridor adjacent to Myara North mine region in which a conveyor, haul road and other infrastructure may be developed. May also be referred to as a transport study area or conveyor/haul road corridor. 5,254 ha
Holyoake Development Envelope	Holyoake mine region and associated infrastructure corridor within the Huntly mine region. 18,700 ha total
Holyoake Infrastructure Corridor	Corridor adjacent to Holyoake mine region in which a conveyor, haul road, access road and other infrastructure may be developed. May also be referred to as a transport study area or conveyor/haul road corridor. 9,542 ha
Mine Development Envelope	Total Mine Development Envelope for the Proposal, this being Myara North and Holyoake mine regions and associated infrastructure corridors. 41,403 ha
Mining region	Sub-regions that comprise the Huntly Mine, including current (Myara), past (O'Neil, McCoy) and future (Myara North, Holyoake), etc.
Haul Road	Truck and mine infrastructure access road linking into existing corridors.
Huntly Mine	Huntly Bauxite Mine within ML1SA. This includes the previous and current mine regions of Del Park, Huntly, White Road, McCoy, O'Neil, and Myara, and the transition to the future mine regions of Myara North and Holyoake.

Abbreviations

Abbreviations	Definition
ADWG	Australian Drinking Water Guidelines
AEP	Annual Exceedance Probability
ANZG	Australia New Zealand Guidelines
ARI	Average Recurrence Interval
BoM	Bureau of Meteorology
CSM	Conceptual Site Model
DALY	Disability Adjusted Life Years
DBCA	Department of Biodiversity, Conservation and Attractions
DE	Development Envelope
DFES	Department of Fire and Emergency Services
DOC	Dissolved Organic Carbon
DWER	Department of Water and Environmental Regulation
DWRA	Drinking Water Risk Assessment
DWSPP	Drinking water Source Protection Plan
EP Act	Environmental Protection Act 1986
EPA	Environmental Protection Authority Western Australia
EPBC Act	Environmental Protection and Biodiversity Conservation Act
ERD	Environmental Review Document
ESD	Environmental Scoping Document
EY	Exceedances per Year
FMP	Forest Management Plan
FPC	Forest Products Commission
GL	Gigalitre
ha	Hectare
HBT	Health Based Target
HRZ	High Rainfall Zone
IRZ	Intermediate Rainfall Zone
IWSS	Integrated Water Supply Scheme
km	Kilometres
LAI	Leaf Area Index
LRV	Log Removal Value
mg/L	Milligrams per Litre
ML	Megalitre
MMP	Mining and Management Program
MMPLG	Mining and Management Program Liaison Group
MWSSD Act	Metropolitan Water Supply, Sewerage, and Drainage Act 1909
NTU	Nephelometric Turbidity Units
PDWSA	Public drinking water source area

Abbreviations	Definition
PER	Public Environmental Review
PFAS	Per- and Polyfluoroalkyl Substances
QMRA	Quantitative Microbial Risk Assessment
RFA	Regional Forest Agreement
ROM	Run of Mine
RPZ	Reservoir Protection Zone
RUSLE	Revised Universal Soil Loss Equation
SDD	South Dandalup Dam
SDPD	South Dandalup Pipehead Dam
SMD	Serpentine Main Dam
SPD	Serpentine Pipehead Dam
SS	Suspended Solids
STP	Sewage Treatment Plant
TCU	True Colour Units
WHO	World Health Organisation
WQPN	Water Quality Protection Note
WTP	Water Treatment Plant
WWTP	Waste Water Treatment Plant

1. Introduction

1.1 Purpose of this report

Alcoa of Australia Ltd (Alcoa) is proposing to increase production at the Pinjarra Alumina Refinery by 5 per cent from 5.0 million tonnes per annum (Mtpa) to 5.25 Mtpa and transition the Huntly Bauxite Mine (Mine) to the proposed Myara North and Holyoake mine regions (the Proposal). The proposed Myara North and Holyoake mine regions primarily lie within the Serpentine Main Dam and South Dandalup Dam Public Drinking Water Source Areas (PDWSAs). A small portion of the Myara North region lies within the Serpentine Pipehead Dam (Pipehead Dam) PDWSA and in the upper catchments of the Canning River and Wungong Brook PDWSAs. The Mine currently operates within the Serpentine Main Dam, Pipehead Dam and North Dandalup Dam PDWSAs and has previously operated within the South Dandalup Dam PDWSA.

The Proposal will be assessed by the WA Environmental Protection Authority (EPA) under Part IV of the *Environmental Protection Act 1986* (EP Act), and the *Environment Protection Biodiversity Conservation Act 1999* (EPBC Act) via the bilateral agreement. The Proposal will be assessed via a Public Environmental Review (PER).

The EPA has identified Inland Waters as a preliminary key environmental factor, noting that the proposed mining areas intersect with PDWSAs. The assessment will be undertaken in accordance with an Environmental Scoping Document (ESD). This report presents a drinking water risk assessment for the Serpentine, Serpentine Pipehead, South Dandalup, and Wungong Brook PDWSA, to meet the requirements of ESD work item 50 (provided below), to support the PER of the Proposal.

“50. Undertake a public drinking water risk assessment for the Serpentine, Pipehead and South Dandalup reservoirs and upper Wungong Brook catchment, including source vulnerability assessment, in accordance with the Australian Drinking Water Quality Standards and relevant contemporary guidance. The risk assessment should consider potential contaminants arising from mining activities and infrastructure, as well as mobilisation of existing contaminants from past catchment activities. For identified high risks to public drinking water beneficial uses, undertake a detailed assessment of potential impacts to human health in accordance with contemporary guidance.”

Separate reports address the baseline hydrology and water quality for the proposed Myara North and Holyoake mine regions and potential water related environmental impacts of the Proposal.

1.2 Scope and limitations

This report: has been prepared by GHD for Alcoa of Australia Limited and may only be used and relied on by Alcoa of Australia Limited for the purpose agreed between GHD and Alcoa of Australia Limited as set out in section 1.1 of this report.

GHD otherwise disclaims responsibility to any person other than Alcoa of Australia Limited arising in connection with this report. GHD also excludes implied warranties and conditions, to the extent legally permissible.

The services undertaken by GHD in connection with preparing this report were limited to those specifically detailed in the report and are subject to the scope limitations set out in the report.

The opinions, conclusions and any recommendations in this report are based on conditions encountered and information reviewed at the date of preparation of the report. GHD has no responsibility or obligation to update this report to account for events or changes occurring subsequent to the date that the report was prepared.

The opinions, conclusions and any recommendations in this report are based on assumptions made by GHD described throughout this report. GHD disclaims liability arising from any of the assumptions being incorrect.

GHD has prepared this report on the basis of information provided by Alcoa of Australia Limited and others who provided information to GHD (including Government authorities), which GHD has not independently verified or checked beyond the agreed scope of work. GHD does not accept liability in connection with such unverified information, including errors and omissions in the report which were caused by errors or omissions in that information.

2. Background

2.1 Alcoa operations

The following description of Alcoa's current and future operations is drawn from the Environmental Scoping Document for the Proposal.

The Pinjarra Alumina Refinery is located approximately 6 km east of Pinjarra town site on South West Highway within the Shire of Murray in the Peel Region of Western Australia. It lies on cleared land on the Swan Coastal Plain. The Huntly Mine is located predominantly within the Shires of Murray, Serpentine Jarrahdale and Boddington within the Peel Region of Western Australia. The Huntly Mine lies on the Jarrah Forest of the Darling Plateau.

The refinery is subject to approvals under environmental legislation including Ministerial Statement 646 (MS 646) under Part IV of the EP Act. Mining operations at Huntly Mine are undertaken in accordance with a five-year Mining and Management Program (MMP) that is approved by the Minister for State Development on advice of the Minister for Environment and the Mining and Management Program Liaison Group (MMPLG).

Alcoa has gradually increased alumina production at the refinery through ongoing efficiency upgrades and expects that production will exceed the 5.0 Mtpa authorised under MS 646, reaching 5.25 Mtpa over the next decade (5 per cent increase from existing 5.0 Mtpa approved rate). The current rate of alumina production at the refinery is approximately 4.75 Mtpa.

The current approved MMP for 2020-2024 authorises mining of an average of just over 16.0 Mtpa (dry tonnes) of bauxite per year at Huntly Mine with associated vegetation clearing at an average of approximately 350 ha/year over the five-year period. The MMP also includes mining for up to 2.0 Mtpa (dry tonnes) of bauxite for export in 2020 and 2021.

The Huntly Mine will be making a progressive transition from the current Myara mining area to the Myara North and Holyoake mining areas starting from about 2023, on receipt of relevant approvals This is an inherent part of bauxite mining and consistent with previous mining area transitions within ML1SA. This will enable continuity of bauxite supply to the Pinjarra Alumina Refinery as well as bauxite export.

2.2 Regulatory and policy framework

This DWRA has been prepared in accordance with contemporary guidance including:

- Australian Drinking Water Guidelines (ADWG) (National Health and Medical Research Council, 2011)
- Guidelines for drinking-water quality (World Health Organization, 2017)
- Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZG) (Australian and New Zealand Governments and Australian state and territory governments, 2018)
- Health Based Targets Manual (WSAA, 2015)
- Department of Water and Environmental Regulation (DWER) Water Quality Protection Notes
- By-Laws, international publications, and any other relevant publication for key contaminants of concern (e.g. turbidity, hydrocarbons and PFAS).

The ADWG provide the authoritative reference for use within Australia's administrative and legislative framework to ensure the accountability of drinking water suppliers (as managers) and of state and territory health authorities (as auditors of the safety of water supplies).

A risk assessment is one element of the ADWG which is a prerequisite for subsequent steps for prevention and control of hazards. The ADWG require identification of all potential hazards, their sources and hazardous events, and an assessment of the level of risk presented by each. The ADWG framework for risk assessment and preventative measures involves:

- Water supply system analysis **(Section 3 of this report)**
- Assess water quality data (historical) **(Section 4 of this report)**
- Hazard Identification **(Section 5 of this report)**
- Risk assessment **(Sections 6 to 13 of this report)**
- Assess existing preventive measures (multiple barrier approach) **(Section 14 of this report)**
- Evaluate alternative preventive measures **(Section 14 of this report)**
- Select critical control points

At the time of writing, the current revision of the ADWG is version 3.6, updated March 2021. This version does not contain guidance of source vulnerability assessment of drinking water catchments. Such guidance is available in a consultation draft section for the ADWG released as version 15 in August 2016, as section 5.7 Microbial health-based target for drinking water supplies (Australian Drinking Water Guidelines: Draft framework on microbial health based targets | NHMRC Public Consultations). This draft was largely based on guidance in the WSAA HBT Manual (2015), including source vulnerability assessment and how it is used to categorise source waters. The source vulnerability assessment performed in this DWRA is based on the WSAA HBT Manual; guidance.

3. Water supply system

This section presents information relating to the first step of the ADWG framework, including an assessment of the existing water supply system, catchment details, existing land uses and future water supply requirements.

3.1 Catchments

The water supply system examined here includes two large catchment areas, the Serpentine and South Dandalup Dam PDWSAs. Raw water from Serpentine Dam is transferred to Serpentine Pipehead Dam (hereafter referred to as Pipehead Dam), which also receives desalination transfers from the Integrated Water Supply Scheme (IWSS). These combined inputs are supplied to the Pipehead Dam water treatment plant (WTP), and following treatment the finished water is then directed to the IWSS. A conceptual diagram of supply and treatment is included as Figure 3.1.

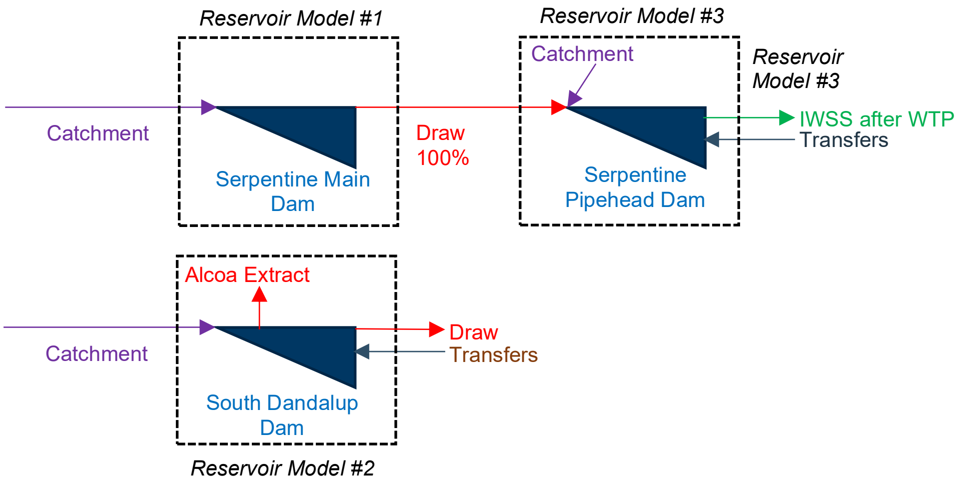

Figure 3.1 Conceptual diagram of supply to Serpentine Pipehead Dam

In the context of the WSAA HBT Manual (2015), the described combined catchment area constitutes a single "source water", culminating at the point of supply of raw water to the Pipehead Dam WTP. The source vulnerability assessment methodology in WSAA (2015) Table 1 differentiates inner and outer catchment areas, with the inner catchment described as typically 2-3 km from full supply level of a storage. However, this assumes that raw water abstraction for supply occurs from a single storage. In this case, multiple sources can be drawn on to supply the Pipehead Dam, which then supplies the WTP. To align with the WSAA (2015) approach for catchment vulnerability assessment, the Pipehead Dam and its immediate catchment area would be treated as the "inner catchment" of this source water, and the other surface water catchments (Serpentine Main Dam, South Dandalup Dam catchments) would be treated as "outer catchment" areas. This would be a slightly different but more accurate approach than treating the immediate surrounds of the upper lake storages (specifically the Reservoir Protection Zones) as inner catchments, which may be otherwise expected.

Summary details of the catchment areas have been drawn from the Drinking Water Source Protection Plans for the Serpentine Main Dam and Serpentine Pipehead Dam PDWSAs (DoW, 2007) and for the South Dandalup Dam PDWSA (DoW, 2005).

3.1.1 Serpentine Main Dam

The Serpentine Main Dam has a full supply capacity of 137.7 GL and collects water from a 664 km^2 catchment. The catchment is proclaimed under the *Metropolitan Water Supply, Sewerage and Drainage (MWSSD) Act (1909)*, and primarily classified as a Priority 1 PDWSA, with some private lands within the catchment classified as Priority

2. The reservoir is surrounded by a 2 km wide ‘Reservoir Protection Zone’ (RPZ) around its top water level, which includes the reservoir itself and does not extend outside the catchment area.

Approximately 12,500 ha of the Myara North mine region lies within the Serpentine Main Dam PDWSA, comprising approximately 19 per cent of the PDWSA, of which a portion will be disturbed by construction and mining. The existing Myara mine region of the Huntly Mine occupies a portion of the PDWSA.

3.1.2 South Dandalup Dam

The 208.2 GL capacity South Dandalup Dam is the largest reservoir supplying the IWSS. The catchment covers 311 km^2 and is proclaimed under the *MWSSD Act 1909*. Similar to Serpentine Main Dam, the catchment is predominantly classified as a priority 1 PDWSA, with a small area of private land managed as a priority 2 PDWSA. The South Dandalup Dam is also connected to the South Dandalup Pipehead Dam, which acts as a pumpback for South Dandalup Dam, adding to the available water for supply. Water from the South Dandalup Pipehead Dam is chlorinated before pump back to the South Dandalup Dam.

Approximately 6700 ha of the Holyoake mine region lies within the South Dandalup Dam PDWSA, comprising approximately 22 per cent of the PDWSA, of which a portion will be disturbed by construction and mining. The historical McCoy mine region of the Huntly Mine has formerly occupied a portion of the PDWSA.

3.1.3 Serpentine Pipehead Dam

The Serpentine Pipehead Dam is located directly downstream of the Serpentine Main Dam. It has a 2.6 GL full supply capacity, and in addition to inflows from Serpentine Main Dam, South Dandalup Dam and desalination inputs from the IWSS, is fed by a 28 km^2 catchment consisting entirely of State Forest and Serpentine National Park.

Approximately 200 ha of the Myara North mine region lies within the Pipehead Dam PDWSA, comprising approximately 7 per cent of the PDWSA, of which a portion may be disturbed by mining. The existing Myara mine region of the Huntly Mine occupies a portion of the PDWSA.

3.1.4 Upper Wungong Brook Catchment

The Upper Wungong Brook catchment comprises 128 km^2 and discharges into Wungong Dam, a drinking water supply reservoir with capacity of 60 GL. The catchment is proclaimed under the *Metropolitan Water Supply, Sewerage and Drainage (MWSSD) Act (1909)*, and primarily classified as a Priority 1 PDWSA, with a small area classified as Priority 2. The reservoir is surrounded by a 2 km wide RPZ around its top water level.

Approximately 2100 ha of the Myara North mine region lies within the Upper Wungong Brook PDWSA, comprising approximately 5 per cent of the PDWSA, of which a portion may be disturbed by construction and mining. The Myara North region lies in the upper reaches of the PDWSA and lies approximately 9 km upstream of the RPZ. The historical Jarrahdale Mine has formerly occupied a portion of the PDWSA.

3.1.5 Supply allocations

Water Corporation’s current allocation licence for Serpentine Main Dam and Serpentine Pipehead Dam (licence 56737) totals 53.89 GL/annum and is issued for the purpose of providing water for public potable water supply and irrigation.

Water Corporation’s current allocation licence for South Dandalup Dam (licence 56734) is 26.9 GL/annum. This licence is issued for the purpose of providing potable water for public water supply to the IWSS. Alcoa currently have two licences (No. 83356 and 153635) to abstract a total of 100 ML/annum from South Dandalup Dam, which is used to supply water (primarily for dust suppression) to the Huntly Mine.

Water Corporation’s current allocation licence for Wungong Dam (licence 58767) is 20.6 GL/annum. This licence is issued for the purpose of providing potable water for public water supply.

3.1.6 Treatment and distribution

Source water arising from the Serpentine, South Dandalup and Pipehead PDWSAs is drawn from the Pipehead Dam and treated with chlorine. Finished water is transferred to the IWSS for distribution to downstream customers.

Source water arising from the Upper Wungong Brook PDWSA is drawn from the Wungong Dam and treated with chlorine before supply to the IWSS.

3.2 Climate

Western Australia's south west region has a 'Mediterranean' type climate characterised by typically high winter rainfalls and an intense summer drought. A summary of the nearest Bureau of Meteorology (BoM) to the Myara North and Holyoake mine regions is provided in Table 3.1.

Table 3.1 Summary of nearest BoM climate stations

BoM Station	Station number	Distance from Mine Development Envelope	Data range
Serpentine Main Dam Station	009115	Within Myara North mine region	1963 to 2016 Rainfall
Karnet Station	009111	4 km south of Myara North, 47 km north of Holyoake mine region	1963 to 2020 Rainfall, evaporation and solar radiation data
Dwellingup Station	009538	7 km from Holyoake mine region	1935 to 2020 Rainfall, evaporation and solar radiation data

Monthly statistics for the Karnet Station since its inception are shown in Figure 3.2, and SILO[1] point data was extracted and annual rainfall plotted in Figure 3.3. Average annual rainfall is within +/-3 per cent between stations.

The mean monthly maximum temperature ranges from 15.8°C in July to 30.9°C in January. Average annual evaporation (1520 mm) typically exceeds average annual rainfall (1153 mm), albeit rainfall exceeds evaporation during winter and shouldering months.

Western Australia's south west region has undergone a 15-20 per cent reduction in rainfall since the 1970s, as illustrated in Figure 3.3 (Petrone K. C., Hughes, Van Niel, & Silberstein, 2010). This trend has been forecast to continue with a further 2 to 14 per cent reduction predicted by 2030. Temperature increase and potential evapotranspiration are also forecast to increase by 0.7 °C and 2 to 3 per cent, respectively (CSIRO, 2009; DoW, 2015).

Rainfall is also known to decline with distance inland. The 1100 mm annual rainfall isohyet (High Rainfall Zone or HRZ) and the 900 to 1100 mm annual rainfall isohyet (Intermediate Rainfall Zone or IRZ) have been identified in research as defining features for differing hydrological effects across the Huntly Mine region.

[1] Rainfall, temperature, and evaporation data sourced from the SILO data downloaded from https://legacy.longpaddock.qld.gov.au/silo/ppd/ on 5 June 2020. Point data from the SILO climate database (Queensland Department of Science, 2015) provides a continuous daily climatic record for a given point with gaps infilled based on interpolation of records from nearby weather stations.

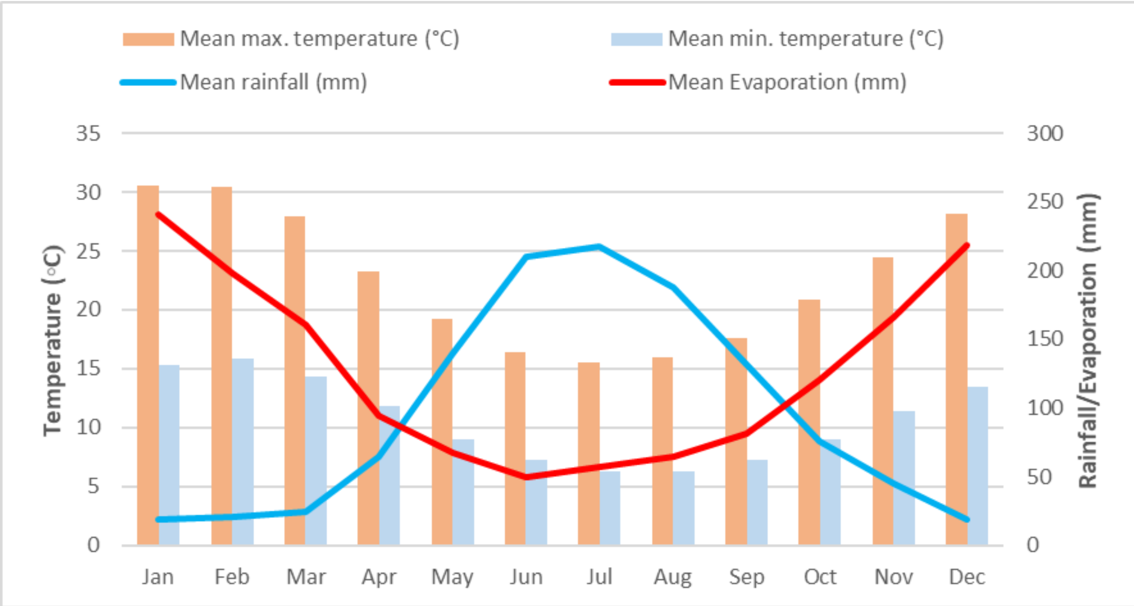

Figure 3.2 Monthly climate statistics at Karnet Station (Years 1965-2020)

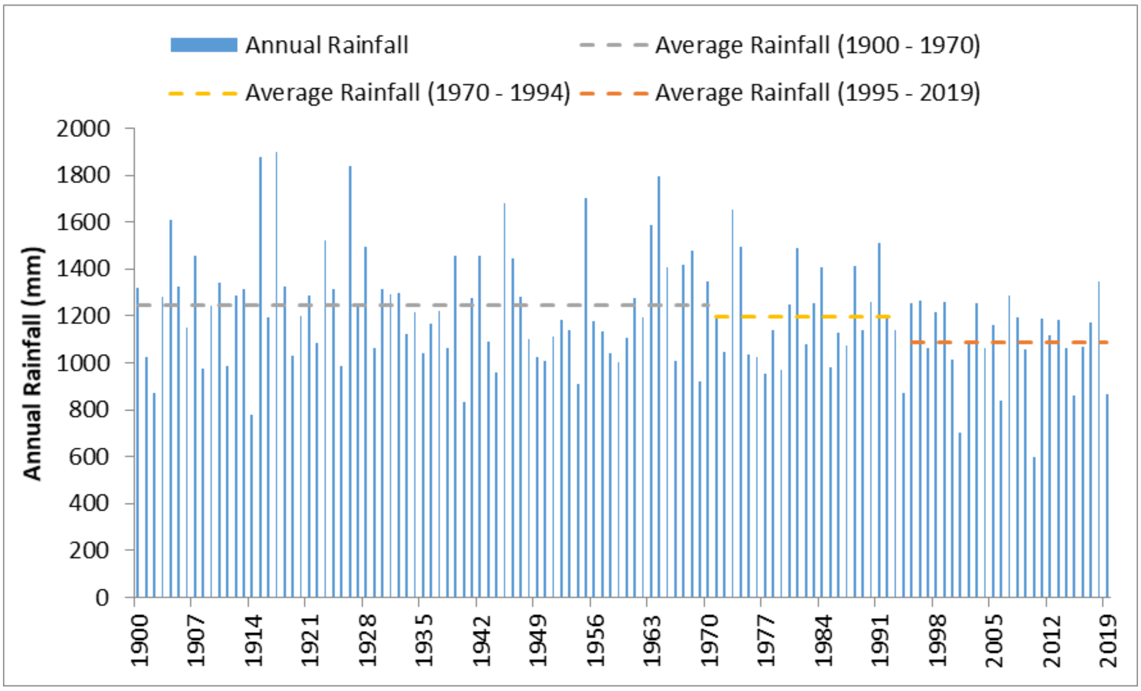

Figure 3.3 Annual rainfall at Karnet Station

3.3 Hydrogeology setting

3.3.1 Overview

The Serpentine Main Dam, South Dandalup Dam and Upper Wungong Brook catchments are located on the Darling Plateau, an undulating lateritic regolith over Archaean granite with dolerite intrusions. The groundwater host rocks predominantly comprise the weathered and fresh Archaean basement crystalline rocks. In addition, more recent sediments are incised into the basement rocks, coincident with existing drainage or palaeodrainage lines.

The generalised hydrogeology over the catchments comprise three main aquifer units:

– Shallow weathered zone aquifer: comprising lateritic caprock (duricrust) and shallow gravely to sandy sediments which represents a seasonal aquifer with significant storage, infiltration and flow capability.

– Deep weathered zone aquifer (lower saprolite) an aquifer of high storage potential, but limited bulk permeability (comprising clays).
– Fractured bedrock aquifer- permeability and yields are dependent on facture development and connectivity of the fractures.
– In addition to the above, where drainage lines are sufficiently developed, and have eroded the basement material, sediments, typically alluvial, have accumulated in the lower lying areas. The permeability of the sediments is variably distributed and related to lithology.

Broadly, groundwater levels within all aquifers appear to follow topography, such that groundwater level is highest in areas of highest topography and lowest in areas of lowest topography. Groundwater provides baseflow, following winter rains and aquifer recharge, to the major surface water bodies of the area.

3.3.2 Groundwater recharge, flow and discharge

Groundwater recharge into the subsurface occurs through rainfall infiltration into soils and downwards percolation of stored rainwater to the groundwater table. Root channels penetrating vertically via fissures and discontinuities in the cemented layer and deep into the clay zones are a consistent feature in the lateritic regolith. These channels form preferential flow paths and are understood to form significant vertical fluxes into groundwater systems (Turner & Johnston, 1987; McFarlane & Williamson, 2002;).

Stored rainwater is also subject to evapotranspiration (water loss) by the overlying vegetation (jarrah forest), so that a portion of infiltrated rainwater would reach and recharge the groundwater table. Where vegetation is cleared (e.g. timber harvesting or mining), evapotranspiration may be reduced which may increase recharge to the groundwater table.

Groundwater migrates from topographical highs towards the groundwater discharge boundaries in topographic flows, is expected to be towards the Serpentine Main Dam, South Dandalup Dam and Wungong Dam.

3.4 Hydrological setting

The Serpentine reservoir is fed by the Serpentine River, originating in the east of the catchment and then flowing north-west towards the reservoir. Big Brook is the main southern tributary, flowing from the south along the western edge towards the reservoir (Kitsios, Bari, & Charles, 2009). 39 Mile Brook collects runoff from the Jack Rocks catchment, draining to the north-east of the reservoir.

The South Dandalup reservoir is fed primarily by the South Dandalup River, generally draining from east to west. Barnett Brook is the only named tributary, draining a 17.6 km^2 catchment on the southern side of South Dandalup River. The 8.5 ha Banksiadale Dam, used for mining purposes, is located approximately 2 km north of the reservoir.

The catchments are in the Darling Plateau, which is characterized by sharply incised drainage lines forming dense drainage networks in the western, higher rainfall zone (HRZ), with these transitioning to open, flat-floored valleys in the eastern, lower rainfall zone (IRZ) (Churchward & Dimmock, 1989).

Seasonality in rainfall is reflected in streamflow seasonality. Some of the larger streams in the HRZ have previously exhibited perennial base flows. However, the drying climate discussed in Section 3.1 has caused a significant reduction in streamflow, leading to a shift from perennial to ephemeral streams and a decline in the runoff coefficient in recent decades. Runoff from Perth’s drinking water catchments has declined up to 70 per cent in the last 40 years that is associated with a 15–20 per cent rainfall reduction (Bates, Hope, Ryan, Smith, & Charles, 2008). The Serpentine reservoir inflow dropped nearly one-half (58 to 32 mm) from 1989–2000 to 2001–2008 (Petrone K. C., Hughes, Van Niel, & Silberstein, 2010).

3.5 Existing land uses

3.5.1 Serpentine PDWSA

The Serpentine Main Dam and Pipehead Dam catchments include the following land uses:

- Land and forest management, including timber harvesting
- Commercial land uses such as mining and pine plantations
- Linear infrastructure including the Muja Northern Terminal Western Power transmission line, pipelines, roads (including Albany Highway), tracks, and telephone lines
- Recreation.

Detail of activities associated with existing land uses and their potential risks that may impact the water supply system can be found in the *Serpentine Dam Catchment Area and Serpentine Pipehead Dam Catchment Area Drinking Water Source Protection Plan* (DoW 2007).

The following aspects are noted with respect to the activities listed:

- **Timber harvesting** – timber harvesting is undertaken by Forest Products Commission (FPC) within the Jarrahdale and Dwellingup State Forests in accordance with the Forest Management Plan (FMP) and Regional Forest Agreement (RFA). Harvesting occurs as a mosaic of infrequent clearing nominally once every several decades. Department of Biodiversity, Conservation and Attractions (DBCA) timber harvesting data indicating that most of the PDWSAs were logged approximately two to three times since 1920. Harvesting is subject to DBCA Silvicultural Guidelines, including retention of older habitat trees and avoidance of old growth forest, fauna habitat zones and reserves. FPC no longer undertakes timber harvesting within the Serpentine National Park or Monadnocks Conservation Park. Future timber harvesting will exclude native forests from 2024, unless the harvesting improves forest health or is for clearing of approved mining operations (WA Government, 2021).
- **Firewood** – firewood is collected within Jarrahdale and Dwellingup State Forests for private use, which is managed via licences issued by DBCA.
- **Plantations** – PDWSAs include pockets of pine plantations, including a 105 ha pine plantation 5 km north of the Serpentine Main Dam reservoir.
- **Mining and rehabilitation** – Alcoa bauxite mining and rehabilitation is occurring within the Myara mine region, south of the Serpentine River and proposed Myara north region, including within the Serpentine Main Dam and Pipehead Dam RPZs. Alcoa previously undertook bauxite mining in the northern corner of the Serpentine Main Dam PDWSA as part of the former Jarrahdale Mine, with rehabilitation conducted in 1999 and 2000.
- **Apiaries** – bee keeping activities are undertaken at designated sites, nominally 3 km apart, within State Forest, under licence with DBCA.
- **Infrastructure** – includes Western Power transmission line, pipelines, roads, telephone lines and towers.
- **Feral animal control** – feral animal baiting occurs for the Western Shield Program, using 1080 bait (sodium monofluoroacetate), which is a naturally occurring chemical. . Studies in Australia and New Zealand have confirmed that there is no evidence of 1080 persisting in or contaminating soil or waterways. This is because sodium fluoroacetate is readily trapped by cellulose and humus material in soils and is degraded into harmless by-products by a number of species of micro-organisms (DoW, 2009). Shooting to control problem animals is undertaken by authorised personnel.
- **Prescribed burns and wildfires** – prescribed burns and fire response activities are undertaken by DBCA and DFES. Figure 3.4 and Figure 3.5 present the extent of prescribed burns and wildfires in the Serpentine Main Dam and Pipehead PDWSAs over the past five decades. Historically, fire response may have used per- and polyfluoroalkyl substances (PFAS) in firefighting foams, which are key contaminants of concern for drinking water. DFES has not used PFAS since 2003.
- **Recreation** – boating, swimming, fishing, and marroning are prohibited in the reservoir for health reasons. Camping, hiking, cycling, horse riding, picnicking, licensed vehicle access, and motor rally events are listed as activities in specific areas, and illegal hunting and unlicenced vehicle access may also occur.

According to the Serpentine Dam and Pipehead Drinking Water Source Protection Plan (DWSPP), motor rally events have not been held in the PDWSA catchment area since 2006, however a motor rally event was held in the Serpentine Main Dam PDWSA on 7 November 2020. Given the national significance of these events to the local area, the DWSPP indicates that the events are giving conditional approval to be hosted within the catchment.

Some public facilities are provided in relation to public access and use of the State Forest, including provision of a car park, fireplaces, picnic facilities and a composting toilet at the Balmoral Road Prisoner of War (POW) Camp Ruins site, east of Jarrahdale in the proposed Myara North mine region.

The PDWSA is intersected by the Munda Biddi Trail, a long distance off-road cycling track, and the Bibbulmum Track, a long distance hiking track. The Munda Biddi Trail does not have designated camping sites within the PDWSA with the closest site, the Wungong campsite, being located to the north within the Wungong Dam PDWSA. The Bibbulmun Track passes along the eastern portion of the Serpentine Main Dam PDWSA including the Monadnocks and White Horse Hill campsites with composting toilets.

Numerous gravel tracks and off-road tracks exist throughout the catchment that are accessed by members of the public.

This review has indicated no additional hazards within the catchment as already detailed in the DWSPP, other than legacy PFAS.

The Shire of Serpentine-Jarrahdale, Shire of Boddington, Shire of Murray and Shire of Wandering all intersect the catchment area. A review of the planning schemes for these shires indicate that land uses remain consistent with those identified in the Serpentine and Pipehead Dam DWSPP.

A review of DWER's contaminated sites database indicates there are no reported contaminated sites within the Serpentine or Pipehead Dam PDWSAs.

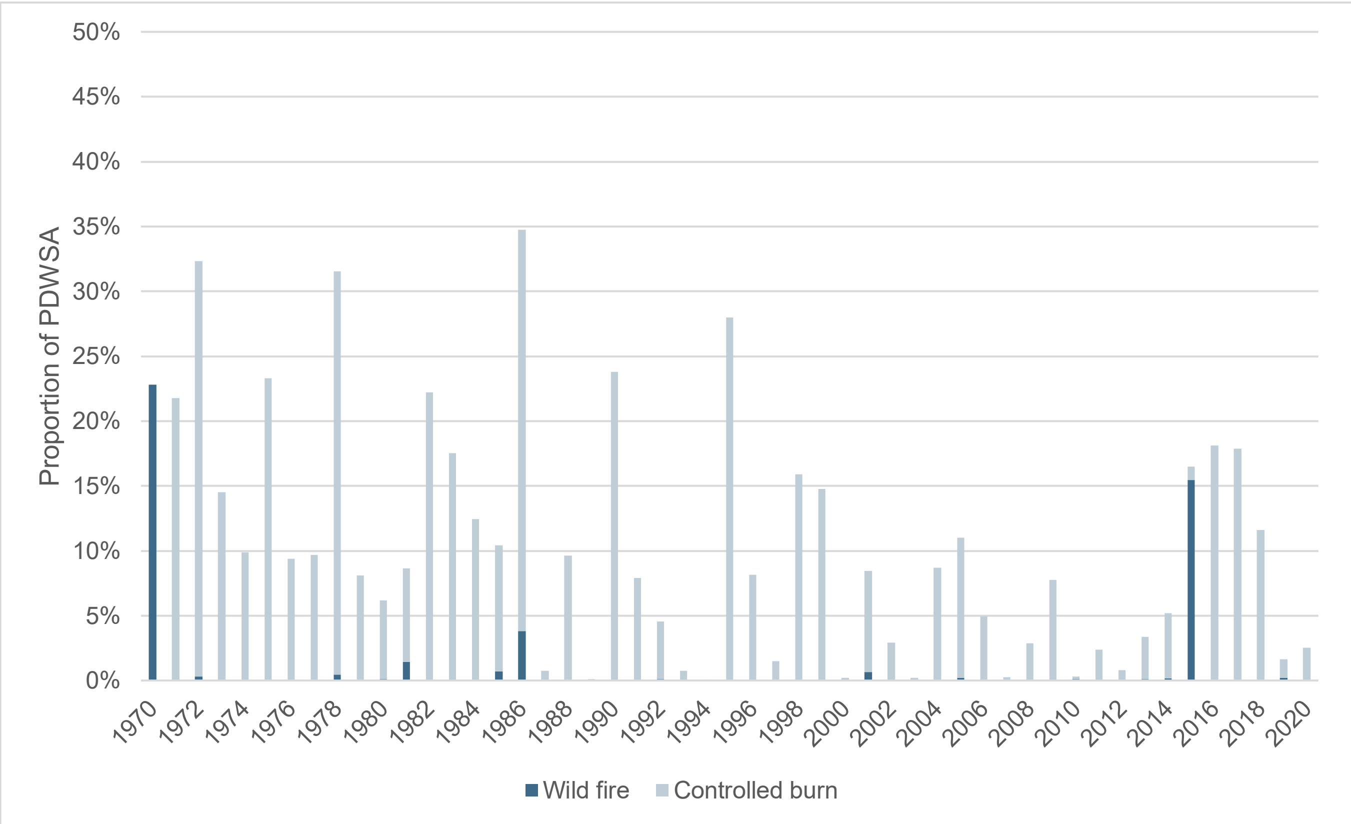

Figure 3.4 ***Serpentine PDWSA bushfire activity and rehabilitation***

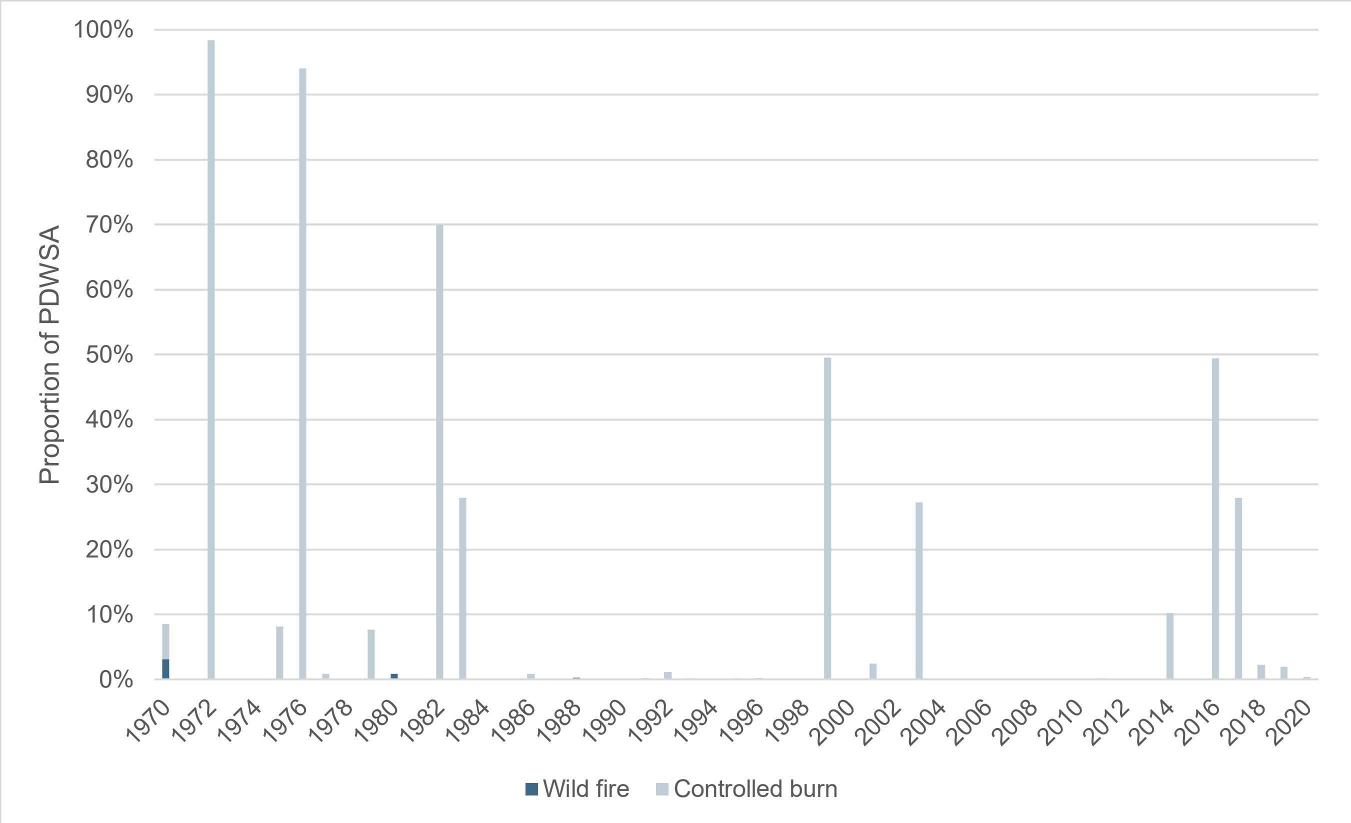

Figure 3.5 ***Serpentine Pipehead PDWSA bushfire activity and rehabilitation***

3.5.2 South Dandalup Dam PDWSA

The South Dandalup Dam (SDD) catchment area includes the following land uses:

- Land and forest management, including timber harvesting;
- Mining and gravel extraction; and
- Recreation.

These land uses are generally the same as those identified for the Serpentine Main Dam catchment area, with the exception that a gold mining lease exists in the SDD catchment area. As such, the water quality hazards from these land-uses are similar to those from the Serpentine Main Dam catchment. Further detail of these activities and their risks can be found in the S*outh Dandalup Dam Drinking Water Source Protection Plan* (DoE, 2005).

The following aspects are noted with respect to the activities listed:

- **Timber harvesting** – FPC undertakes timber harvesting within the Dwellingup State Forest in accordance with the FMP and RFA. DBCA timber harvesting data indicating that most of the PDWSA was logged approximately two to three times since 1920. Harvesting is subject to DBCA Silvicultural Guidelines. Future timber harvesting will exclude native forests from 2024, unless the harvesting improves forest health or is for clearing of approved mining operations (WA Government, 2021).
- **Firewood** – firewood is collected within Dwellingup State Forest for private use, which is managed via licences issued by DBCA.
- **Mining and rehabilitation** – Alcoa bauxite mining was previously undertaken in the South Dandalup PDWSA as part of its Huntly Mine.
- **Recreation** - the only authorised activity is hiking and camping on the Bibbulmun Track, however unauthorised activities may include swimming, fishing, marroning, broader camping, cycling, horse riding, picnicking, illegal hunting, and vehicle access.

The Bibbulmun Track intersects the eastern side of the SDD catchment, including the associated Mt Wells campsite which has a composting toilet.

Numerous gravel tracks and off-road tracks exist throughout the catchment that are accessed by members of the public.

– **Apiaries** – bee keeping activities are undertaken at designated sites, nominally 3 km apart, within State Forest, under licence with DBCA.
– **Infrastructure** – includes Western Power transmission line, pipelines, roads, telephone lines and towers.
– **Feral animal control** – feral animal baiting occurs for DBCA's Western Shield Program, using 1080 bait. Shooting to control problem animals is undertaken by authorised personnel.
– **Prescribed burns and wildfires** – prescribed burns and fire response activities are undertaken by DBCA and DFES. Figure 3.6 and Figure 3.7 present the extent of prescribed burns and wildfires in the SDD and SDPD PDWSAs over the past five decades. Historically, fire response may have used PFAS in firefighting foams. DFES has not used PFAS since 2003.

About 400 ha, or 1.2 per cent, of the SDD catchment is private land. Two private properties owned by Bunnings Forest Products Pty Ltd (Bunnings) and Boddington Gold Mine joint venture (operating as Boddington Gold Mine) are located along the eastern boundary of the catchment. The area of private land within the catchment is primarily native vegetation.

A review of DWER's contaminated sites database indicates there are no reported contaminated sites within the SDD PDWSA.

The shires of Murray and Boddington intersect the catchment area. A review of the planning schemes for these shires indicate that land uses within the SDD catchment area are consistent with those identified in the SDD DWSPP (DoE, 2005).

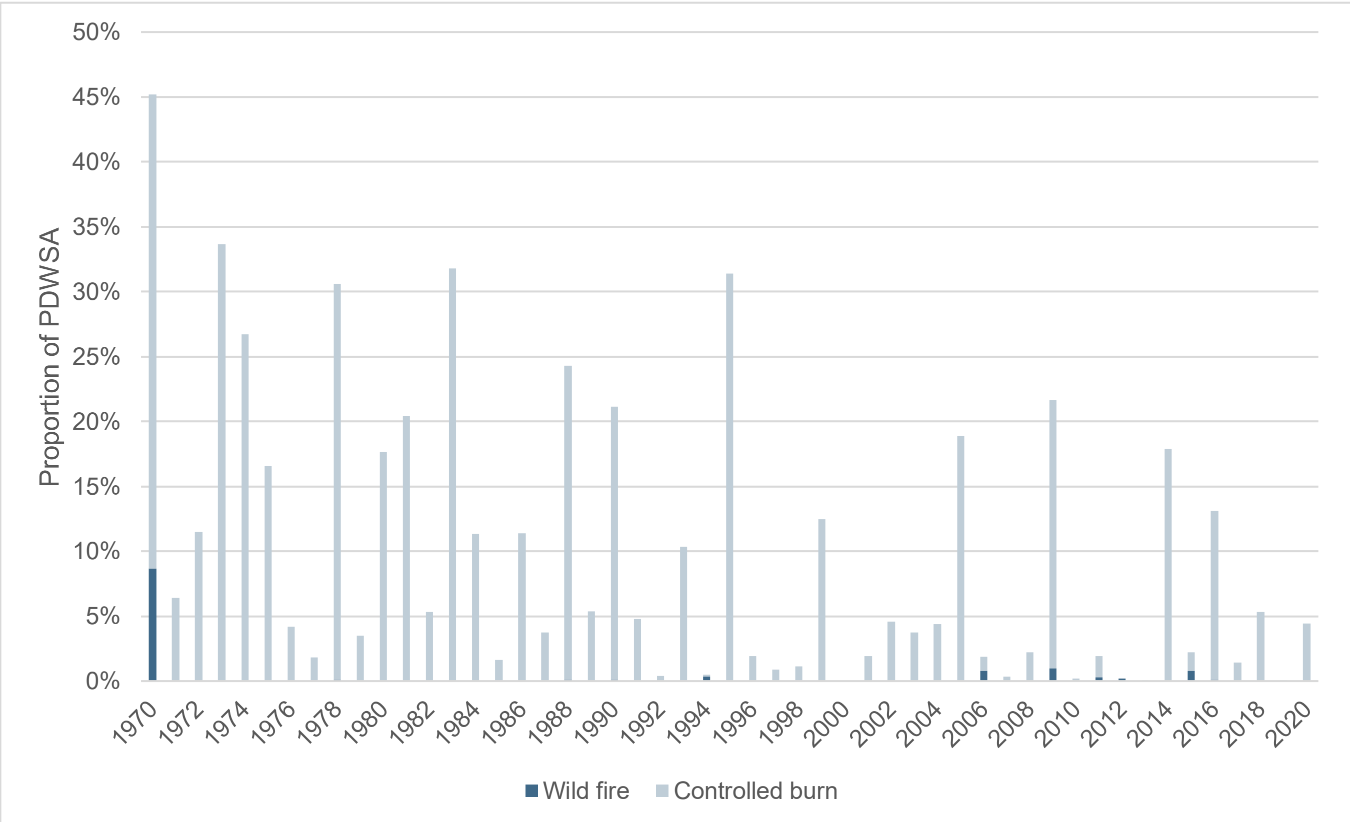

Figure 3.6 South Dandalup PDWSA bushfire activity and rehabilitation

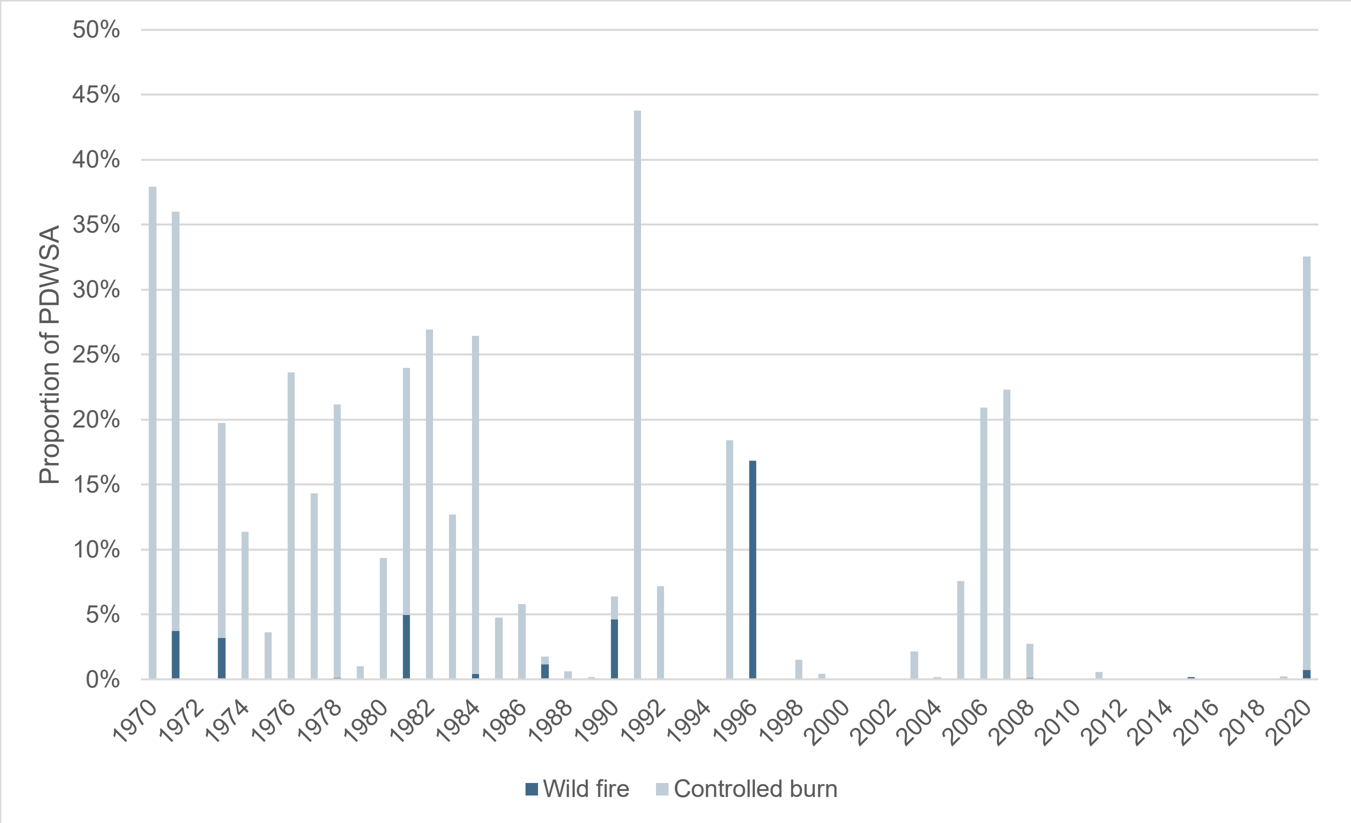

Figure 3.7 South Dandalup Pipehead PDWSA bushfire activity and rehabilitation

3.5.3 Upper Wungong Brook PDWSA

Upper Wungong Brook PDWSA primarily lies within Jarrahdale State Forest, with a small portion within Monadnocks Conservation Park and also private properties. Land uses include:

– Land and forest management, including timber harvesting and timber plantations
– Private land including general farming, horse stables and residences
– Apiaries and private resource harvesting
– Gravel pits
– Recreation
– Mine site rehabilitation associated with the former Jarrahdale Mine, now closed.

3.6 Potential water quality hazards from existing land uses

The potential hazards to source water quality related to the existing land uses in the Serpentine Main Dam and South Dandalup Dam PDWSAs are presented in the relevant DWSPPs for these catchments (respectively DoE 2005, DoW 2007). These hazards have been considered in relation to the Proposal in the hazard identification and conceptual site models (see Section 5).

3.7 Future water supply

The Serpentine Main Dam and SDD will continue to be key reservoirs for supply to the IWSS (Water Forever, Water Corporation 2009). However, future water supplies for the IWSS will increasingly come from desalination, groundwater replenishment and deeper groundwater aquifers rather than surface water supplies. Catchment yields into the Serpentine Main Dam and SDD are expected to reduce over time due to the effects of climate change. (DoW 2009, CSIRO 2009). Accordingly, Serpentine Main Dam, SDD and Pipehead Dams may be subject to increasing storage of desalinated water in the future.

4. Historical water quality

This section presents information relating to the second step of the ADWG framework, comprising review of existing and historical water quality within the Serpentine Main Dam and SDD. The review was based on the following information:

– Microbial data collected by GHD in 2020 as part of baseline surveys for the Proposal.
– Water Corporation data provided for the period 01/01/2000 to 31/12/2020, for turbidity and colour. No historical data was available for microbes or toxicants.

4.1 Microbial data

As noted in WSAA (2015) section 3.1.4, routinely collected *E. coli* data on raw water immediately prior to treatment is used to define a microbial indicator assessment. This assessment would be used to confirm the vulnerability assessment to determine the source water category.

In this case, raw water immediately prior to treatment would include the source water for the Serpentine Pipehead Water Treatment Plant (WTP). This WTP has only chlorination for inactivation of microbes which is only applicable for a Category 1 source. As *E. coli* monitoring data for this point have not been made available, the maximum *E. coli* concentration at the monitoring point has been assumed to be <20 *E. coli* per 100 mL, aligning with a Category 1 source water designation.

Greater concentrations of *E. coli* can be expected in the water courses coming from surface water catchment areas, including inflows from Serpentine and South Dandalup. However, the transport of the surface waters through large storages will result in the reduction of those concentrations. This is due to the combined effects of microbial die-off from processes such as solar exposure and predation, removal processes such as sedimentation, and the dilution of surface water inflows to Serpentine Pipehead Dam with desalination inputs.

The available microbial data from sampling within the catchment have been summarised here, so as to indicate the current microbial status of those areas. The amount of available data is small, and so this summary is not intended to be comprehensive.

Figure 4.1 and Figure 4.2 provide a summary of available microbial data taken within the proposed Myara North and Holyoake regions within the Serpentine Main Dam and SDD PDWSAs. These data were collected by GHD in 2020 as part of baseline surveys for the Proposal. No microbial data were available from Water Corporation for the Serpentine Main Dam or SDD.

Data were collected over four sampling events in 2020 and are sourced from 17 locations within the Myara North region, and 15 locations within the Holyoake region. A total of 48 data points were available for the Serpentine Main Dam PDWSA and 24 for the SDD PDWSA, however each individual location has up to 4 data points total.

As shown in Figure 4.1 and Figure 4.2, the concentrations at the sampled locations included *E. coli* concentrations ranging between 0 and 200 organisms per 100 mL. As noted previously, indicator concentrations in catchment water courses can be expected to be more elevated than the maximum concentrations expected in a Category 1 source water, of <20 *E. coli* per 100 mL. The environmental effects from surface water transport through a large storage have not yet occurred at the sampling locations shown in these figures.

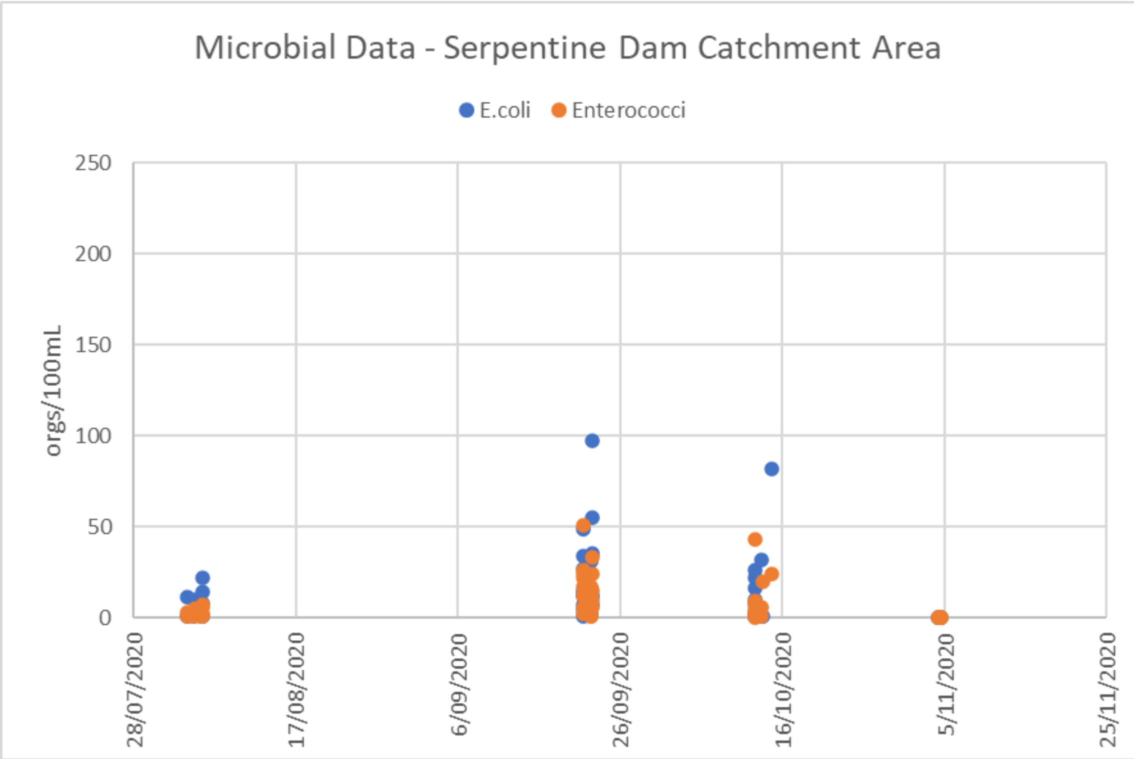

Figure 4.1 ***Serpentine Main Dam catchment microbial data summary***

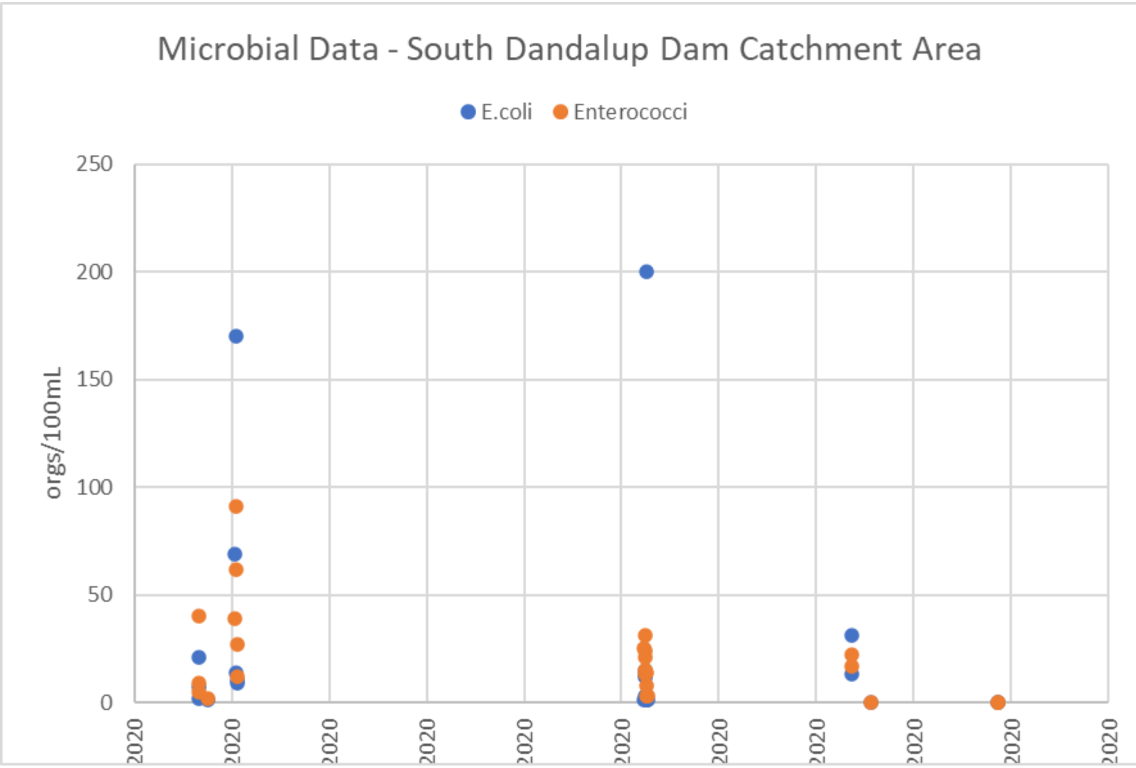

Figure 4.2 ***South Dandalup Dam catchment microbial data summary***

4.2 Turbidity

Figure 4.3, Figure 4.4 and Figure 4.5 present historical (2000-2020) turbidity in Nephelometric Turbidity Units (NTU) and inflow data provided by Water Corporation for the Serpentine, Serpentine Pipehead and South Dandalup reservoirs. The monthly inflow data was based on water balance estimates. The turbidity data is reported for the offtake and was recorded at varying frequencies over the twenty-year period (see Table 4.1), at the Serpentine and Pipehead Dams approximately weekly to fortnightly from 2002 to 2012 and approximately monthly from 2013 to 2020, and approximately fortnightly to monthly throughout for the South Dandalup Dam.

Table 4.1 Frequency of water quality records – no. records per year measured at the offtake

Year	Serpentine Main Dam	Serpentine Pipehead Dam	South Dandalup Dam
2000	13	5	9
2001	9	6	11
2002	90	92	47
2003	34	41	36
2004	36	36	12
2005	30	30	12
2006	36	36	15
2007	39	39	12
2008	39	39	12
2009	45	39	12
2010	30	33	30
2011	36	33	36
2012	41	39	30
2013	15	36	12
2014	12	39	12
2015	21	45	18
2016	12	42	21
2017	12	36	21
2018	15	42	16
2019	15	36	18
2020	15	27	14

To analyse the potential effects of mining and bushfires on turbidity, the figures also present the cumulative mining disturbance area (cleared or rehabilitated) within the RPZ and outside the RPZ, as well as the annual bushfire areas within and outside the RPZ. The mining disturbance areas within the RPZ are presented as a percentage of the RPZ area, and the mining disturbance and annual bushfire areas outside the RPZ are presented as a percentage of the PDWSA area outside the RPZ. Controlled burns represent all non-wildfire burns, e.g., prescribed burns and plantation burns.

The historical turbidity data indicates that offtake turbidity was generally less than 1 NTU throughout the twenty-year period, including during mining disturbance within the PDWSAs and RPZ. The data does not display any increasing trend with turbidity associated with cumulative mining disturbance or the effects of large bushfires within the PDWSAs or RPZ. The turbidity data was collected on an approximately monthly basis between 2013-2020 and there is some potential for turbidity spikes to have occurred within the monthly timestep, however this would be limited by the dispersion and mixing across the reservoir prior, which would tend to flatten turbidity spikes, therefore significant turbidity events should be noticeable in monthly records at the outlet.

Between February 2017 and September 2020, the Myara mine region experienced 128 drainage failures, of which 38 events generated turbid discharge exceeding 25 NTU for 1-hour or more and were located within the Serpentine RPZ or Pipehead catchment. These discharges were from mining areas, haul roads, or other infrastructure, discharging to land that eventually drains to the reservoir. Failure mechanisms are described in Appendix I. No anomalous readings were observed at the offtake following these events, suggesting that the reservoirs provide significant dilution and settlement services.

High turbidity levels in the Serpentine and South Dandalup reservoirs correspond to periods of low reservoir storage.

Wungong Reservoir turbidity readings ceased in 2003 and are therefore not plotted.

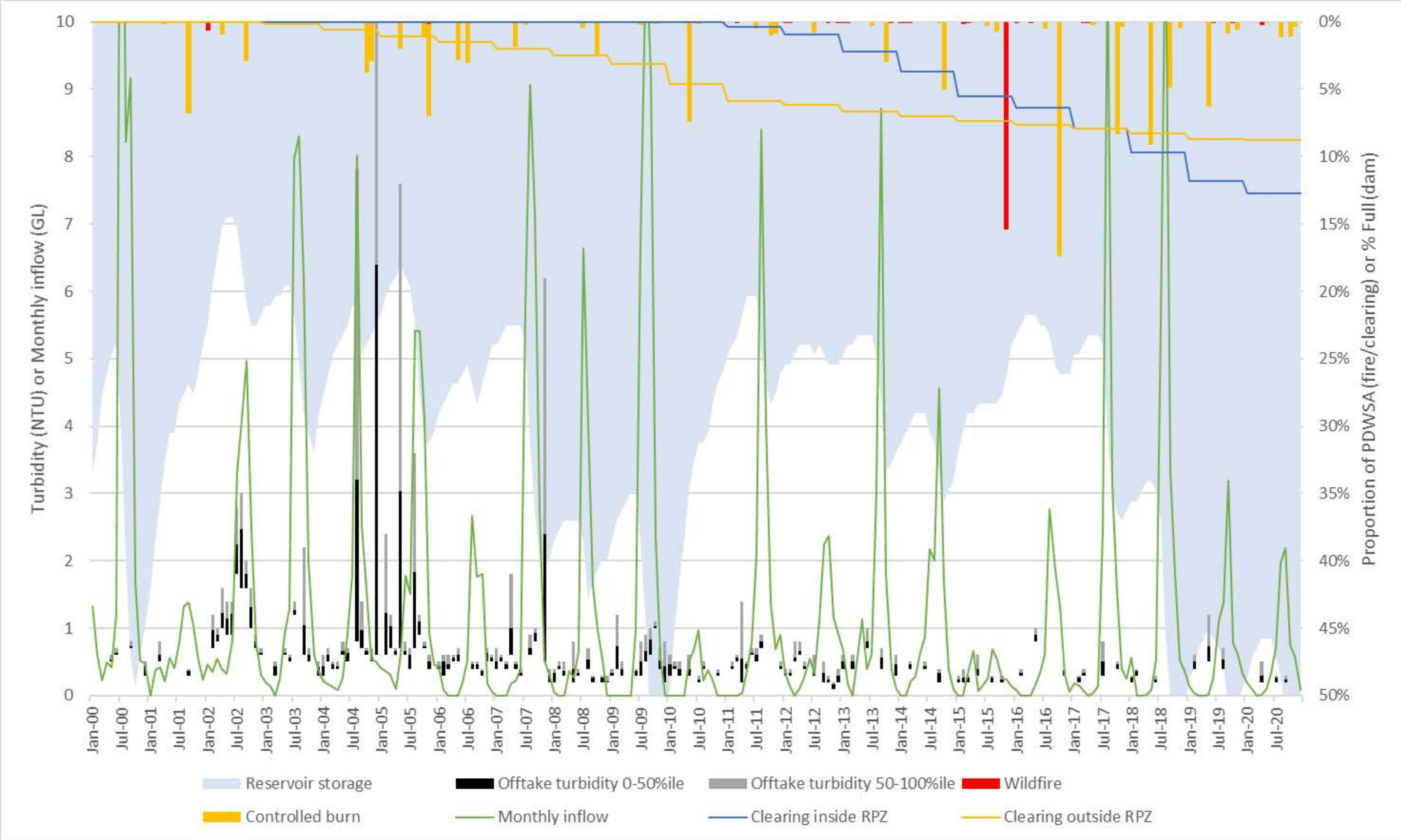

Figure 4.3 ***Serpentine Reservoir – offtake turbidity, reservoir storage, inflows, mining, and bushfires***

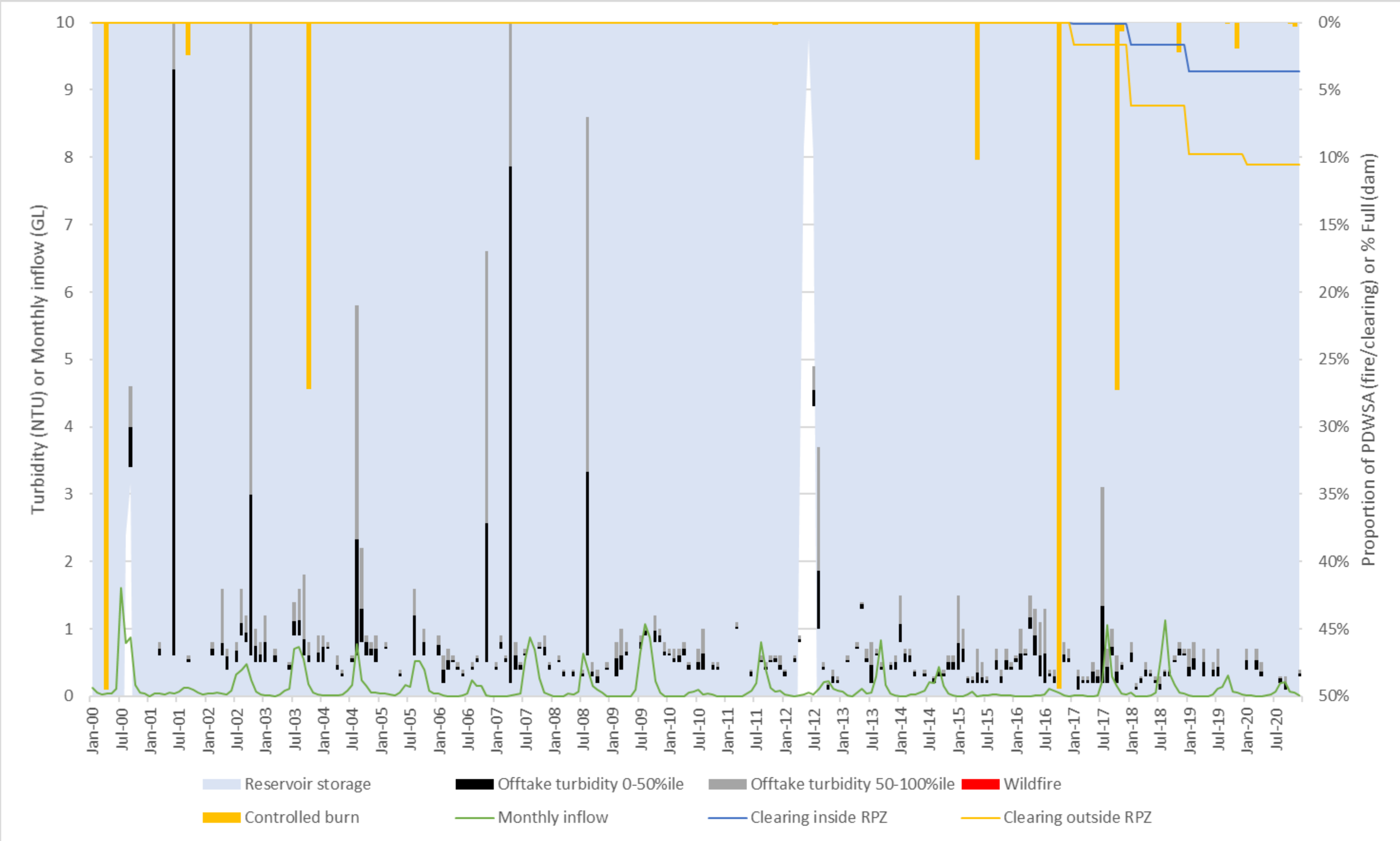

Figure 4.4 Serpentine Pipehead Reservoir – turbidity, storage, inflows, mining, and bushfires

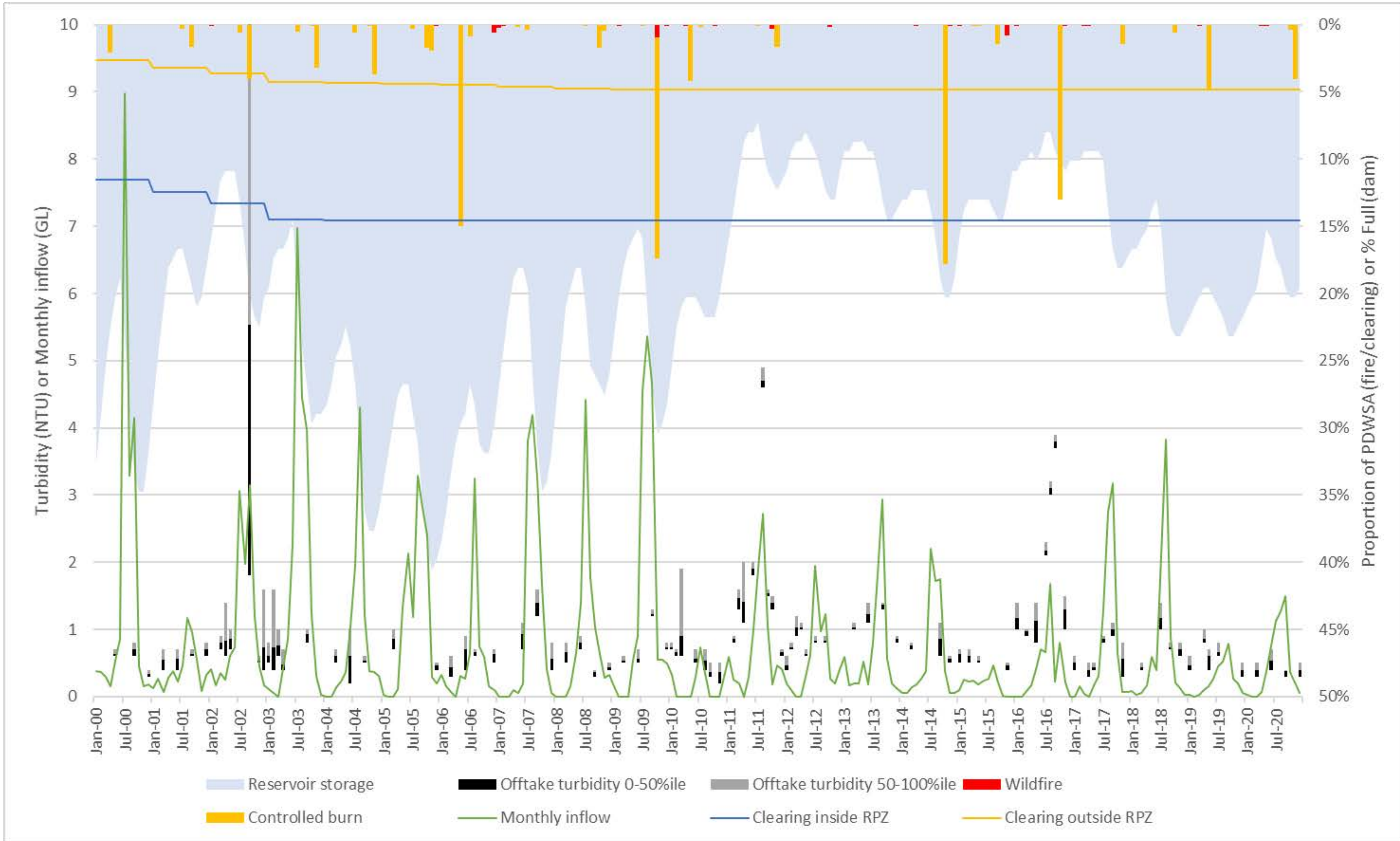

Figure 4.5 *South Dandalup Reservoir – turbidity, storage, inflows, mining, and bushfires*

4.3 Colour

Figure 4.6, Figure 4.7 and Figure 4.8 present historical data (2000-2020) for colour in True Colour Units (TCU), as an analogue of dissolved organic carbon (DOC), provided by Water Corporation for the Serpentine, Serpentine Pipehead and South Dandalup reservoirs. The colour data was recorded at varying frequency over the twenty-year period (see Table 4.1), on the same dates as turbidity.

To analyse the potential effects of mining and bushfires on DOC, the figures also present the cumulative mining disturbance area (cleared or rehabilitated) within the RPZ and outside the RPZ, as well as the annual bushfire areas within and outside the RPZ. The mining disturbance and annual bushfire areas within the RPZ are presented as a percentage of the RPZ area, and the mining disturbance and annual bushfire areas outside the RPZ are presented as a percentage of the PDWSA area outside the RPZ.

The historical colour data indicates that colour has varied between approximately 1-4 TCU over the twenty year period and does not display any increasing trend associated with mining disturbance or the effects of large bushfires within the PDWSAs. As with turbidity, any significant colour spikes associated with washout of DOC following bushfires or clearing should be evident in the colour records, due to dispersion and mixing in the reservoir prior to sampling at the offtake.

High colour levels in the Serpentine and South Dandalup reservoirs correspond to low reservoir storage volumes.

Wungong Reservoir turbidity readings ceased in 2003 and are therefore not plotted.

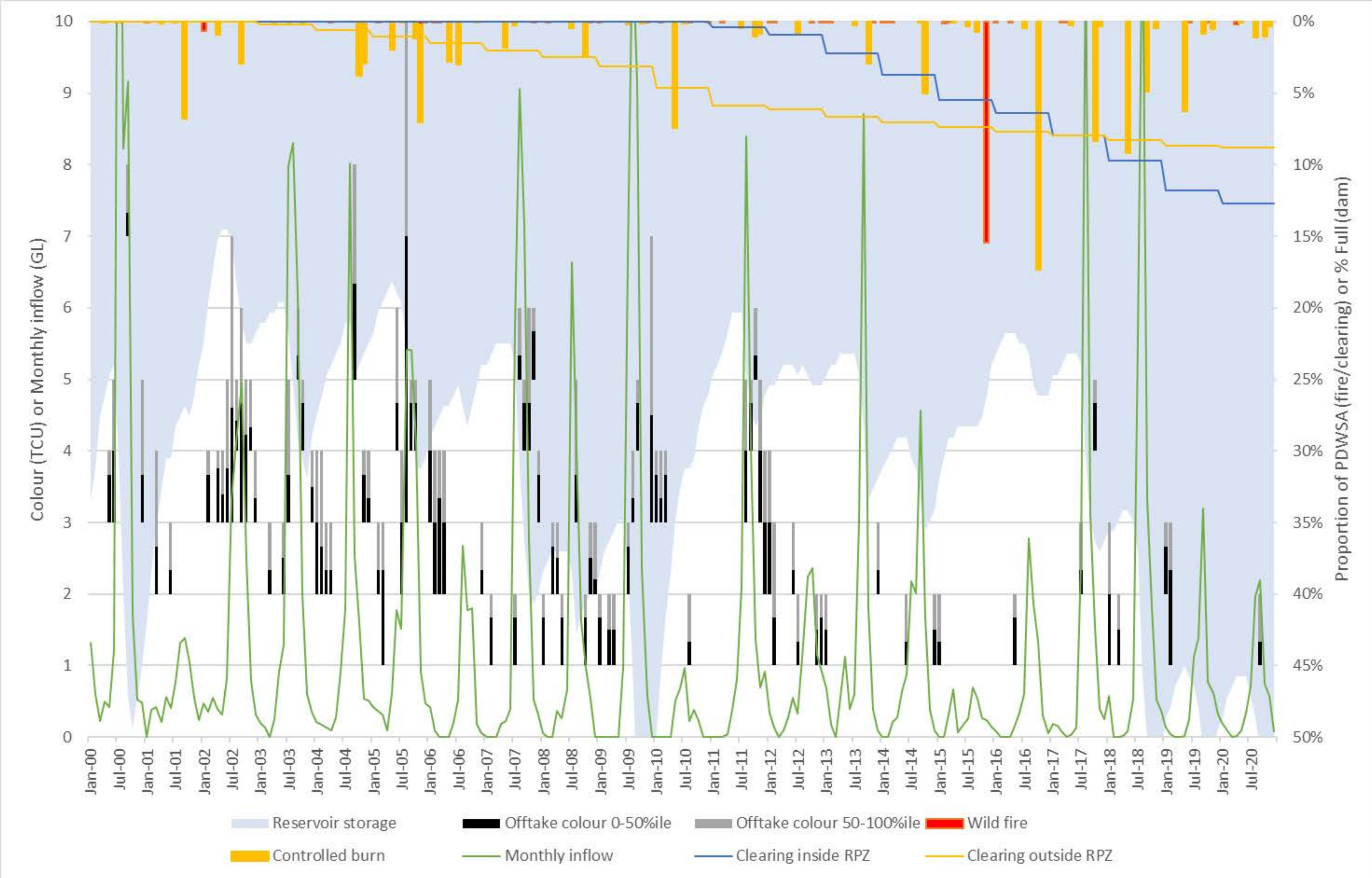

Figure 4.6 ***Serpentine Reservoir – offtake colour, reservoir storage, inflows, mining, and bushfires***

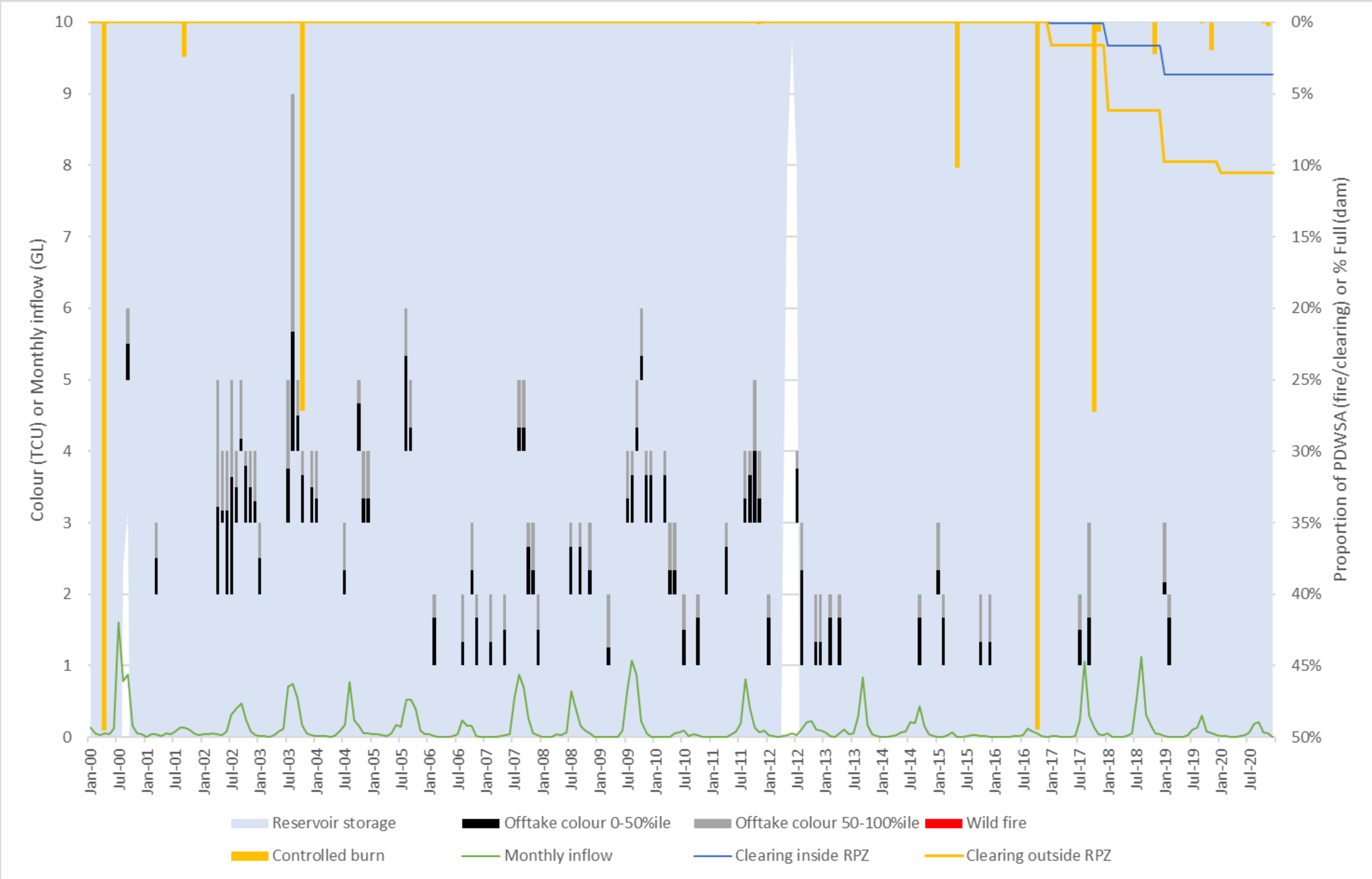

Figure 4.7 ***Serpentine Pipehead Reservoir – offtake colour, reservoir storage, inflows, mining, and bushfires***

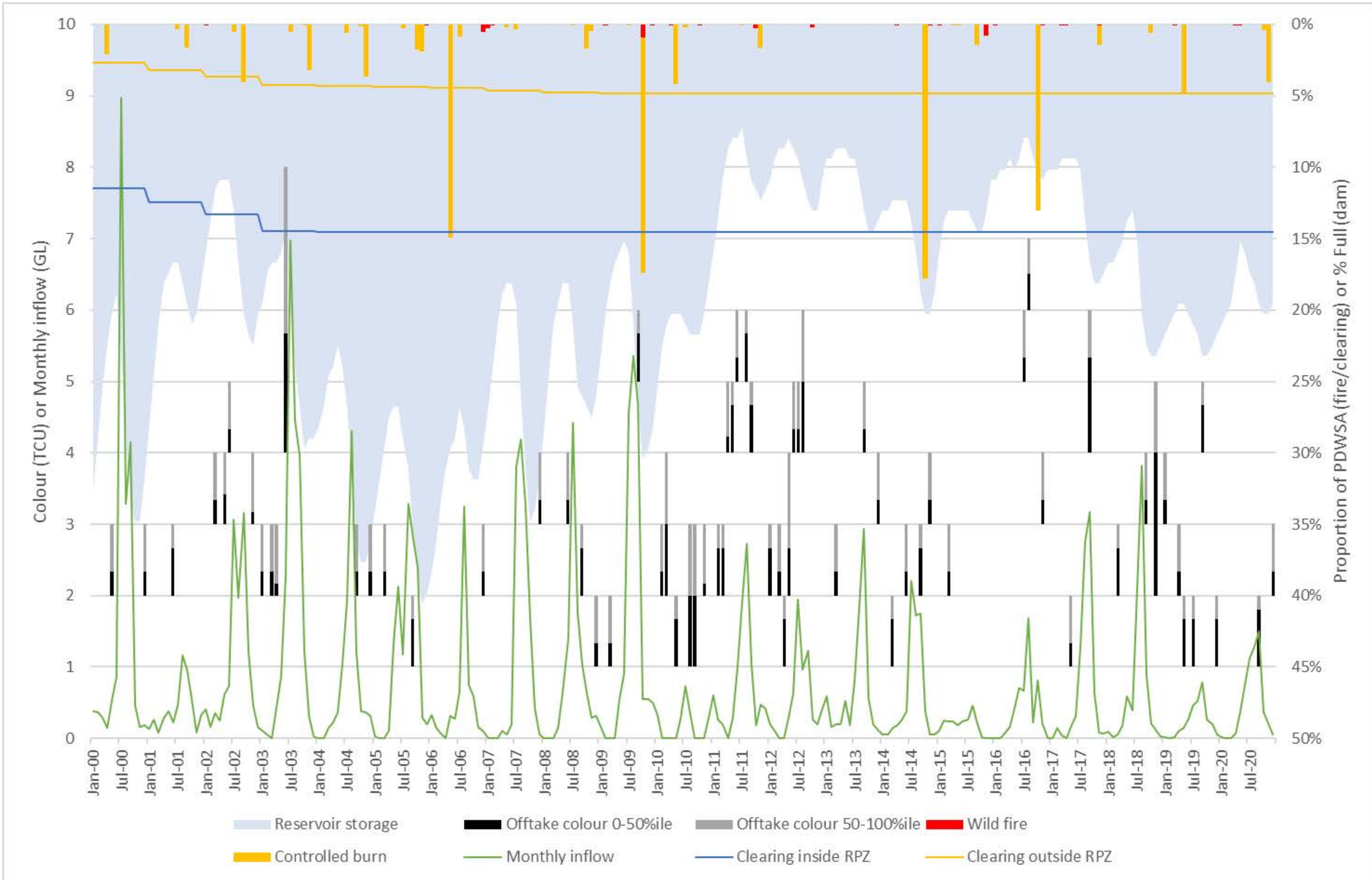

Figure 4.8 ***South Dandalup Reservoir – offtake colour, reservoir storage, inflows, mining, and bushfires***

4.4 Salinity

Figure 4.9, Figure 4.10, and Figure 4.11 present historical data (2000-2020) for salinity expressed as Electrical Conductivity (µS/cm), unadjusted for temperature, provided by Water Corporation for the Serpentine, Serpentine Pipehead and South Dandalup reservoirs. The salinity data was recorded in a temperature range typically between 12°C and 25°C, at varying frequency over the twenty-year period (see Table 4.1), on the same dates as turbidity and colour.

To analyse the potential effects of mining on salinity, the figures also present the cumulative mining disturbance area (cleared or rehabilitated) within the RPZ and outside the RPZ. The mining disturbance areas within the RPZ are presented as a percentage of the RPZ area, and the mining disturbance areas outside the RPZ are presented as a percentage of the PDWSA area outside the RPZ.

The historical salinity data indicates that salinity has varied between approximately 20-35 µS/cm over the twenty year period and does not display any increasing decreasing trend associated with mining disturbance within the PDWSAs.

Salinity levels in the Serpentine and South Dandalup reservoirs trend lower in response to increasing reservoir levels, and higher with falling reservoir levels.

Wungong Reservoir turbidity readings ceased in 2003 and are therefore not plotted.

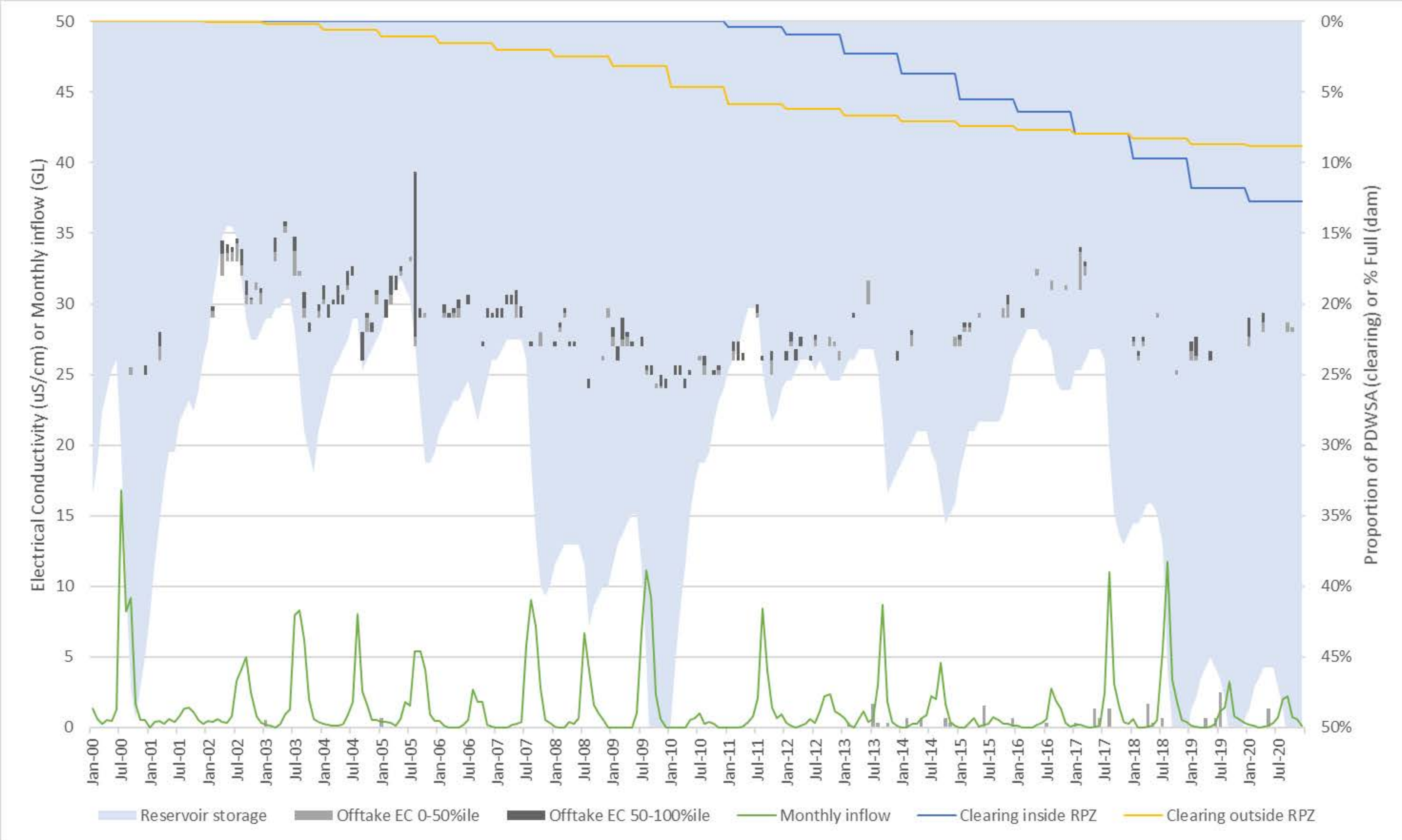

Figure 4.9 ***Serpentine Reservoir – offtake salinity, reservoir storage, inflows, and mining***

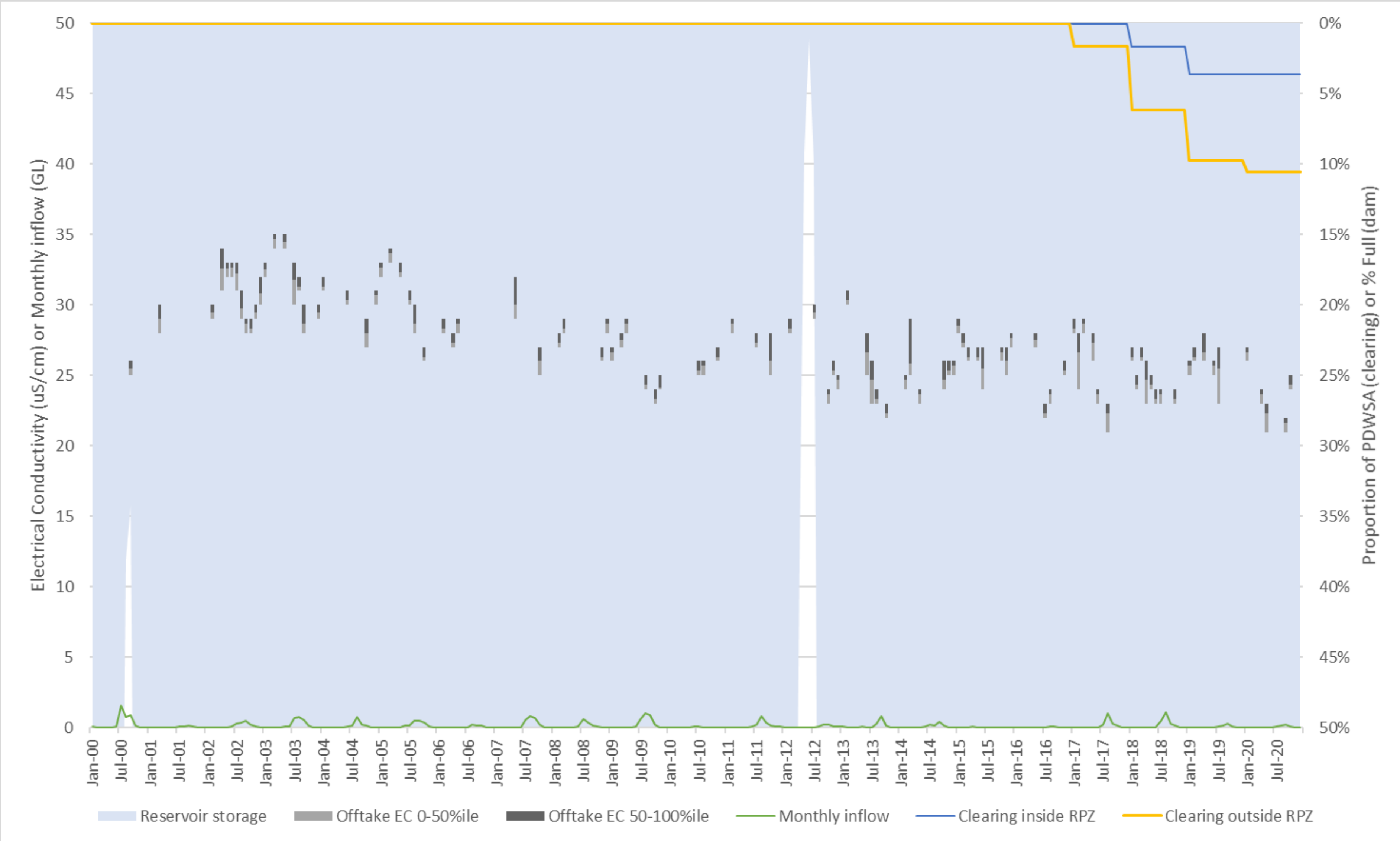

Figure 4.10 ***Serpentine Pipehead Reservoir – offtake salinity, reservoir storage, inflows, and mining***

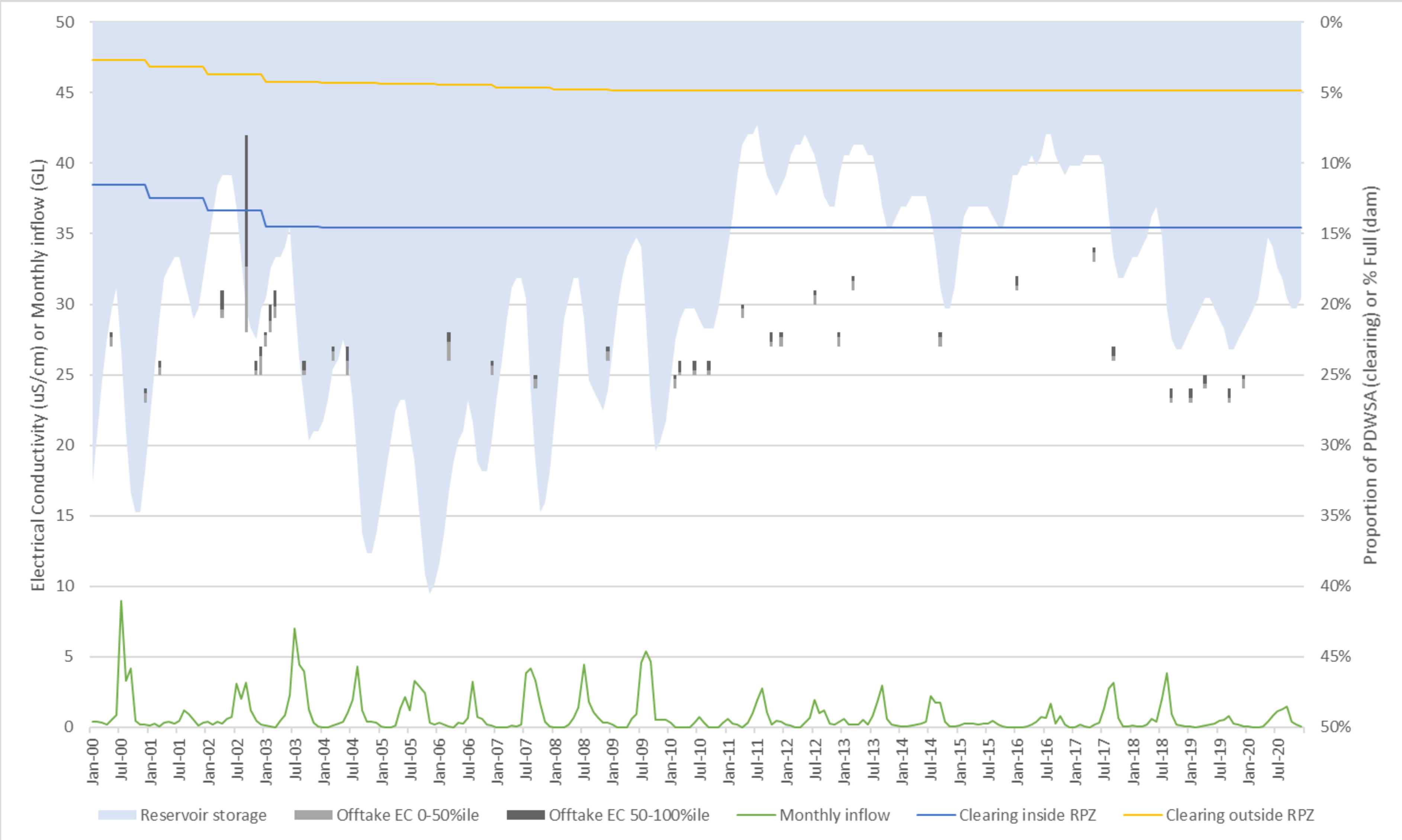

Figure 4.11 *South Dandalup Reservoir – offtake salinity, reservoir storage, inflows, and mining*

5. Hazard identification

This section presents information relating to the third step of the ADWG framework, comprising a hazard identification based on proposed land uses and conceptual site models, and a Tier 1 catchment vulnerability assessment in accordance with the Health Based Targets (HBT) Manual (WSAA, 2015).

The catchment vulnerability assessment is targeted to pathogens, which ADWG consider the greatest risk to consumers of drinking water, whereas the hazard identification is comprehensive, covering a range of contaminants including pathogens, turbidity and toxicants.

5.1 Proposed land uses

The Proposal comprises transition of the existing Myara operations of the Huntly mine that occur within the Serpentine and North Dandalup Dam PDWSAs into the Myara North and Holyoake mine regions.

The proposed Myara North and Holyoake regions are shown in Figure A-1 and Figure A-2 in Appendix A. These figures show the extent of land uses, along with the outline of proposed mining areas, and the locations of indicative mine pits and mine facilities.

The proposed Myara North mine region is located south-east of the town of Jarrahdale in the Shire of Serpentine Jarrahdale. Alcoa previously mined north of Jarrahdale from 1963 to 1998.

The proposed Holyoake mine region is located approximately 5 kilometres east of Dwellingup within the shires of Murray and Boddington.

The bauxite mining process involves:

– Harvesting of timber by FPC and wood waste by Simcoa.
– Vegetation clearing and, as a last resort, burning of residue that cannot be reused by third parties, with coarse woody debris retained for rehabilitation.
– Topsoil and overburden removal. Material is stockpiled or used directly for rehabilitation.
– Ripping or drilling and blasting of caprock, and excavation of bauxite. Bauxite is transported by haul roads to a central Run of Mine (ROM) pad and is then subject to blending and crushing prior to conveying to stockpiles at Pinjarra Alumina Refinery.
– Rehabilitation to jarrah forest by deep ripping to remove compaction of pit floors, re-contouring the surface, returning of topsoil and overburden, seeding, planting and fertilising.

The development of the Myara North and Holyoake regions will require new mine facilities, overland conveyors, haul roads, access roads, power generation and transmission infrastructure.

The new mine facilities will include ROM pads, crushers, vehicle refuelling bays, fuel storage laydown areas, offices and crib rooms, staff ablutions, light vehicle washdown and maintenance, and sewage and oily wastewater treatment. Power generation will involve diesel generators supplied by above ground diesel storage tanks, with a substation comprising transformers and switchgear. Water will be piped from existing facilities at Myara or McCoy and stored in lined water storage ponds. Heavy vehicle maintenance and washdowns will occur at existing facilities at McCoy, which are not part of the Proposal.

5.2 Preliminary conceptual site models

Preliminary conceptual site models (CSM) were developed to identify the potential contaminant sources and pathways from the Proposal to the Serpentine Main Dam, Serpentine Pipehead and South Dandalup reservoirs. The CSMs were developed based on a detailed review of the water supply system, catchment characteristics and proposed land uses associated with the Proposal and are presented in Appendix B. The CSMs include:

Figure B-1 Conceptual model overview

Figure B-2 Clearing and mining conceptual model

Figure B-3 Exploration and rehabilitation conceptual model

Figure B-4 Mine facilities conceptual model

Figure B-5 Bushfire and controls conceptual model

Figure B-6 Conveyor operation conceptual model

Figure B-7 Haul road operation conceptual model

Figure B-8 Linear infrastructure stream crossing conceptual model

Figure B-9 Climate change considerations conceptual model

Further detail into each source, pathway and receptor as identified from these models is captured in Appendix C.

5.3 Latency and long-term impacts

While proposed mining and rehabilitation has a limited time span of perhaps 20 years, the reservoirs and catchments are intended to remain as a permanent public drinking water supplies. Hazards may only become present long after mining is complete, and the likelihood and consequences of all hazards need to be considered in the context of their potential longer-term and cumulative impacts with respect to existing land uses and short and long-term environmental stressors.

Climate change is expected to result in rising temperatures and associated increased evapotranspiration, less frequent and more intense rainfall events and declining annual rainfalls. These changes have the potential to lead to:

- a decline in groundwater levels, streamflow and hence reservoir levels
- a decline in salt yields to surface water as groundwater levels decline
- increased fire intensity and frequency
- decline in forest density and health
- greater soil loss volumes as a result of reduced soil structure associated with vegetation loss and more intense rainfall events. Analysis of soil loss risk data for the catchments (Viscarra Rossel, et al., 2016) shows little east-west variation in soil loss risk despite the lower rainfall intensity in the eastern catchments.

The above impacts may ultimately result in reduced catchment yields and potentially a greater likelihood for increased concentrations of pollutants to enter the reservoirs. There is insufficient evidence on whether the decline in streamflow will counteract with increased pollutant concentrations to alter pollutant loads. The interactions between proposed mining and rehabilitation activities with those arising from climate change and existing land uses will need to be considered in the assessment of these hazards.

5.4 Site images

A number of site images have been included in Appendix D, to illustrate relevant aspects of mining works in the catchment. The images include:

Figure D-1 Erosion barriers (watershots, blasted drainage lines) or cleared hillside

Figure D-2 Erosion barriers (watershots, blasted drainage lines) or cleared hillside #2

Figure D-3 Temporary facilities, overhead view

Figure D-4 Temporary facilities, angle view

Figure D-5 Effluent discharge area, signage

Figure D-6 Effluent discharge area, metering

Figure D-7 Effluent discharge area, purple dripper pipe dispersing to leaf litter on ground surface

Figure D-8 Effluent discharge area, overland piping prior to discharge area

Figure D-9 20-year jarrah and marri rehabilitation at Banya

Figure D-10 0-year rehabilitation at Kisler

5.5 Summary of hazards

The key potential hazards to Serpentine Main Dam, Pipehead Dam and SDD from the Proposal include:

Generation and discharge of pathogenic microorganisms from increased human activity. Pathogen contamination of drinking water can have significant effects on human health, if pathogen risks are not mitigated.

Pathogen hazards are further examined in sections 6 and 7.

Increases in sediment, suspended solids, and turbidity from erosion during mining activities. Erosion results in the mobilisation of soil particles, which are released into the air and tributaries and increase the turbidity within the water body. Pathogens adsorb onto these soil particles and may be shielded from the effects of disinfection.

Turbidity hazards are further examined in section 8.

Increases in stream salinity as a result of mining-induced saline groundwater discharge. Saline water is not potable, and smaller increases in salinity can affect the aesthetic of the source water. Salinity can also have a wider ecosystem impact due to its effect on plant growth/health.

This potential hazard is described in the Hydrology and Water Quality Report (GHD, 2021b) and has not been further examined here.

Contamination from spills, leaks, and/or emissions from the storage, handling, and use of hazardous materials and waste. Pesticides are toxic and some are potentially carcinogenic. Nutrients from fertiliser are toxic to humans at high levels, with infants less than 3 months old being most susceptible. Hydrocarbons and other chemicals are potentially toxic and carcinogenic, and harmful by-products may be formed when they are combined with chlorine (i.e., during chlorine disinfection). The risks from some additional potential hazards have not been examined here, including metals, microplastics, and explosives. Assessments have instead focused on those hazards presenting a higher risk to the catchment as a source water.

It is noted that Alcoa will not use PFAS in firefighting foams in the Myara North and Holyoake regions, and that all water supplies to construction and operations in the Myara North and Holyoake regions will be sourced from public water sources, captured onsite stormwater or from licensed onsite water treatment facilities where approved for reuse, within the drinking water catchment. Further discussion about PFAS assessment is included in section 12.

Diesel spill hazards are further examined in section 11.

Table 5.1 provides a summary of the potential unique contaminant sources from the Proposal.

The unique pathways of contaminants from the Proposal include:

- Overland flow – surface flows during heavy rainfall and wet ground conditions, discharging into stream or direct to reservoir
- Infiltration and subsurface flow - infiltration through soils into groundwater, subsurface flow discharging into stream or direct to reservoir
- Seasonal flow path - transport along watercourse during winter / spring flow period, discharging into reservoir
- Direct inhalation (only applies to irrigation of treated wastewater, should this be via sprinklers, and dust suppression).

Table 5.1 Summary of contaminant sources from the Proposal

Source type	Source description	Contaminant
Exploration, construction and operational workforce	Use of bushland for toileting	Pathogens
Sewage	Treatment of workforce sewage	Pathogens, nutrients, suspended solids
	Irrigation of treated effluent over bushland near construction compound and mine facilities	
	Mobile ablutions facilities	
	Pump out and transport of raw sewage for off-site disposal	
	Raw sewage leaks during tanker collisions	
	WWTP process upsets / failure resulting in reduced treatment efficacy / higher contaminant loading	
Waste	Solid and liquid waste generation from construction and operational activities	Nutrients, hydrocarbons, metals, pathogens, surfactants, plastics, suspended solids
	On-site waste disposal	
Fire and controls	Bushfire due to machinery or electrical sparks	Suspended solids - soot/ash / bushfire induced soil erosion / specific ionic species, trihalomethanes, industrial hydrocarbons, pesticides, and herbicides
	Fires caused by leaks or spills during refuelling or vehicle collisions	
Rehabilitation	Use of fertiliser for vegetation	Nutrients, herbicide
	Use of herbicide for vegetation	
Clearing	Clearing of vegetation and removal of caprock	Salinity, hydrocarbons, PFAS (legacy), suspended solids
	Change in hydrological regime	
	Rising groundwater mobilising salts in soils and/or pre-mining contaminants	
Conveyor operation	Spilling ore and/or sediment from damaged equipment or dusting off the belt	Sediments, suspended solids, metals, plastics, hydrocarbons
	Abrasion of the belt discharging pollutants	
	Oil leaks from bearings on conveyor idlers	
	Fuel or oil leaks from accidents of maintenance/inspection vehicles along conveyor corridor	
Power plant	Construction and operations power supply	Hydrocarbons
	Diesel power plant fuel farm leak or spill	
	Substation transformer oil leak or spills	

Source type	Source description	Contaminant
Mine infrastructure	Hazardous materials / package chemical storage and use for vehicle and equipment maintenance	Suspended solids, hydrocarbons, surfactants, nutrients, metals, organic solvents, PFAS (legacy)
	Fuel storage and handling at mine facilities	
	Washbay washwater generation	
	Vehicle and equipment washdowns	
	Overflow of potentially contaminated water ponds	
Light and heavy vehicles	Fuel leaks during refuelling on-site	Hydrocarbons, metals, microplastics, suspended solids, nutrients, metals
	Oil leaks during vehicle/equipment maintenance	
	Fuel or oil leaks whilst driving or during vehicle collisions	
	Tyre wear	
	Vehicle parking at mine facilities	
	Vehicle and equipment maintenance at mine facilities	
Linear infrastructure construction near waterways	Disturbance to bed and banks of waterways or reservoir leading to erosion	Suspended solids
	Temporary material stockpiling	
	Contaminated bulk construction material brought to site	Hydrocarbons, suspended solids, metals, other chemicals

6. Source vulnerability assessment

As required in the ESD Required Work item 50, a source vulnerability assessment of the Serpentine, Pipehead and South Dandalup Reservoirs is required, in accordance with the Australian Drinking Water Quality Standards and relevant contemporary guidance. This is constituted by the ADWG and other supporting documentation.

The ADWG is moving towards adoption of Health Based Targets (HBTs). These include risk assessment metrics for pathogen infection rates and disability adjusted life years (DALYs) to increasingly quantify pathogen risks to drinking water.

Historically, the approach to microbial safety of water supplies has been that pathogens should be absent from drinking water. This is primarily verified by *Escherichia coli* (*E. coli*) monitoring of supplied water in conjunction with qualitative 'catchment to tap' risk assessments as part of a drinking water quality management plan.

In contrast, HBTs require estimation of source water pathogen risk and the effectiveness of catchment management and treatment processes to reduce risks to acceptable levels. The WSAA HBT Manual outlines two tiers of source water assessment:

Tier 1 is recommended for all drinking water sources. Sanitary survey information together with source water microbial indicator data are used to categorise the source in terms of its vulnerability to pathogen contamination.

Tier 2 is optional and involves carrying out a quantitative microbial risk assessment (subject to ample source water pathogen data) to complement the Tier 1 assessment.

To that end, a sanitary survey (SS) and source vulnerability assessment were undertaken to better understand the **microbial risk** from the Proposal to the drinking water supply systems. This has been conducted in accordance with Chapter 5 of the ADWG, and the Draft ADWG Chapter 5.7 HBT (2016).

6.1 Methodology

This preliminary catchment assessment adopts a desktop-based SS of the Proposal, to characterise microbial risks from mining in the proposed Myara North and Holyoake regions.

The first step of a SS is to establish the area of influence and scope of the SS. In general, several $\log_{10}$ orders of pathogen inactivation occur over weeks to months following pathogens entering the natural environment, so reducing the SS boundary to inner catchment areas is worthwhile in some cases. However, for this vulnerability assessment the SS boundary has been kept to the entire catchment area for both PDWSAs as a conservative measure.

The microbial sources and pathways described as part of the catchment assessment in Section 5.2 is considered representative of a desktop SS.

The vulnerability assessment process as described in Figure 5 of the HBT Manual has been used to define the source category of the catchment with respect to the existing land uses and the Proposal. This has been based on the catchment details in section 3.1, and the hazard identification in sections 5.1 and 5.2. The CSM process diagrams shown in Section 5.2 include all of the potential pathogen sources and their pathways from mining and existing land uses. The use of this conceptual model representation is in line with the *Good Practice Guide*.

The SS provides key outputs relating to (WSAA 2015):

– pathogen sources arising from the presence of people and cattle
– intensity of these developments/activities
– proximity to feeder streams and water storage
– presence of in situ barriers such as riparian vegetation, fencing and detention in storage

The SS outputs are then aggregated into a vulnerability assessment, which assesses the relevant land use challenges to classify the water source into one of four vulnerability categories:

– Protected catchment

– Moderately protected catchment
– Poorly protected catchment
– Unprotected catchment

The four vulnerability categories are directly related to the required pathogen removal by treatment processes.

The vulnerability assessment and catchment categorisation has been semi-quantitatively validated based on the Baker et al (2016) standardised survey method, along with a review of likely pathogen travel times from mining areas. A review of available microbial monitoring data within the proposed mining catchment area has also been undertaken.

6.2 Source categorisation

The source categorisation in the HBT Manual (WSAA 2015) considers three land use challenges that are targeted to microbial risk: namely from permanent human, itinerant human, and stock animal sources. Table 6.1 presents a summary of how these three land use challenges are applicable to the PDWSAs.

Table 6.1 Land use challenges applicable to the PDWSAs

Land use challenge	Application to the Serpentine Main Dam and South Dandalup Dam PDWSAs
Permanent human	Serpentine Main Dam café caretaker's residence. No other human settlements existing or proposed within PDWSAs No living in accommodation (LIA) for mining, timber harvesting and other forest industries, all workforces are drive in-drive out
Itinerant human	Recreational public use of Serpentine Main Dam facilities, South Dandalup Dam facilities, Munda Biddi Trail, Bibbulmun Track, Balmoral Track, POW camp. Composting toilets at Serpentine Main Dam and South Dandalup Dam recreational areas, POW camp, Bibbulmun track campsites. Serpentine Main Dam café includes on-site sewage treatment plant (STP) and effluent disposal. Mine facilities include on-site STP and effluent disposal. Mobile mine ablutions block with septage pump out and tankering off-site. Mobile workforce for Proposal construction, mining, ore haulage and rehabilitation. Mobile workforce for timber harvesting, prescribed burns and fire response. Apiary operators at designated apiary sites.
Stock animals	No stock animals are expected to be kept within either PDWSA.

The vulnerability assessment comprises an assessment of the land use challenges with respect to their intensity, proximity to waterways and level of protection (preventative barriers). Table 6.2 and Table 6.3 present the vulnerability assessments for the Serpentine Main Dam and South Dandalup Dam, respectively, based on a review of the existing and proposed land uses described in Sections 3.5 and 5.1.

As noted in Section 2.2, the ADWG (2021) categorises drinking water sources as WSAA (2015), however does not include guidance around vulnerability assessment, and so the WSAA (2015) guidance is drawn on here for that aspect of assessment. As described in WSAA (2015) Table 1, the different vulnerability assessment categories for drinking water sources typically have particular challenges from land use. These challenges include impacts from permanent human habitation, itinerant human activities, and from stock animals. In this case, the existing challenges have been summarised as follows:

Existing challenges

– Negligible human settlements, limited to a caretaker's residence at Serpentine Main Dam
– Low level or negligible recreation in the outer catchment, including a café and facilities adjacent to Serpentine Main Dam
– No rural properties with stock animals, and active management of feral pig populations

These challenges align with either category 1 or category 2 source waters in WSAA (2015). Other characteristics typically associated with each of these categories include:

Category 1, typical characteristics:

– Human settlements and recreation excluded from the whole area of influence, typically the whole hydrological catchment and reservoir.
– Natural bushland
– Protection enforced by policed regulation
– Low intensity/low risk activities many be allowed in the outer catchment but active source protection (e.g. ranger patrols) is practiced to ensure negligible contamination risk
– Supply is from a large reservoir with long detention time for the water

Category 2, typical characteristics:

– Human settlements excluded from inner catchment
– Recreation excluded from inner catchment, and no recreation close to or on the main water body
– Farming excluded from inner catchment
– Bushland inner catchment, low density rural outer catchment
– Stock fully fenced out of main feeder streams behind vegetated buffer zones
– Protection enforced by policed regulation
– Low level and low intensity activities may be allowed within the outer catchment but active source protection (e.g., ranger patrols) is practiced minimising contamination risk

The existing human settlement and stock animal challenges align well with category 1 source waters. Some challenges presented from itinerant human activity could be regarded as within either category. However, with the consideration of other mitigating factors, including the dilution of surface water inputs within Serpentine Pipehead Dam from groundwater and desalination inputs, the source water could be classified as a category 1 source, given the present challenges to water quality. Raw water from this source is currently treated to a level applicable for a Category 1 source

The source vulnerability assessment indicates that the classification of the source water is unlikely to change with the Proposal. The Proposal involves a move of the Huntly Mine workforce and operations from the existing Myara region to the Myara North region, both of which are predominantly within the Serpentine Main Dam PDWSA. The Proposal will result in a re-introduction of the Huntly Mine workforce and operations to the South Dandalup Dam PDWSA, which previously occurred in that PDWSA in the 1990s and 2000s. The Proposal will act to restrict itinerant public access (authorised and un-authorised) within both PDWSAs.

6.3 Western Australian guidance

The categorisation is consistent in the context of Western Australian guidance. With respect to mining in P1 PDWSAs in Western Australia, the Strategic Policy (DoW 2016a) refers to WQPN no. 25: Land use compatibility tables for PDWSAs, which '*outlines appropriate land uses and activities within PDWSAs and their priority areas, and should be referred to when making decisions about land use*'.

WQPN 25 states that mining within a P1 PDWSA but outside protection zones is compatible, subject to conditions on:

– licensing to abstract surface or groundwater
– storage of fuels and chemicals, depth of excavation, and rehabilitation criteria.
– mining within the RPZ subject to demonstration that the risk of water contamination is effectively controlled under all circumstances

Mining within a P1 PDWSA and inside a protection zones is classified as incompatible, however applicants can apply for special consideration and will be required to:

– demonstrate that alternative locations for the land use have been considered
– site specific information about the land uses and activities is provided; and
– a risk assessment is undertaken in accordance with ADWG.

The DWSPPs for the three PDWSAs states that the acceptability of mining is subject to more specific conditions related to mining and rehabilitation, for example:

– “[Bauxite mining is] acceptable if operated in compliance with conditions imposed by [Mining Management Program Liaison Group] MMPLG.
– Ensure the conditions imposed by the MMPLG specifically pertaining to water quality protection are adhered to.
– Ensure Alcoa continues to manage water protection in accordance with their Environmental Management Manual (updated bi-annually).
– Ensure Alcoa operates according to the “Working Arrangements between Alcoa World Alumina – Australia, the Water and Rivers Commission and the Water Corporation Covering Alcoa’s Mining Operations in the Darling Range”.
– Ensure Alcoa’s monitoring program continues.”

The State Government policies indicate that mining in P1 PDWSAs is conditionally acceptable, with key conditions being demonstrated satisfactory management of impacts, and demonstrated effective control of risks within the RPZ ‘*under all circumstances*’.

Table 6.2 Source categorisation – Serpentine Main Dam

Land use challenge	Existing land use			Existing land use plus Proposal		
	Intensity	Proximity	Protection	Intensity	Proximity	Protection
Permanent human	Single residence – Serpentine Main Dam caretaker.	Caretaker residence within RPZ ~ 250 m from reservoir.	n/a	No change	No change.	No change.
	No living-in accommodation (LIA) for mining and forest industries workforce. All workforce drive in-drive out.	n/a	n/a	No change. No LIA proposed for Myara North construction or operations workforce.	n/a	n/a
	No other settlements within PDWSA.	n/a	PDWSA classification restricts urban and residential development.	No change.	n/a	n/a
Itinerant human	Myara mine facilities include STP and effluent disposal. Myara mine demountable ablutions block with septage pump out and tankering off-site, no on-site disposal. Myara mine mobile workforce for construction, mining, ore haulage and rehabilitation.	Myara mine facilities STP and mobile ablutions block located outside RPZ. Myara mine mobile workforce operate throughout PDWSA, including RPZ subject to Water Corporation Working Arrangements.	STP effluent disposal via above ground irrigation, located away from creekline. Demountable ablutions block serviced by bunded pump out tank, zero on-site discharge. Bushland inner and outer catchment. Large water supply reservoir (capacity > 1 GL and annual throughflow).	No change Mine workforce will remain similar size to existing, moving from Myara region to Myara North region. Myara North mine facilities STP will accept similar loading as existing Myara facilities STP. Myara North demountable ablutions block will accept similar loading to existing Myara mobile ablutions block.	No change Myara North mine facilities STP and mobile ablutions block will be located outside RPZ.	No change.
	Recreational public use of Serpentine Main Dam facilities, Munda Biddi Trail, Bibbulmun Track, Balmoral Track, POW camp. Composting toilets at Serpentine Main Dam recreational area,	Munda Biddi Trail, Bibbulmun Track, Balmoral Track, POW camp outside of RPZ. Serpentine Main Dam facilities within RPZ of	Public access restricted within RPZ, apart from Serpentine Main Dam facilities and café. Camping not permitted within RPZ.	No change	Public access excluded from Myara North region during construction, operations and rehabilitation, including RPZ.	Public access restricted within Myara North region, via locked gates on current access points from public roads. Surveillance from mine workforce

Land use challenge	Existing land use			Existing land use plus Proposal		
	Intensity	Proximity	Protection	Intensity	Proximity	Protection
	POW camp, Bibbulmun track campsites. Serpentine Main Dam café includes on-site sewage treatment plant (STP) and effluent disposal. DBCA and FPC mobile workforce for timber harvesting, prescribed burns and fire response. Apiary operators at designated apiary sites. Un-authorised public access for recreation.	Serpentine Main Dam or Pipehead Dam. Serpentine Main Dam café STP within RPZ of Serpentine Main Dam or Pipehead Dam. DBCA and FPC operations through PDWSA including within RPZ subject to Water Corporation approval. Un-authorised public access may occur throughout PDWSA.	Signage, locked gates and ranger patrols within RPZ. Water Corporation undertakes surveillance throughout PDWSA and particularly RPZ. Bushland inner and outer catchment. Large water supply reservoir (capacity > 1 GL and annual throughflow).			operating in Myara North region. Reduced authorised and un-authorised recreational activity in Myara North portion of PDWSA.
Stock animals	No stock animals within PDWSA. Feral pigs occur within PDWSA and pose a risk of pathogen spread.	n/a	Water Corporation rangers and licensed hunters undertake hunting and trapping of feral pigs.	No change	n/a	n/a

Table 6.3 Source categorisation – South Dandalup Dam

Land use challenge	Existing land use			Existing land use plus Proposal		
	Intensity	Proximity	Protection	Intensity	Proximity	Protection
Permanent human	No living-in accommodation (LIA) for forest industries workforce. All workforce drive in-drive out.	n/a	n/a	No change. No LIA proposed for Holyoake construction or operations workforce.	n/a	n/a
	No settlements within PDWSA.	n/a	PDWSA classification restricts urban and residential development.	No change.	n/a	n/a
Itinerant human	No current mine facilities or mining workforce within PDWSA. Holyoake region mobile workforce for exploration. Past Huntly region (1990s) and White region (2000s) mobile workforce for construction, mining, ore haulage and rehabilitation.	n/a	n/a	Holyoake mine facilities will include STP and effluent disposal. Holyoake mine demountable ablutions block with septage pump out and tankering off-site, no on-site disposal. Holyoake mine mobile workforce for construction, mining, ore haulage and rehabilitation.	Holyoake mine facilities STP and mobile ablutions block will be located outside RPZ. Holyoake mine mobile workforce will operate in PDWSA outside of RPZ.	STP effluent disposal will be via above ground irrigation, located away from creekline. Demountable ablutions block will be serviced by bunded pump out tank, zero on-site discharge. Bushland inner and outer catchment. Large water supply reservoir (capacity > 1 GL and annual throughflow).
	Recreational public use of South Dandalup Dam facilities, Bibbulmun Track. Composting toilets at Bibbulmun track campsites. DBCA and FPC mobile workforce for timber harvesting, prescribed burns and fire response. Apiary operators at designated apiary sites. Un-authorised public access for recreation.	Bibbulmun Track and campsite outside of RPZ. South Dandalup Dam facilities within RPZ, toilets located outside of PDWSA. DBCA and FPC operations within RPZ subject to Water Corporation approval.	Recreation restricted within PDWSA, apart from Bibbulmun Track and South Dandalup Dam facilities. Signage, locked gates and ranger patrols within RPZ. Water Corporation undertakes surveillance throughout PDWSA and particularly RPZ.	No change	Public access excluded from Holyoake region during construction, operations and rehabilitation.	Public access restricted within Holyoake region, via locked gates on current access points from public roads. Surveillance from mine workforce operating in Holyoake region. Reduced authorised and un-authorised recreational activity in

Land use challenge	Existing land use			Existing land use plus Proposal		
	Intensity	Proximity	Protection	Intensity	Proximity	Protection
		Un-authorised public access may occur throughout PDWSA.	Bushland inner and outer catchment. Large water supply reservoir (capacity > 1 GL and annual throughflow).			Holyoake portion of PDWSA.
Stock animals	No stock animals within PDWSA. Feral pigs occur within PDWSA and pose a risk of pathogen spread.	n/a	Water Corporation rangers and licensed hunters undertake hunting and trapping of feral pigs.	No change	n/a	n/a

6.4 Source vulnerability assessment verification

A verification of the source vulnerability assessment was undertaken, based on the Baker et al. (2016) standardised survey method, along with a review of likely pathogen travel times from mining areas. This method is in essence a sanitary survey, with a greater level of detail than is described in high-level methods such as described in WSAA (2015). As a sanitary survey is an integral part of a source vulnerability assessment, this is a supplement to and verification of the high-level survey described in section 6.1, and supports the source vulnerability assessment required in the ESD work item 50.

Baker et al (2016) describes a systematic methodology to identify microbial risk sources in catchment areas, and to assign risk scores to those sites, based on the likelihood of the site affecting catchment water quality and of the potential consequences. *Escherichia coli* (*E coli)* and protozoan pathogens are included in the assessment as indices of chlorine sensitive and chlorine resistant microorganisms, respectively. The likelihood of faecal contamination entering the waterway at a given location is determined (usually from collected field data, but in this case from the catchment assessment) by evaluating the generation of contaminants and the potential connectivity with catchment waterways and mitigated by the factors which can moderate or prevent contamination from entering the waterways. The method then adopts consequence scores, which are approximately equivalent to the $logarithmic_{10}$ load of the organism generated per day based on literature values. The methodology has been used extensively in Queensland and Victorian water sources, to identify the relative risks of contamination sources within catchment areas, and to allow the prioritisation of management actions to locations presenting the greatest risks to water quality.

This methodology has been applied here so as to assess the relative risks of contamination sources associated with mining activities. Mining involves two distinct microbial risk areas, these being:

– Sewage treatment systems and treated effluent irrigation within the mine facilities area; and
– Mobile work teams in construction, mining and rehabilitation

Worst-case and normal conditions for each of these microbial risk areas have been reviewed with respect to the Baker et al. (2016) methodology, and the likelihood, consequence and risk rating from each system is provided in Table 6.4.

6.4.1 Sewage treatment systems and irrigation

The proposed mine facilities are located at the centroid of the Myara North and Holyoake regions, outside the RPZ of the Serpentine Main Dam and SDD PDWSAs, and it is assumed that the treated effluent irrigation area will be located at a high point within the facilities areas, and located at a minimum 500 m away from the nearest watercourse. The average slope from this high point to each of the nearest watercourses is 1-6 per cent. It is further assumed that the wastewater treatment system will include secondary treatment, chlorination, and UV disinfection; and designed to be compatible with:

– Water quality protection note 22 Irrigation with nutrient-rich wastewater (DoW, 2010)
– Water quality protection note 33 Nutrient and irrigation management plans (DoW, 2016)
– *Government sewerage policy* (DPLH, 2019)

The Huntly mine operations have a total workforce of approximately 230, comprising 135 during the day shift and 95 during the night shift, with a total equivalent persons of approximately 50-100 (depending on whether showers are used). Assuming that the mine facilities Sewage Treatment Plant (STP) treats sewage from the entire workforce, the STP would be considered a "decentralised system" under the Baker et al. (2016) definitions of on-site systems. The worst-case condition for this treatment system is a hydraulic failure (i.e. overflow of treated wastewater).

There will also be a demountable ablution block for workers located closer to mining areas, but still outside the RPZ. This will have an on-site system with no effluent irrigation, whereby effluent is pumped out and removed from the catchment. This treatment facility is assumed to be an "on-site system" (10 EP or less) for the purpose of this assessment. The location of this system is unknown at this stage, so the slope from the system is conservatively assumed to be steep, and located at least >100 m away from the nearest water course.

Based on the above information and assumptions, residual risks relating to normal operations of the sewage systems were determined to be low. The worst-case hydraulic failure scenario without downstream mitigation in place resulted in a moderate[2] microbial risk rating.

6.4.2 Mobile work teams

At a worst case, the mobile mining and rehabilitation workforce may comprise up to 20 staff in a subcatchment area at any one time (J. White, Alcoa, pers. comm.). These workers have been treated as "passive recreators" (i.e. no water contact) under the Baker et al. (2016) designations of likelihood. The "medium recreator numbers (100 individuals)" designation has been adopted to assign a consequence rating for these workers. Workers within these areas will have access to toilet facilities which will be located at a demountable ablution block and at the mine facilities, and will also be educated on the significance of the PDWSA and their responsibilities in this regard. Nonetheless, it is conservatively assumed that workers in these areas will not have access to toilet facilities.

The residual microbial risk rating from workers on-site is low.

A cumulative risk rating has not been undertaken at this stage, as a field-based sanitary survey of the entire catchment would be required to inform such an assessment.

6.4.3 Summary

Given the worst-case outcomes from this assessment produced either medium or low results, -this assessment is considered in line with the outcomes of the vulnerability assessment and source categorisation in Section 6.2.

While it is acknowledged that downstream treatment should not be relied upon to ensure high quality drinking water, the expected log reduction values of chlorine disinfection are shown in Table 6.5 to highlight that chlorine disinfection at the dam water treatment plants can remove some bacteria and viruses, but does not remove any protozoa. Therefore, the need to control pathogenic risks at the source (i.e. at the proposed STP and irrigation systems) through multiple barriers is critical to protecting water source quality.

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[2] It is noted that as the Baker et al 2016 methodology is typically based on field surveys, the likelihood classifications are based on actual site conditions, such that the likelihood adopted for the worst-case scenario would be the likelihood of microbial contaminants reaching the waterway **after** a hydraulic failure has occurred, without accounting for the likelihood of the hydraulic failure occurring in the first place. This is considered inappropriate for this assessment as the actual likelihood of a failure occurring needs to be considered. As such, the ADWG likelihood classifications have been referred for this scenario, as discussed in Table 6.4.

Table 6.4 ***Microbial risk assessment (Baker, Ferguson, Chier, Warnecke, & Watkinson, 2016)***

Primary hazard	Scenario	Secondary hazard	Likelihood	Consequence			Attenuation			Attenuated score		Risk rating
				Source	E coli score	Protozoa score	Measure(s)	E coli score	Protozoa score	E coli	Protozoa	
Treated effluent irrigation	Worst-case hydraulic failure, no on-site treatment (no mitigation)	Hydraulic failure* Moderate slope** Watercourse >100m	Unlikely***	Decentralised system (~100 EP)	9	5	Buffer zone of 50m or more in land irrigation area	-1	-1	8	4	Medium***
	Normal operations	Normal function Moderate slope** Watercourse >100m	Unlikely		9	5	Buffer zone of 50m or more in land irrigation area Land irrigation of effluent by surface irrigation Secondary treatment Chlorinated UV disinfection	-9	-4	0	1	Low
On-site system	Worst-case hydraulic failure (no mitigation)	Hydraulic failure* Steep slope** Watercourse >100m	Unlikely***	On-site system (10 EP or less)	8	4	None (treatment failure)	0	0	8	4	Medium***
	Normal operation	Normal function Steep slope** Watercourse >100m	Rare		8	4	No discharge (composting toilet, pump-out system, portaloo)*	-8	-5	0	-1	Low
Workers	Worst-case (no mitigation)	Passive recreation (no water contact), toilet facilities absent	Possible	Medium recreator numbers (100 individuals)	2	2	Work sites do not allow small children recreating in water	-1	-1	1	1	Low
Notes	As defined by Baker et al. 2016: *Hydraulic failure = overflow of effluent **Steep slope = greater than 10 per cent slope. A moderate slope is regarded as 5 – 10 per cent slope. ***The likelihood adopted by Baker et al. (2016) is the likelihood of microbial contaminants reaching the waterways **after** a hydraulic failure has occurred, and would therefore be "Possible" in this instance. However this measure of likelihood does not account for the likelihood of a hydraulic failure actually occurring. As such, the assessment has deferred to the ADWG classifications of likelihood in this case, in which case the likelihood of a hydraulic failure occurring is considered to be "Not impossible, but more likely not to occur than to occur", i.e. "unlikely".											

Table 6.5 Assumed Log Removal Values (LRVs) for Serpentine and South Dandalup Dam Water Treatment Plants

Process	Log reduction value (score)			Process control limits
	Protozoa	Bacteria	Virus	
Chlorine disinfection	0	4	4	Ct>15 mg/L.min with pH <8.5 (based on ADWG default). Feed water turbidity <1.0 NTU

6.4.4 Pathogen travel times

In order to further verify the low-risk outcome regarding workers within the catchment, worst-case pathogen transport times from the edge of the proposed mining pits to the nearest streams have been estimated. As streamflow generation is dominated by groundwater discharge, with direct surface run-off a lesser fraction of total flow (as discussed in Section 3.4), travel times via groundwater flow have been estimated. Only the indicative Myara North mine layout has been assessed as no equivalent indicative mine plan exists for Holyoake at this stage.

Figure 6.1 illustrates a histogram of the shortest distance from mine pits to the nearest stream as well as a histogram of the associated average slope over that distance. The majority of mine pits are more than 100 m away from the nearest stream, and have an average slope below 9 per cent. Of the 1100 pits, 10 per cent have both a distance of <200 m to the nearest stream and an average slope of >8 per cent.

The estimated travel time for water to travel via subsurface flow from the mine pit edge to the nearest water course is shown in Figure 6.2. These travel times have been calculated from Darcy's Law, under the conservative assumptions outlined in Table 6.6. Application of Darcy's Law in this instance is simplistic and conservative in that it assumes the travel pathway is a direct lateral subsurface flow (i.e. interflow) from mine pit edge to the stream, of which recent studies have indicated is likely only relevant within valley floors and immediate surrounds (beyond mine pit areas) (Grigg, 2017; Jackson, Bitew, & Du, 2014).

Table 6.6 Adopted hydrogeological parameters

	Maximum travel time	Likely average travel time	Description
Hydraulic conductivity (m/d)	2 (maximum)	0.3 (average)	Maximum and average as measured from slug testing of 14 bores within the Myara North area.
Porosity	0.1	0.1	Conservative representation of saprock, which is typically constrained to 0.1 to 0.3

The worst case and likely average travel time based on these assumptions is 12 days and 78 days from mine pit boundary to reservoir. The time required for a given level of pathogen reduction varies according to pathogen type and key process variables such as temperature, UV intensity and substrate. However, in general, several log10 orders of pathogen inactivation occur over weeks to months following pathogens entering the natural environment. The estimated travel time for subsurface flow from the pits to the nearest water course is within 60 days for around 110 pits (i.e. 10per cent of the total). This aligns with the number of pits that are both a distance of <200 m to the nearest watercourse and have an average slope of >8 per cent.

Accordingly, the likelihood of pathogens entering a waterway and subsequently entering the reservoir from subsurface flow is considered rare for the majority of mine pits, however there are over a hundred proposed pits that would require strict hygiene management to appropriately mitigate the risk of pathogens entering a nearby water course.

This review has not assessed the location of specific pits with respect to the reservoir itself, nor whether the nearest watercourses to the pits actually produce flow during normal rainfall events. Regardless, while groundwater discharge is the dominant source for streamflow, there remains the greater risk that a major rainfall event would result in overland flow and direct discharge into the reservoir and/or watercourse.

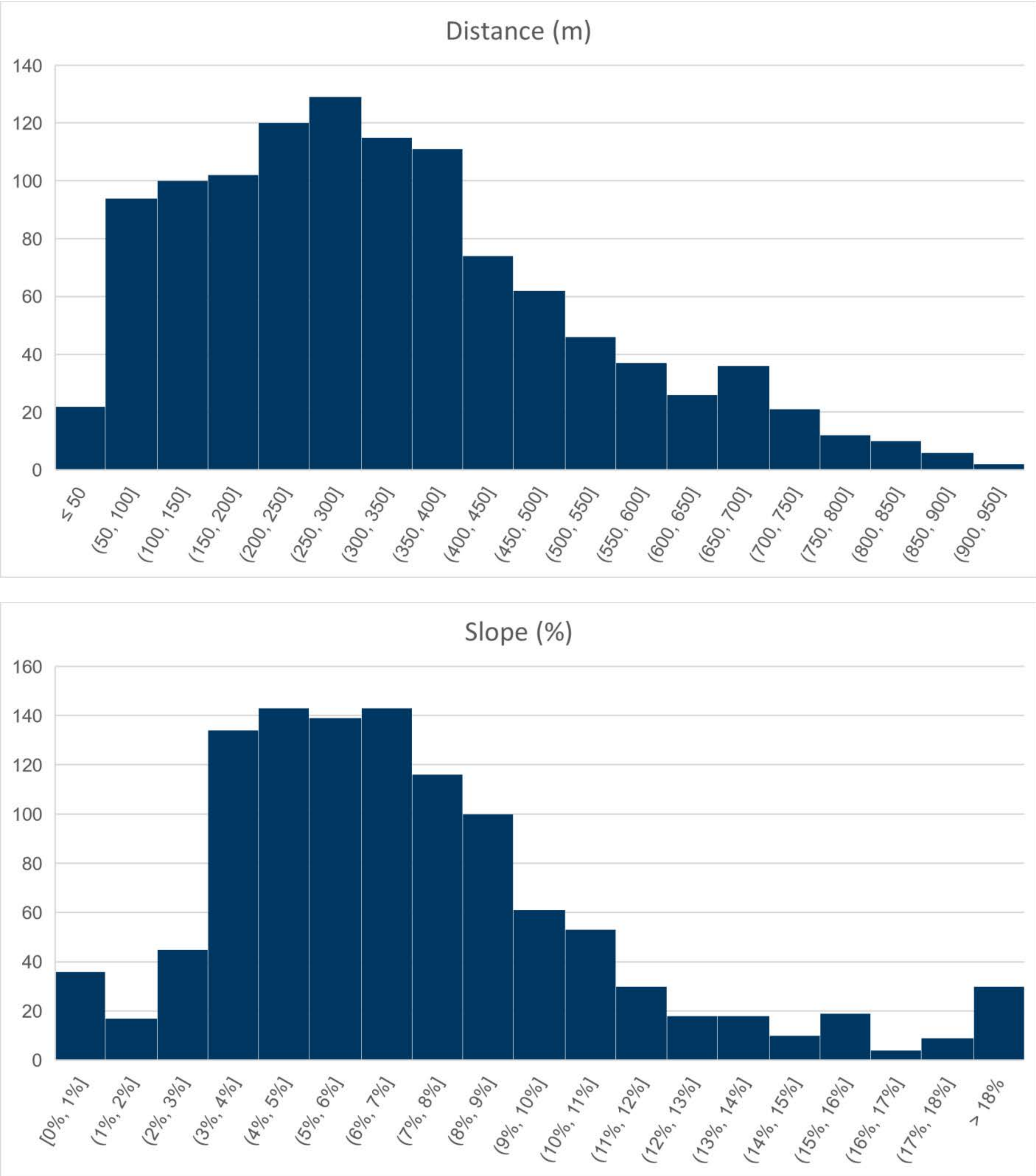

Figure 6.1 Histogram of mine pit distance and average slope from edge of pit to nearest stream

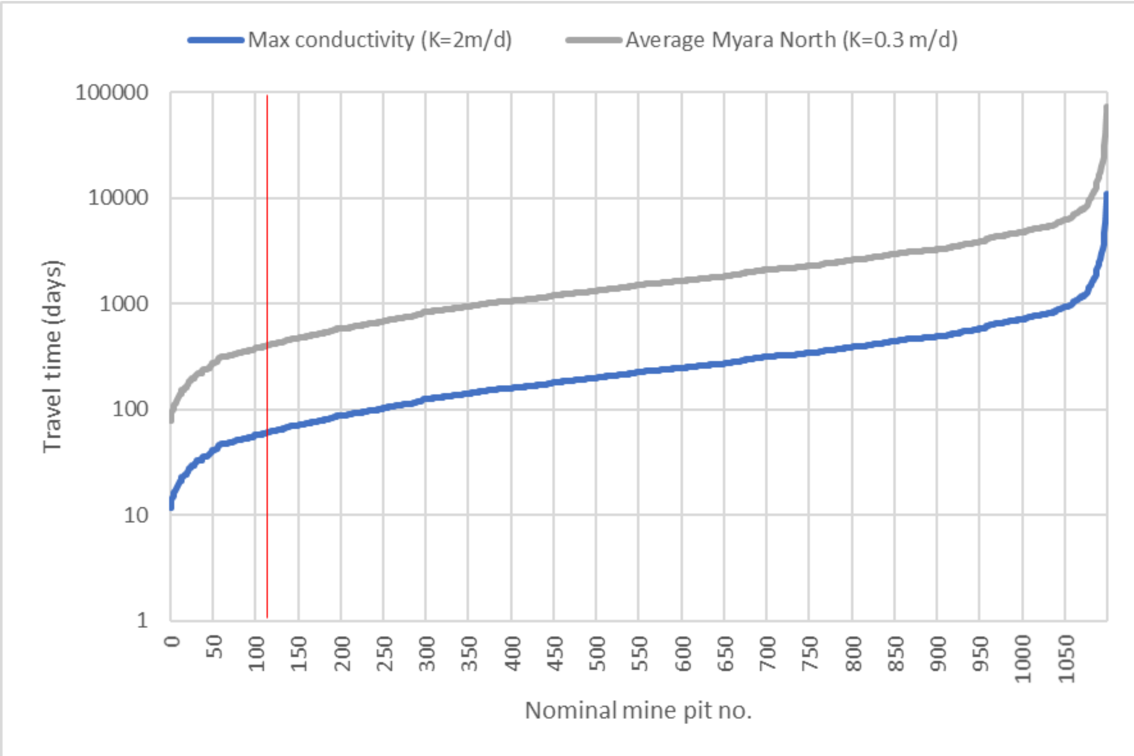

Figure 6.2 ***Distribution of travel time of groundwater from mine pit edge to nearest water course***

7. Quantitative microbial risk assessment

This section describes a quantitative microbial risk assessment (QMRA), which has been conducted to estimate the impacts of pathogen inputs in the described drinking water catchment areas that potentially become entrained in the source waters for drinking water supply, The QMRA examines the concentration of a reference pathogen (*Cryptosporidium*) through to potential exposure to the local population.

Due to the number of variables involved in the calculation of a QMRA, the preferred approach has been to define simple upper limit scenarios and use these to estimate the approximate health risks for those scenarios. This is consistent with other characterisations of catchment risks using a QMRA approach, such as used by Billington et al (2011). The examined scenarios are outlined in section 7.1. These include potential events able to introduce pathogens to the catchment, and estimation of the subsequent dilution and removal by environmental effects of those pathogens, which are described in much greater detail in the hydrological modelling of the reservoirs in GHD (2021). This modelling has been performed with AEM3D, a 3D numerical model that includes hydrodynamic, thermodynamic and biogeochemical modules to simulate the temporal behaviour of stratified water bodies from environmental forcing. It was configured in this study to simulate the spatial and temporal variations of TSS, *Cryptosporidium* and hydrocarbons under various scenarios.

The general format for the QMRA is that described in the AGWR (2006) and WSAA (2015). This format allows clarity with the assumptions used, the transparent calculation of pathogen risks and of concentrations of pathogens through the exposure pathways examined, and the ready update of calculations in the event that the assumptions are subsequently updated. Where applicable, quantitative values for assumptions have been drawn from AGWR (2020).

The following considerations have been made in this QMRA:

– *Cryptosporidium* is the standard reference pathogen in the WSAA (2015) guidance for Tier 2 assessment of source waters. This reference describes the use of monitoring data for this pathogen, however in the absence of such data, literature-based assumptions have been made as to the concentration of viable and human-infective *Cryptosporidium* in contamination events. Other reference pathogens could be simultaneously examined, to represent other pathogen groups including viruses and bacteria. However, *Cryptosporidium* is resistant to chlorination, the mode of water treatment employed for this source, making it the worst-case pathogen in this situation.

– The exposure pathway by which human populations could potentially be exposed to pathogens is limited to the consumption of treated drinking water. Other pathways such as recreation in catchment waters are not considered to be likely, due to restrictions on such activities and the other practical barriers that prevent them from occurring.

– The risk of illness for exposed populations have been estimated and expressed as Disability Adjusted Life Years (DALYs). Dose response information for the reference pathogens has been drawn from AGWR (2021).

The various inputs to the QMRA are summarised in section 7.2. These inputs are drawn from literature sources, and from the reservoir modelling performed for this catchment area in GHD (2021).

The QMRA outputs are summarised in section 7.3. The outputs of the QMRA include the estimated risk of illness from exposure to *Cryptosporidium* via drinking water for the various scenarios, expressed in DALYs. As a comparative risk expressed in DALYs, the health based target for drinking water favoured by WSAA is a risk of 10^{-6} DALYs per person per annum. The scenarios have been examined by calculating the unmitigated or raw risks, and then applying applicable factors to calculate mitigated risks. The estimated mitigated risks are also summarised as QMRA outputs.

7.1 Scenarios

Four pathogen discharge hazardous events have been examined as scenarios, as expanded on in section 7.1.1. These are calculated using two different sets of assumptions, as follows:

– Direct deposition. This is the worst case, and assumes that no pathogens are removed via surface (overland) transport to the reservoir. This is effectively the same as if the contamination was directly deposited into the reservoir. The pathogen inputs by scenario are summarised in Table 7.1.
– Some removal via surface (overland) flow. This case assumes that some pathogen removal occurs during overland flow. The extent of this removal is based on specific conditions (slope, rainfall, vegetation coverage, etc), an assumed value for removal has been applied based on available overland transport literature (section 7.2.2). The pathogen inputs by scenario are summarised in Table 7.2.

Numerous citations have been made in the scenario descriptions. Further discussion about the cited literature has been included in section 7.2.

In particular, assumptions have been made about the amount of pathogen removal during surface (overland) and sub-surface transport, and from additional mitigation measures. The literature on which these assumptions have been based is very briefly described in the footnotes of Table 7.1 and Table 7.2. The amount of removal that can be expected in practice will vary depending on local conditions, such as terrain slope, rainfall intensity and duration, vegetation cover, the presence of gullies and other channels, and distance between the hazard and the reservoir. Consequently, the assumed removals are general, and may need to be changed when examining specific situations.

The transport assumptions are removed in the worst case (direct deposition) scenario set, so as to allow the effect of the transport assumptions to be clearly identified. Some attenuation via transport will occur with all of the described hazards, and should be included in the assessment of those hazards.

Where specific considerations have been made in the modelling (GHD, 2021), these are summarised in section 7.1.2. These include sub-catchment locations where the hazard is introduced.

7.1.1 Scenario descriptions

Hazard 1

A raw sewage overflow event located within a STP within the catchment area, during wet catchment conditions with heavy rainfall. An overflow could result from an undersized effluent storage, inadequate maintenance of the storage, blockage within the system, infiltration of rainwater flows into the storage, leakage of the storage, and/or other circumstances resulting in storage failure. As a worst case event, the overflow has been assumed to have a small distance of surface (overland) transport before being transported via steep gullies or ephemeral waterways into the reservoir or its tributaries. A conservative attenuation of 2 logs of pathogen load has been assumed for the worst case scenario. This assumes a 10 per cent mobilization rate, (i.e. transported via flow from rainfall) as estimated for manure in connected source areas (Billington, 2010), with an additional 1 log removal from overland transport across bare soil from the overflow to the gully (a minimal removal estimate from overland transport studies - Tate et al 2000; Atwill et al 2002; Davies et al 2003; Trask et al 2004; Ferguson et al 2007).

Hazard 2

Treated effluent accumulates at the surface of a designated irrigation area, and is subsequently washed out by heavy rainfall. Accumulation of effluent could result from improper irrigation practices, irrigation equipment breakages, blockages or other maintenance failure, poor siting of irrigation areas, and/or other circumstances resulting in irrigation area failure. As per Hazard 1, a worst case event assumes only a small distance of surface (overland) transport prior to flow into a steep gully and then into a creek or reservoir. Also as with Hazard 1, the worst case assumes 2 logs of attenuation from mobilization and minimal removal from bare soil prior to unimpeded flow.

Hazard 3

Treated effluent leaches into a subsurface perched aquifer during a period when rainfall exceeds evapotranspiration, flows to a steep creek or a downstream seepage face over tens of metres, and then in the reservoir or a creek. Subsurface flows to a waterway could result from poor siting or under sizing of irrigation areas, irrigation area failures, flow volumes elevated by rainfall beyond the receiving capacity of an irrigation area, and/or other circumstances of greatly increased input flows. A greater degree of attenuation (4 logs) has been assumed than with Hazards 1 and 2, due to the greater potential for removal during surface (overland) flow and from subsurface flows over greater distances than assumed for Hazards 1 and 2, and is similarly based on the literature values for expected *Cryptosporidium* removal during those processes (as cited for Hazards 1 and 2, as well as Atwill et al (2002), where the effects of overland and shallow sub-surface flows on Cryptosporidium transport are described).

Hazard 4

An asymptomatic staff member with cryptosporidiosis defecates in bushland in the catchment area, shortly before a heavy rainfall event. This could result from uncontrolled access by staff to sensitive catchment areas (particularly near gully lines and riparian zones), where staff are unaware of the potential consequences of such actions, where ablution block access is difficult for field staff, where contingencies for staff toilet access needs have not been otherwise made, and/or other circumstances enabling this hazard to occur are present. As a worst case event, the faecal material is deposited in a gully or a riparian zone and is highly mobilized during the rainfall event, and 10 per cent of the material is transported into the reservoir or a creek, as a minimal attenuation value drawn from the surface (overland) transport literature previously cited for Hazard 1. This 10 per cent attenuation value is drawn from the manure mobilization estimate used by Billington (2011).

Additional scenario notes

Hazards 2 and 3 have potential to occur on a seasonal basis and will be modelled to occur concurrently, and also in combination with either Hazard 1 or Hazard 4. As a conservative assumption, pathogen concentrations have been modelled during a 1 EY storm scenario, which is more frequent and provides less dilution.

Table 7.1 Pathogen discharge, unmitigated hazards, no removal via overland flow

Hazard	Source	Pathway	Receptor	Duration
1: STP raw sewage overflow	Raw sewage overflow at some point in STP 18 m^3/day sewage @ 2,000 oocysts/L[3] = 36 million oocysts/day	Overflow occurs during wet catchment conditions and heavy rainfall No attenuation via overland flow i.e. direct deposition into reservoir assumed	36,000,000 oocysts/day discharge into creek Direct deposition into reservoir	Two days overflow[4]
2: STP effluent irrigation area washout	Treated effluent accumulates at surface of irrigation area during wet catchment conditions 18m^3/day treated sewage @ 200 oocysts/L[5] = 3.6 million oocysts/day Sustained heavy rainfall causes wash out of accumulated oocysts ~ ten times daily deposition = 36 million oocysts/day	Washout occurs during wet catchment conditions and heavy rainfall No attenuation via overland flow i.e. direct deposition into reservoir assumed	36,000,000 oocysts/day discharge into creek Direct deposition into reservoir	Two days heavy rainfall
3. STP effluent irrigation area subsurface flow	Treated effluent leaches into subsurface during winter/spring when rainfall exceeds evapotranspiration 18m^3/day treated sewage @ 200 oocysts/L = 3.6 million oocysts/day	Oocysts in leachate transported by shallow perched aquifer. No attenuation via overland or subsurface flow i.e. direct deposition into reservoir assumed	3,600,000 oocysts/day discharge into creek Direct deposition into reservoir	Three months shallow seepage per year
4. Defecation in the field	Asymptomatic infected staff member defecates in the field in gully or riparian zone, in bushland adjacent to mine pit or rehabilitation area 150 g stool @ 1 million oocysts/g = 150 million oocysts[6]	Stool present/remaining in riparian zone or gully near reservoir, wet catchment conditions during heavy rainfall event Assumed 100 per cent is washed into reservoir, no attenuation i.e. direct deposition into reservoir assumed.	150,000,000 oocysts discharge into creek Creek flowing into reservoir	Two days heavy rainfall

[3] Pathogen concentrations in faecal material can vary over a wide range. Analysis from two Australian sewerage schemes have been used to form default values in determining sewage treatment performance targets (AGWR 2006 and 2020, using unpublished data from SA Department of Health and Melbourne Water), which are consistent with international data. The default concentration of 2000 *Cryptosporidium* oocysts per litre is the 95th percentile concentration from these data, and has been used here as the pathogen concentration estimate for sewage inputs in this QMRA.

[4] Two days is a reasonable period for a 24 hr/day manned site to notice a continuous noxious discharge and arrange for emergency tinkering.

[5] AGWR (2006) cites an indicative removal of 0.5-1.0 logs of Cryptosporidium from secondary treatment. A 1-log removal applied to the default concentration results in an estimated concentration of 200 oocysts/L.

[6] Chappell et al, as reported in WHO 2006, describe humans at the peak of infection as shedding up to 10^{5-7} oocysts per gram of faeces. The higher shedding rates can be expected to be associated with symptomatic infection; the mid-range concentration of 10^6 oocysts/g has been used as a conservative estimate for shedding from an asymptomatic case. Feachem et al (1983) reported that the rate of excretion of faeces is 100-200 g/day. The mid-point of this range (150 g/day) has been applied to the QMRA as an assumed rate.

Table 7.2 Pathogen discharge, unmitigated hazards, some removal via overland flow

Hazard	Source	Pathway [7]	Receptor	Duration
1: STP raw sewage overflow	Raw sewage overflow at some point in STP 18 m^3/day sewage @ 2,000 oocysts/L[8] = 36 million oocysts/day	Overflow occurs during wet catchment conditions and heavy rainfall Transport via overland flow and shallow channel flow ~ several hundred metres of gullies with ephemeral storm flow, in Jarrah forest @ 5-10 per cent slope Attenuation ~2 $\log_{10}$	360,000 oocysts/day discharge into creek Creek flowing into reservoir	Two days overflow[9]
2: STP effluent irrigation area washout	Treated effluent accumulates at surface of irrigation area during wet catchment conditions 18m^3/day treated sewage @ 200 oocysts/L[10] = 3.6 million oocysts/day Sustained heavy rainfall causes wash out of accumulated oocysts ~ ten times daily deposition = 36 million oocysts/day	Washout occurs during wet catchment conditions and heavy rainfall Transport via overland flow and shallow channel flow ~ several hundred metres of gullies with ephemeral storm flow, in Jarrah forest @ 5-10 per cent slope Attenuation ~2 $\log_{10}$	360,000 oocysts/day discharge into creek Creek flowing into reservoir	Two days heavy rainfall
3. STP effluent irrigation area subsurface flow	Treated effluent leaches into subsurface during winter/spring when rainfall exceeds evapotranspiration 18m^3/day treated sewage @ 200 oocysts/L = 3.6 million oocysts/day	Oocysts in leachate transported by shallow perched aquifer ~ several tens of metres to creek or downslope seepage face Attenuation ~ 4 $\log_{10}$	360 oocysts/day discharge into creek Creek flowing into reservoir	Three months shallow seepage per year
4. Defecation in the field	Asymptomatic infected staff member defecates in the field in gully or riparian zone, in bushland adjacent to mine pit or rehabilitation area 150 g stool @ 1 million oocysts/g = 150 million oocysts[11]	Stool present/remaining in riparian zone or gully near reservoir, wet catchment conditions during heavy rainfall event Approximately 10 per cent is washed out and transported via overland flow and shallow channel flow ~ minimal distance over Jarrah forest @ 5-10 per cent slope	15,000,000 oocysts discharge into creek Creek flowing into reservoir	Two days heavy rainfall

[7] Water Futures (2011), Table 3-4, baseline manure mobilization rates. 10 per cent assumption for manure deposited within connected source areas. 1 per cent assumption of mobilization from land in the absence of riparian fencing and vegetation cover. Additional removal (to 4-log) assumed from subsurface transport of leachate

[8] Pathogen concentrations in faecal material can vary over a wide range. Analysis from two Australian sewerage schemes have been used to form default values in determining sewage treatment performance targets (AGWR 2006 and 2020, using unpublished data from SA Department of Health and Melbourne Water), which are consistent with international data. The default concentration of 2000 *Cryptosporidium* oocysts per litre is the 95th percentile concentration from these data, and has been used here as the pathogen concentration estimate for sewage inputs in this QMRA.

[9] Two days is a reasonable period for a 24 hr/day manned site to notice a continuous noxious discharge and arrange for emergency tinkering.

[10] AGWR (2006) cites an indicative removal of 0.5-1.0 logs of Cryptosporidium from secondary treatment. A 1-log removal applied to the default concentration results in an estimated concentration of 200 oocysts/L.

[11] Chappell et al, as reported in WHO 2006, describe humans at the peak of infection as shedding up to 10^{5-7} oocysts per gram of faeces. The higher shedding rates can be expected to be associated with symptomatic infection; the mid-range concentration of 10^6 oocysts/g has been used as a conservative estimate for shedding from an asymptomatic case. Feachem et al (1983) reported that the rate of excretion of faeces is 100-200 g/day. The mid-point of this range (150 g/day) has been applied to the QMRA as an assumed rate.

7.1.2 Catchment-specific considerations in the modelling

Serpentine Main Dam

The modelling (GHD, 2021) has been performed assuming that the described hazard is presented in particular catchment areas. These are tabulated in Table 7.3 (reproduced from Table 8: Pathogen hazard locations, in GHD 2021). The noted catchment areas are the worst case locations for contamination to occur within the overall larger catchment, being the closest to the off-take points, and are further described in GHD (2021).

Table 7.3 Pathogen hazard locations

Hazard	Serpentine Main Dam, Existing Location	Serpentine Main Dam, Proposed Locations
1: STP raw sewage overflow	Catchment 13	Catchment 5
2: STP effluent irrigation area washout	Catchment 13	Catchment 5
3. STP effluent irrigation area subsurface flow	Catchment 13	Catchment 5
4. Defecation in the field	Catchments 16 (4A), 10 (4B), 9 (4C) Reference: Catchment 1 (4D, Dam recreation area)	Catchments 3 (4A), 5 (4B), 7 (4C) Reference: Catchment 1 (4D, Dam recreation area)
Hazard	**South Dandalup, Proposed Locations**	**Serpentine Pipehead Dam, Proposed Location(s)**
1: STP raw sewage overflow	Catchment 35	N/A
2: STP effluent irrigation area washout	Catchment 35	N/A
3. STP effluent irrigation area subsurface flow	Catchment 35	N/A
4. Defecation in the field	Catchments 35 (4A), 34 (4B), 33 (4C) Reference: Catchment 30 (4D, Dam recreation area)	Catchments 23 (4A), 24 (4B) Reference: Catchment 20 (4D, not a mining area)

Notes:

The “Existing locations” are the locations of existing activities which could lead to the described hazards.

The “Proposed location(s) are where the proposed activities could lead to the described hazards.

Hazard 4 has been examined as 4 variants of the same scenario (i.e. Hazards 4A, 4B, 4C and 4D), based on the effect should the hazard be presented in different parts of the catchment. Hazard 4D has been modelled as a hazard from dam recreation areas, as it is not sourced from proposed or existing mining activities it has not been examined further in this QMRA.

Frequency of hazards: Hazard 1 has been assumed as occurring once within a two year period (i.e. 0.5 events per year). The other hazards have all been assumed as occurring twice per year (i.e. 2 events per year).

7.2 QMRA inputs

7.2.1 Pathogen sources

The sources of pathogens examined here include leakage of raw or partially-treated sewage from sewerage infrastructure, and from human faeces deposited in the catchment area during itinerant human activity.

Pathogen concentrations in faecal material can vary over a wide range. Analysis from two Australian sewerage schemes have been used to form default values in determining sewage treatment performance targets (AGWR 2006 and 2020, using unpublished data from SA Department of Health and Melbourne Water), which are consistent with international data. The default concentration of 2000 *Cryptosporidium* oocysts per litre is the 95th

percentile concentration from these data, and has been used here as the pathogen concentration estimate for sewage inputs in this QMRA.

The AGWR (2006) cites an indicative removal of 0.5-1.0 logs of *Cryptosporidium* from secondary treatment. A 1-log removal applied to the default concentration results in an estimated concentration of 200 oocysts/L, for pathogen sources where secondary treatment of sewage has occurred.

Cryptosporidium oocysts can be found in high numbers in the faeces of a host. Chappell et al, as reported in WHO 2006, describe humans at the peak of infection as shedding up to 10^{5-7} oocysts per gram of faeces. The higher shedding rates can be expected to be associated with symptomatic infection; the mid-range concentration of 10^6 oocysts/g has been used as a conservative estimate for shedding from an asymptomatic case. Feachem et al (1983) reported that the rate of excretion of faeces is 100-200 g/day. The mid-point of this range (150 g/day) has been applied to the QMRA as an assumed rate.

7.2.2 Overland and subsurface transport

The surface (overland) transport of *Cryptosporidium* oocysts sourced from cattle faeces has examined at some length in the literature. No literature containing experimental data examined the overland transport rates of *Cryptosporidium* from sewage or human faeces has been identified, so the available cattle data has been utilised here.

Billington et al (2011) reviewed catchment factors that affect the transport of *Cryptosporidium* oocysts to waterways, such as vegetation cover, slope type and depth, antecedent rainfall, rainfall intensity and location, and transport distance. These authors cited Ferguson (2005) in forming an estimate of *Cryptosporidium* mobilisation and overland transport under two sets of conditions, as follows:

– *Cryptosporidium* mobilisation of 1 per cent, from land in the absence of riparian fencing and vegetation cover.
– *Cryptosporidium* mobilisation of 0.002 per cent, from land with riparian fencing with >5 m setback and good vegetation cover.

Ferguson et al (2007) seeded artificial bovine pats with *Cryptosporidium* and other reference organisms, placed them on soil plots, and subjected them to artificial rainfall events of 55 mm/h for 30 minutes. The plots were divided into bare soil and natural vegetation, and the pats were tested as "fresh" pats and one-week "aged" pats. Transportation efficiency increased with decreasing size of the organism studied, so *Cryptosporidium* as the largest of the reference pathogens was the least transportable. Rainfall events mobilised 0.5-0.9 per cent of the seeded oocysts from the fresh pats, and transported them a distance of 10 m across the bare soil plots. Subsequent rainfall events applied to aged pats mobilised 0.01-0.06 per cent of the seeded oocysts. On the vegetated test plots, *Cryptosporidium* concentrations were less than half the concentrations of the bare soil plots, indicating a slower initial release of oocysts. On both bare and vegetated plots, *Cryptosporidium* showed significant reductions in mean concentrations with increasing distance transported.

Tate et al (2000), as reported in Ferguson et al (2007), simulated the release of oocysts from calf pats under storm conditions. Model pats containing $1.5x10^8$ oocysts/kg were placed on a soil plot, and subjected to intense artificial rainfall of 7.62 cm/h for 90 minutes. The overflow flow from the plot was captured and examined for *Cryptosporidium*. Approximately 1.2 per cent of the total oocysts were detected in the flow, the majority in the first 30 minutes.

Similarly, Davies et al (2003) seeded artificial pats with approximately 10^7 oocysts, placed the pats on soil plots, subjected the plots to rainfall treatments, collected the runoff, and examined the runoff for *Cryptosporidium*. Experimental variables included differing vegetation (plots that were either devoid of vegetation or with natural vegetation cover), differing degrees of slope (5° and 10°), and differing rainfall events (rainfall of either 55 mm/h for 30 minutes, or 25 mm/h for 180 minutes). Surface runoff transported from $10^{0.2}$ oocysts from vegetated loam soil (25-mm/h, 180-min event on 10° slope) to up to $10^{4.5}$ oocysts from unvegetated soil (55-mm/h, 30-min event on 10° slope) over a 1-m distance. In the worst described case, approximately 0.3 per cent of oocysts were transported overland for a one metre distance.

Atwill et al (2002) examined the efficacy of vegetated buffer strips at *Cryptosporidium* removal from surface and shallow sub-surface flows, during simulated rainfall rates of 15 or 40 mm/h for 4 h. Log reductions of spiked *Cryptosporidium* oocysts ranged from 1.0 to 3.1 per metre of vegetated buffer, with slope, amount of vegetation cover and soil texture and density examined as different treatments. The authors concluded that a vegetated buffer strip of a length of at least 3 m, at a slope of <20 per cent, should remove at least 3 logs of oocysts from agricultural runoff generated during events involving mild to moderate precipitation.

Trask et al (2004) examined the effects of slope, vegetation and rainfall intensities on oocyst transport in a tilting soil chamber. Slopes of up to 4.5 per cent, vegetation of bare ground or brome vegetation, and simulated rainfall intensities of 25.4 mm/h and 63.5 mm/h for 44 min were examined. Total recoveries of seeded oocysts in the overland flow (i.e. the proportion transported across the chamber) varied between 0.6 and 59 per cent.

7.2.3 Waterborne transport

The hydrology of the Serpentine Main Dam, Serpentine Pipehead Dam and South Dandalup reservoirs has been modelled in GHD (2021). The calculation of the *Cryptosporidium* dilution during waterborne transport through these reservoirs was the key objective of this modelling, and was expressed as the pathogen concentration (oocysts/L) in outflows from each reservoir, as an annual average so as to allow the calculation of annualised risks. This estimate includes losses due to sedimentation during retention within the reservoir bodies. It also includes losses from pathogen die-off, which are discussed in section 7.2.4. The calculated average pathogen concentrations in the reservoir output waters, based on the hazard inputs, are tabulated in Table 7.4. The calculated concentrations are at the output waters of the noted catchments (Serpentine Main Dam, South Dandalup Dam or Serpentine Pipehead Dam), it is noted that waters from Serpentine Main Dam are subsequently transported through and diluted within Serpentine Pipehead Dam prior to transfer to the IWSS.

Table 7.4 Reservoir outflow pathogen annual average concentrations (oocysts/L), by hazard

Hazard	Serpentine Main Dam, existing	Serpentine Main Dam, proposed	South Dandalup Dam, existing	South Dandalup Dam, proposed	Pipehead Dam, proposed
1	1.94×10^{-8}	3.16×10^{-8}	N/A	1.86×10^{-8}	N/A
2	2.90×10^{-8}	6.93×10^{-8}	N/A	3.74×10^{-8}	N/A
3	1.21×10^{-9}	2.96×10^{-9}	N/A	2.86×10^{-9}	N/A
4A	2.28×10^{-6}	2.35×10^{-6}	N/A	7.79×10^{-7}	1.01×10^{-7}
4B	1.89×10^{-6}	1.44×10^{-6}	N/A	4.02×10^{-7}	1.52×10^{-5}
4C	1.26×10^{-6}	1.46×10^{-6}	N/A	8.53×10^{-7}	N/A

Note: The South Dandalup *Cryptosporidium* concentrations are marked as Not Applicable (N/A) as there is no mining access occurring presently, with all mining being historical and considered 'fully rehabilitated'. Similarly, the Pipehead Dam scenarios do not include mining infrastructure in that catchment.

Further dilution of flows from Serpentine Main Dam occurs in Serpentine Pipehead Dam, due to desalination inputs that are introduced in this storage. This has been applied as a mitigation factor of 1 LRV, applied to the calculated unmitigated risks from the tested scenarios. This estimate of mitigation is conservative, with a greater amount of mitigation for flows into Pipehead Dam estimated in GHD (2021)

7.2.4 Pathogen die-off

Cryptosporidium survival in surface waters under environmental conditions was reviewed by Murphy (2017), who examined two studies under dark conditions at various temperatures. Pathogen survival was expressed as the number of days required for a 1-log or 2-log reduction in numbers, and was summarised as follows:

- At 5 °C, the time taken for a 2-log reduction was >200 days (Ives et al, 2007)
- At 20-25 °C, the time taken for a 1-log reduction was 38-86 days (Sidhu & Toze, 2012; Sidhu et al, 2015, Ives et al, 2007), and for a 2-log reduction was 30-45 days (Ives et al, 2007)
- At 30 °C, the time taken for a 2-log reduction was 10-11 days (Ives et al, 2007)

As noted by Murphy (2017), the environmental survival of this organism seems to be very temperature sensitive. No studies were found on *Cryptosporidium* survival when exposed to sunlight, however as this organism can be inactivated by UV disinfection, a more rapid die-off is expected under such conditions. This author concluded that more data are needed about the survival of *Cryptosporidium* under a variety of environmental conditions.

Microbial die-off can also be expressed as a mortality or decay rate per day (K_d). The time for 1-log and 2-log reductions summarised in Murphy (2017) when converted to a decay rate are as follows:

– At 5 °C, a 2-log reduction over >200 days converts to a rate of <0.015/day
– At 20-25 °C, a 1-log reduction over 38-86 days converts to a rate of ~0.025-0.07/day, and a 2-log reduction over 30-45 days converts to a rate of ~0.1-0.14/day
– At 30 °C, a 2-log reduction over 10-11 days converts to a rate of ~0.35-0.4/day

Hipsey et al (2008) describe a *Cryptosporidium* decay rate in freshwater at 20 °C of 0.03-0.08/day, citing Walker and Stedinger (1999). The average of this rate – 0.055/day – has been used to model *Cryptosporidium* die-off in this QMRA. This rate is relatively conservative when compared with the other literature values, due to the consideration of higher temperature rates (i.e. 25 °C and 30 °C conditions) in the other cited literature. Given the uncertainty and variability associated with die-off due to environmental influences, this conservatism is regarded as prudent.

The 0.055/day rate of pathogen die-off has been incorporated into the hydrodynamic modelling (GHD, 2021), and is included in the amount of dilution resulting from waterborne transport (as noted in section 7.2.3).

7.2.5 Water treatment

Existing water treatment is chlorination only. Whilst chlorination can be highly effective at inactivating bacterial and viral pathogens, it is not effective at the inactivation of protozoa such as *Cryptosporidium*. No removal of this pathogen by chlorination has been assumed in this QMRA.

7.2.6 Exposure events

As exposure is via drinking water, 365 exposure events per year have been assumed, with 1 L of drinking water consumed per day. These default values have been drawn from WSAA (2015).

7.2.7 Pathogen dose response estimates

The dose response characteristics of *Cryptosporidium* have been drawn from WSAA (2015), Table A2.3, and from ADWG (2018), Tables A.5 and A.7. Different values for DALYs per case are presented in these references (2.46×10^{-3} in WSAA (2015) Table A2.3, and 1.7×10^{-3} in ADWG (2018) Table A.7); the ADWG value is based on more recent and complete literature, and has been applied here. These are literature values that describe the probability of infection, probability of illness, the disease burden, and the proportion of the population susceptible to illness. The relevant values for this assessment have been summarised in Table 7.5.

Table 7.5 Cryptosporidium dose response characteristics

Dose response parameter	*Cryptosporidium*
Probability of infection/organism	0.2
Probability of illness/infection	0.7
DALYs per case	1.7×10^{-3}

For the proportion of population susceptible to illness, a value of 1 has been used for *Cryptosporidium* (WHO, 2011).

7.3 Results of QMRA

The calculations of the QMRA for Serpentine Main Dam as a source are presented in Table 7.6, and for South Dandalup and Serpentine Pipehead Dams in Table 7.7. The key outputs from the calculations are the (unmitigated) risk in DALYS/person/year from use of each dam as a source water (line I in the tables), and the additional LRVs that are required through mitigation to reduce the risk to the acceptable threshold of 10^{-6} DALYS/person/year.

The risks calculated in Table 7.6 and Table 7.7 are unmitigated. There are a number of applicable mitigation factors that require consideration in determination of risk from Serpentine Pipehead Dam, which is the source water used for supply. These factors are described below.

Dilution in SPD

As noted in section 3, there are substantial inputs of desalinated water to SPD, and these inputs are expected to make up an increasing proportion of total supply in the future. These inputs dilute the flows received from Serpentine Main Dam. Transit through SPD can be expected to result in some further pathogen removal, through microbial die-off and sedimentation, although these factors are relatively minor compared to the effects of dilution. A key factor in risk management is also selectivity about when water is transferred from the large storages to SPD, it is assumed that transfers would not occur during or immediately following flood events, when pathogen concentrations and turbidity could be expected to be at their most elevated. A conservative LRV of 1 has been assumed as an applicable risk mitigation factor to the calculated pathogen risks from Serpentine Main Dam flows.

Siting of infrastructure to minimize pathogen hazards

As noted in section 7.1.1, the unmitigated risks from sewerage infrastructure (hazards 1, 2 and 3) assume that the hazards are sited where overflows and leachate can be transported relatively unimpeded to surface waters through steep gullies or ephemeral waterways. Mitigation measures that impede ready transport can be applied to reduce the pathogen risks from such infrastructure, and include approaches such as the inclusion of vegetated buffer strips and porous infiltration trenches on drainage paths from the infrastructure.

The amount of removal expected from such measures will be dependent upon local circumstances. The available literature discussing *Cryptosporidium* removal during overland and sub-surface transport has been briefly summarised in section 7.2.2.

Restriction of personnel access to minimize pathogen hazards

As noted in section 7.1.1, the unmitigated risks from defecation by an infected but asymptomatic staff member (hazard 4) assumes access to and defecation in areas where flows are relatively unimpeded to surface waters through steep gullies or ephemeral waterways. Mitigation measures to restrict ready access to such areas can be applied to reduce the pathogen risks from such access, such as restricting access with fencing, ranger patrols, strict controls on personnel movements near water courses, and a policy of not accessing the catchment if gastrointestinal symptoms are suspected by staff.

As above, the amount of removal expected from such measures will depend upon local circumstances, and indicative estimates are available in the available literature.

Multiple hazards

The risk associated with multiple hazards can be calculated for the source water. In such scenarios, the calculated risks are additive, and the resulting pathogen risk can be compared with the acceptable risk threshold. The probabilities of multiple hazards occurring in combination becomes increasingly unlikely, however they become more likely in a situation where there are no or few oversight measures on activities in the catchment.

Table 7.6 *Serpentine Main Dam, calculated risks from described scenarios (based on unmitigated risks with some removal from overland flow)*

		Serpentine Main Dam												
Line	HBT Calculation Parameter	Hazard 1 Existing	Hazard 2 Existing	Hazard 3 Existing	Hazard 4A Existing	Hazard 4B Existing	Hazard 4C Existing	Hazard 1 Proposed	Hazard 2 Proposed	Hazard 3 Proposed	Hazard 4A Proposed	Hazard 4B Proposed	Hazard 4C Proposed	Calculation Notes/References
a	oocysts/L in source water	2.23E-07	3.34E-07	1.39E-08	2.62E-05	2.18E-05	1.45E-05	3.63E-07	7.97E-07	3.41E-08	2.71E-05	1.66E-05	1.68E-05	Average of simulation (GHD, 2021)
b	exposure per event (L)	1	1	1	1	1	1	1	1	1	1	1	1	1L of drinking water/person/day
c	Dose per event (orgs)	2.23E-07	3.34E-07	1.39E-08	2.62E-05	2.18E-05	1.45E-05	3.63E-07	7.97E-07	3.41E-08	2.71E-05	1.66E-05	1.68E-05	a x b
d	Number of events per year	365	365	365	365	365	365	365	365	365	365	365	365	
e	Dose per year	8.15E-05	1.22E-04	5.07E-06	9.57E-03	7.95E-03	5.28E-03	1.33E-04	2.91E-04	1.25E-05	9.89E-03	6.06E-03	6.14E-03	c x d
f	Probability of infection/organism	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	ADWG (2018), based on WHO (2016)
g	Probability of infection/year	1.63E-05	2.43E-05	1.01E-06	1.91E-03	1.59E-03	1.06E-03	2.65E-05	5.82E-05	2.49E-06	1.98E-03	1.21E-03	1.23E-03	e x f
h	Proportion of infection leading to illness	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	ADWG (2018), based on WHO (2016)
i	Probability of illness per year	1.14E-05	1.70E-05	7.10E-07	1.34E-03	1.11E-03	7.39E-04	1.86E-05	4.07E-05	1.74E-06	1.38E-03	8.48E-04	8.60E-04	g x h
j	DALYs per case	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	ADWG (2018), based on WHO (2016)
k	Proportion of population susceptible to illness	1	1	1	1	1	1	1	1	1	1	1	1	Assume 100% of population is susceptible to illness
l	Source water DALYs per person per year	1.94E-08	2.90E-08	1.21E-09	2.28E-06	1.89E-06	1.26E-06	3.16E-08	6.93E-08	2.96E-09	2.35E-06	1.44E-06	1.46E-06	i x j x k

Table 7.7 *South Dandalup Dam and Serpentine Pipehead Dam, calculated risks from described scenarios (based on unmitigated risks with some removal from overland flow)*

		South Dandalup, proposed						Pipehead, proposed		
Line	HBT Calculation Parameter	Hazard 1 Proposed	Hazard 2 Proposed	Hazard 3 Proposed	Hazard 4A Proposed	Hazard 4B Proposed	Hazard 4C Proposed	Hazard 4A Proposed	Hazard 4B Proposed	Calculation Notes/References
a	oocysts/L in source water	2.14E-07	4.31E-07	3.30E-08	8.97E-06	4.62E-06	9.82E-06	1.17E-06	1.75E-04	Average of simulation (GHD, 2021)
b	exposure per event (L)	1	1	1	1	1	1	1	1	1L of drinking water/person/day
c	Dose per event (orgs)	2.14E-07	4.31E-07	3.30E-08	8.97E-06	4.62E-06	9.82E-06	1.17E-06	1.75E-04	a x b
d	Number of events per year	365	365	365	365	365	365	365	365	
e	Dose per year	7.81E-05	1.57E-04	1.20E-05	3.27E-03	1.69E-03	3.59E-03	4.26E-04	6.40E-02	c x d
f	Probability of infection/organism	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	ADWG (2018), based on WHO (2016)
g	Probability of infection/year	1.56E-05	3.15E-05	2.41E-06	6.55E-04	3.37E-04	7.17E-04	8.52E-05	1.28E-02	e x f
h	Proportion of infection leading to illness	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	ADWG (2018), based on WHO (2016)
i	Probability of illness per year	1.09E-05	2.20E-05	1.69E-06	4.58E-04	2.36E-04	5.02E-04	5.96E-05	8.96E-03	g x h
j	DALYs per case	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	ADWG (2018), based on WHO (2016)
k	Proportion of population susceptible to illness	1	1	1	1	1	1	1	1	Assume 100% of population is susceptible to illness
l	Source water DALYs per person per year	1.86E-08	3.74E-08	2.86E-09	7.79E-07	4.02E-07	8.53E-07	1.01E-07	1.52E-05	i x j x k

Table 7.8 Summary of risk estimates from tested hazards

	Serpentine (existing) risk inputs						Serpentine (proposed) risk inputs					
Hazard	1	2	3	4A	4B	4C	1	2	3	4A	4B	4C
Unmitigated risk, direct deposition (DALYs/person/year)	1.94E-06	2.90E-06	1.21E-05	2.28E-05	1.89E-05	1.26E-05	3.16E-06	6.93E-06	2.96E-05	2.35E-05	1.44E-05	1.46E-05
Dilution in SPD (factor)	1-log	1-log	1-log	1-log	1-log	1-log	1-log	1-log	1-log	1-log	1-log	1-log
Residual risk after dilution (DALYs/person/year)	1.94E-07	2.90E-07	1.21E-06	2.28E-06	1.89E-06	1.26E-06	3.16E-07	6.93E-07	2.96E-06	2.35E-06	1.44E-06	1.46E-06
Indicative removal, overland transport (factor)	2-log	2-log	4-log	1-log	1-log	1-log	2-log	2-log	4-log	1-log	1-log	1-log
Unmitigated risk, with overland transport (DALYs/person/year)	1.94E-09	2.90E-09	1.21E-10	2.28E-07	1.89E-07	1.26E-07	3.16E-09	6.93E-09	2.96E-10	2.35E-07	1.44E-07	1.46E-07

	South Dandalup (proposed) risk inputs						Serpentine Pipehead Dam risk inputs	
Hazard	1	2	3	4A	4B	4C	4A	4B
Unmitigated risk, direct deposition (DALYs/person/year)	1.86E-06	3.74E-06	2.86E-05	7.79E-06	4.02E-06	8.53E-06	1.01E-06	1.52E-04
Dilution in SPD (factor)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Residual risk after dilution (DALYs/person/year)	1.86E-06	3.74E-06	2.86E-05	7.79E-06	4.02E-06	8.53E-06	1.01E-06	1.52E-04
Indicative removal, overland transport (factor)	2-log	2-log	4-log	1-log	1-log	1-log	1-log	1-log
Unmitigated risk, with overland transport (DALYs/person/year)	1.86E-08	3.74E-08	2.86E-09	7.79E-07	4.02E-07	8.53E-07	1.01E-07	1.52E-05

Notes: Orange shading indicates calculated risk of >10^{-6} DALYs/person/year. Blue shading indicates a calculated risk of <10^{-6} DALYs/person/year.

7.4 Discussion of QMRA results

7.4.1 Mitigation factors

As noted in section 7.3, some of the risks calculated for unmitigated hazards, and combinations of unmitigated hazards, are greater than the HBT acceptable risk threshold of 10^{-6} DALYs/person/year. Further mitigation of risks could be used to control the actual risks presented through the use of multiple barriers. The following observations are made about potential mitigation factors:

– Under the current supply arrangements to the source water of SPD, the surface water supplies make up a relatively small proportion of the overall source volume. This proportion is expected to decrease further into the future. Consequently, the 1 LRV mitigation factor for Serpentine Main Dam flow dilution in SPD should be applied for any realistic estimate of risk from this source water.
– The inclusion of mitigation factors for sewerage infrastructure is regarded as a prudent minimum requirement for any construction or operations in a drinking water catchment area. This would include measures able to prevent unimpeded flows from overflows or leachate into waterways, and the removal of hazards where practicable.
– The restriction of personnel movement in a drinking water catchment is also regarded as a sensible minimum requirement. The aim of such restrictions would be to prevent access to vulnerable locations such as riparian areas, gullies and ephemeral waterways.

7.4.2 Identified elevated risks *(unmitigated)*

As identified in Table 19, the assessed unmitigated risk for Hazard 4B in the Serpentine Pipehead Dam was elevated above the 10^{-6} DALYs/person/year threshold of acceptable risk. As an elevated risk, this hazard requires attention during detailed design, so as to define how to reduce the risk to an acceptable level.

Further to the annualized risk estimation, exposure to elevated concentrations of *Cryptosporidium* for shorter periods of time presents a risk of infection. The ADWG does not set a guideline concentration for *Cryptosporidium* in drinking water, so there is no formalized threshold of acceptability of this risk. The ADWG does note that if such a guideline were established, it would be well below one oocyst/L, and involve the testing of impractically large volumes of water.

In addition to the averaged annual concentration of Cryptosporidium resulting from the examined hazards, GHD (2021) predicted the peak concentrations of this organism resulting the hazards. For the highest risk hazards presented in the Serpentine Pipehead Dam catchment, these included concentrations of ~0.00001 oocysts/L (Hazard 4A in catchment 23), and ~0.01 oocysts/L (Hazard 4B in catchment 24). From these calculated concentrations, the latter hazard presents an unacceptable short-term high risk (unmitigated) of cryptosporidiosis, in addition to the annualized risk. This observation supports the conclusion that the mitigation of this hazard to a level of acceptable risk requires attention during detailed design.

7.4.3 Combined risks

There are many contamination hazards which have been described in section 7.1. Whilst highly conservative and unrealistic due to a very low likelihood, a combined risk can be considered of all of the mitigated Serpentine, South Dandalup and Serpentine Pipehead Dam hazards occurring simultaneously (i.e Hazards 1, 2, 3, 4A, 4B, and 4C). This can be considered for the existing hazards, which include only the Serpentine inputs due to the current absence of mining activities in South Dandalup; and compared with the proposed inputs. These risks include the assumed dilution within Serpentine Pipehead Dam of flows from Serpentine Main Dam.

– Serpentine Main Dam (existing risks) = 5.48×10^{-7} DALYs/person/year
– Serpentine Main Dam (proposed risks) = 5.36×10^{-7} DALYs/person/year
– South Dandalup Dam (proposed risks) = 2.09×10^{-6} DALYs/person/year
– Serpentine Pipehead Dam (proposed risks) = 1.53×10^{-5} DALYs/person/year
– All dams (proposed risks) = 1.80×10^{-5} DALYs/person/year

The risks from the proposed South Dandalup and Serpentine Pipehead Dam combined hazards do not meet the $1x10^{-6}$ DALYs/person/year threshold. The assumptions for this risk assessment are conservative but are reasonable given the water is used downstream for drinking water supply to Perth.

It is emphasized that this conclusion is reached when no mitigation factors have been applied. The calculated values for the individual hazards are summarised in Table 7.8.

8. Turbidity assessment

8.1 Background

Turbidity is a key water quality concern for the described catchment. While not hazardous in itself, turbidity is able to reduce the efficacy of treatment processes able to inactivate or remove pathogens. The existing water treatment for water supplied from the catchment is limited to chlorination, and does not include a mechanism to reduce turbidity concentration in the raw water supplied to the WTP.

The ADWG notes that high turbidity has been shown to shield microorganisms from the action of disinfectants. If the turbidity of a water supply exceeds 1 NTU, adequate disinfection may be more difficult to maintain, but may still be achievable. Where the water has not been previously filtered, it is desirable that turbidity be <1 NTU at the time of disinfection, dependant upon the disinfection processes being used. For chlorine-only treatment, the effectiveness of disinfection may be affected at turbidities greater than 1 NTU. Generally, the lower the turbidity of the water at the time of chlorination the more effective chlorination will be, and validation work should be undertaken to demonstrate that disinfection of water under higher turbidity conditions is effective (ADWG turbidity fact sheet, 2018).

In addition to current disinfection efficacy, there are other relevant considerations about elevated turbidity in the catchment waters:

– Should additional further treatment at the WTP be introduced in the future for risk management purposes, the most cost effective measures (UV disinfection) require consistently low turbidity in source waters for assured disinfection efficacy.
– Maintaining the turbidity of water at customer taps of <5 NTU, as per ADWG guidelines.
– The potential impacts of turbidity within the catchment areas.

8.2 Turbidity and disinfection

The regulatory requirement for source waters turbidities to be <1 NTU may have originated with US regulations dating from the 1960s. Hoff (1979) questioned the utility of turbidity as an indicator of disinfectability in US regulations, due to the lack of specificity in determining the nature of the particles in generating turbidity. This was drawn from experimental work showing that clay and aluminium phosphate-based turbidity resulted in negligible or relatively minor interference with disinfection efficiency. Alternative parameters for the measurement of interference with disinfection were recommended for future consideration, including total organic carbon or nitrogen assays to determine whether solids were of organic or inorganic origin, and the determination of chlorine demand in source waters.

Other studies where the impacts from turbidity have been examined have also described other parameters that are of greater accuracy in predicting loss of efficiency. For example, turbidity effects on coliform detection and chlorination were examined by LeChevallier et al (1981). These authors found that disinfection was negatively correlated with turbidity, and was linked to the total organic carbon that was associated with the turbidity creating a chlorine demand. The effect of reduced disinfection was measured via the masking of membrane filtered coliform counts, concluding that the magnitude of masking increased from <1 coliform/100 mL in waters of <5 NTU, compared to >1 coliform/100 mL in waters of >5 NTU.

Keegan et al (2012) have reviewed the effects of turbidity and particulates on the disinfection of different pathogen groups. Particles may be organic or inorganic, with some particles being colloids. Colloidal particles comprise a large proportion of turbidity-causing substances in water. The size, type and concentration of particles can profoundly affect turbidity. Larger particles such as clays scatter light efficiently and yield higher turbidities than equivalent concentrations of substances such as humic acids. The presence of turbidity and particles is assumed to have an effect on disinfection, although it has been demonstrated that compounds such as clays, humic acids and fulvic acids have no effect on disinfection. Particulate matter may interfere with disinfection resulting in a tailing effect on an inactivation curve, whether by acting chemically to create a disinfectant demand, or by physically shielding an organism from the disinfectant. It is also thought that smaller organisms such as viruses may gain greater protection than larger organisms at lower turbidity conditions and from smaller particles.

Experimentation by Keegan et al (2012) on disinfecting the highly chlorine-resistant virus CB5 in recycled waters with chlorine and chloramine examined waters with adjusted turbidities, through the addition of turbidity isolated from wastewater. These authors found that small increases in turbidity (0.2 to 5 NTU) demonstrated only slightly increased Ct values for virus disinfection. However, high turbidity (20 NTU) waters resulted in an increase of >2-fold to Ct. This study demonstrated that higher turbidity waters can be effectively disinfected for viruses with chlorine, but require higher chlorine Cts to factor in the chlorine demand from wastewater particulates. A Ct value is the product of the concentration of a disinfectant and the contact time with the water being disinfected. The particles causing turbidity were predominantly 3 µm in size and organic in origin. Lower turbidities, including 0.2 and 2 NTU, showed no significant difference in Cts. Viruses were still able to be disinfected in higher turbidity waters, examined up to 20 NTU, when longer contact times were used.

Where source waters are outside of the tested range for disinfection parameters such as turbidity, a challenge test can be undertaken to determine a specific log inactivation for the tested conditions. As an example of disinfection validation, a range of chlorination conditions were able to be defined by Canning et al (2015) in order to tailor and optimise virus disinfection in southeast Queensland source waters, using the Keegan et al (2012) values for the highly chlorine-resistant CB5 virus.

8.3 Turbidity modelling

An examination of turbidity in the catchment waters has been performed in GHD (2021) (Appendix F), using hydrologic and turbidity inputs presented in Appendix E. This has included the modelling of suspended solids inputs to the reservoirs, in the form of 1 µm diameter inorganic particles (clay) and 5 µm diameter inorganic particles (silt). The proportion of these particles in the modelled inputs was allocated to simulate natural waterways for un-mined catchment areas, and to simulate mining sumps for inputs from mined catchment areas.

The introduction of particles was modelled as a range of scenarios using combinations of the following variables:

– Catchment clearing associated with the baseline (pre-mining), existing mining, and proposed mining;
– Summer and Winter reservoir conditions;
– Storm intensity (1 Exceedance per Year (EY), 1 per cent Annual Exceedance Probability (AEP), and 10 per cent AEP);
– Drainage failure rates (5 per cent, 30 per cent and 75 per cent corresponding to 1 EY, 10 per cent and 1 per cent AEP storms)
– SS runoff concentrations of both mined (12.6 and 15.8 mg/L of SS_{Clay} and SS_{Silt}, respectively) and unmined (25.2 mg/L and 31.5 mg/L of SS_{Clay} and SS_{Silt}, respectively) catchments.

All turbidity scenarios are described in Appendix G. Whilst turbidity risk at the drinking water catchment scale is of primary concern to this report, turbidity risk at other scales has been assessed, and is presented in Appendix H.

8.4 Scenario results

The 1 EY events consistently had no impact on offtake SS concentrations. The predicted effects of large inflow events and associated drainage failures on the SS in the reservoirs and withdrawals include:

– Increases to SS_{silt} in all reservoirs and for all scenarios were short duration due to the relatively rapid settling as described beforehand for the verification simulations. Most SS variations were due to SS_{Clay}.
– For SMD with moderate drainage failure SS levels, minimal changes were predicted in the SS at the dam and withdrawals between the baseline, existing and proposed scenarios for either the winter or summer 10 per cent AEP inflow events. SS increases of up to ~0.5 mg/L and ~0.2-0.3 mg/L were simulated with the moderate drainage failure SS levels for the summer and winter 1 per cent AEP inflow events, respectively. With high drainage failure SS levels, minimal variations were again predicted for the 10 per cent AEP winter and summer events. SS increases of up to ~1 mg/L and ~0.3-0.4 mg/L were simulated with the high sump failure SS levels for the summer and winter 1 per cent AEP events, respectively.

– For SDD, material differences in SS at the dam wall and withdrawals were not predicted for the 1 per cent and 10 per cent AEP summer and winter inflow events between the baseline and proposed scenarios (note no existing mining scenario for SDD) for both moderate and high drainage failure SS levels. The relatively small proportion of the SDD catchment that is proposed to undergo mining activity does not generate sufficient additional SS loads over the baseline (no mining) scenario to cause a substantive increase.
– As with SDD, material differences in the 1 per cent and 10 per cent AEP summer and winter inflow events between the baseline and proposed SPD scenarios (note no existing mining scenario for SDD) for moderate and high drainage failure SS levels are not predicted. The hydrodynamic barrier effect induced by the SPD primary inflow and outflow in proximity to the dam wall increases the duration of particle settling in the up-reservoir volume prior to transport to the dam wall. Further, the high external transfers with low SS concentrations also dilutes the elevated catchment-derived SS_{clay} levels as they are transported to the dam wall after inflow loading events.

In summary;

– Serpentine Main Dam turbidity concentrations are sensitive to changes in sump failure suspended solids concentrations, as mining comprises a sufficient proportion of the catchment landscape to do so.
– In contrast, South Dandalup Dam is not sensitive to sump failure suspended solids concentrations, as the future mining area is a small proportion of the overall catchment area. There are no ‘existing mining’ scenarios for South Dandalup, as there is no current mining in the catchment, and areas mined in previous decades are assumed to be fully rehabilitated.

9. Fire risk assessment

9.1 Bushfire impacts to reservoir water quality

The impact of bushfires on reservoir water quality has been reviewed by several Australian authors (Smith et al 2011a, Smith et al 2011b, Canning et al 2020, Kahn 2020), with key findings as follows:

– bushfire intensity is a key determinant of water quality impacts
– high intensity fires lead to deposited inorganic ash, nutrients and metals
– high intensity fires can result in loss of riparian vegetation and stream bank stability, leading to gullies and mass erosion
– low intensity fires lead to increased leaf litter, organic ash and dissolved organic carbon (DOC)
– major water quality impacts from wildfires typically occur during subsequent heavy rainfall events, with runoff carrying large quantities of sediment, ash and nutrients in particulate and soluble form
– suspended sediments from burnt catchments form composite particles (flocs or aggregates) with higher potential for bound contaminants but significantly higher settling velocities, attributed to the effects of soil heating
– ash layers from a severe fire may be 2-10 cm thick and low in density, being readily eroded with rainfall and entrained with overland flow
– elevated DOC and/or nitrogen in reservoir water quality following a fire has potential to result in generation of disinfection by-products, such as trihalomethanes, haloacetic acids, haloacetonitriles and halonitromethanes.

Smith et al (2011a) summarised reported contaminant loads from catchments in the first year following fire, as follows:

– suspended sediment loads from 0.017 to 50 t/ha/yr, representing an increase of one to three orders of magnitude from un-burnt catchments
– suspended sediment concentrations from 11 mg/L to about 500,000 mg/L, the highest being during flash floods in a semi-arid ephemeral stream
– total nitrogen loads from 1.1-27 kg/ha/yr and total phosphorus loads from 0.03-3.2 kg/ha/yr, representing an increase of one to two orders of magnitude from un-burnt catchments

The sediment loads reported by Smith et al (2011a) correlate with estimates by Blake et al (2020) for the Northern Jarrah Forest impacted by the 2016 Waroona-Yarloop wildfire. Blake et al (2020) used the Revised Universal Soil Loss Equation (RUSLE) to estimate erosion risk, which indicated an approximate ten-fold increase in erosion risk from in the order of 0.01-0.1 t/ha/yr before the fire to in the order of 0.1-1 t/ha/yr following the fire. Erosion risk was estimated to increase by two orders of magnitude over localised areas, to in the order of 1-10 t/ha/yr, with hot spots identified in forested headwaters associated with steep terrain and high fire intensity.

Khan (2020) reported that during the 2019/2020 bushfires in NSW, most significant water quality impacts were avoided due to a combination of:

– very large reservoirs, providing time for sedimentation prior to water reaching offtakes
– in some cases, use of floating silt curtains to contain stratified water layers, providing additional opportunity for sedimentation
– adjustment of offtakes to target the best water quality and avoid the worst water quality
– some systems were able to draw on multiple sources to select those that were un-impacted
– use of off-river storages where available, drawing from rivers when quality is satisfactory.

Khan (2020) notes that not all water supply systems have these attributes and thus the capacity to manage water quality impacts from bushfire impacted catchments. An example was Brogo Dam in Bega Valley, which has a capacity of 9 GL and catchment of approximately 400 km^2. The catchment was substantially burnt in January 2020 then received 150 mm of rainfall, which resulted in turbidity at the offtake peaking at 600 NTU then remaining above 20 NTU for a number of weeks. Consequently, the Bega Valley Shire Council was required to truck water to towns and the Australian Defence Force set up a mobile water treatment plant to filter some of the water from the dam.

9.2 Bushfire impacts to reservoirs in the Northern Jarrah forest

The water quality impacts to reservoirs has been demonstrated through two recent fires in the Northern Jarrah Forest, both of which were wildfires that affected large areas catchment:

– 2005 Perth Hills bushfire
– 2016 Waroona-Yarloop bushfire

The 2005 Perth Hills bushfire burnt approximately 27,000 ha of drinking water catchments, predominantly that of Mundaring Weir. The bushfire covering approximately 19 per cent of the catchment of Mundaring Weir, which had a water volume of approximately 27 GL at the time. Turbidity in the catchment streams increased with ranges from 5 NTU to more than 1000 NTU. A turbid plume was observed within the upper end of Mundaring reservoir (Battini and Barrett 2007), with turbidity peaks of up to 37 NTU, attenuating towards the dam wall (Battin and Barrett 2007, WSAA 2020). Water Corporation undertook flocculant dosing in the Darkin River over June to October 2005 to reduce turbidity levels. The flocculant dosing reduced turbidity in the reservoir, enabling Mundaring Weir to be kept online, however there was an increase in soluble aluminium which indicated limitations to ongoing dosing. Large volumes of floating ash were deposited in the reservoir and accumulated at the dam wall under certain wind conditions, requiring removal on three occasions during 2005 (WSAA 2020).

The 2016 Waroona-Yarloop bushfire burnt over 69,000 ha of land, including more than 90 per cent of the catchment of Samson Brook Dam and Samson Brook Pipehead Dam (DWER 2019). The Samson Brook Dam had a water level of less than 1 GL at the time. The fire resulted in elevated levels of turbidity, pathogens and other contaminants, resulting in the Water Corporation keeping the dams offline for over a year (DWER 2019).

The evidence reviewed by Australian authors and the impact of 2005 Perth Hills and 2016 Waroona-Yarloop fires suggest that the Serpentine Main Dam, South Dandalup Dam and Wungong Dam reservoirs may be susceptible to water quality impacts from bushfires. Such an event may include a high intensity wildfire that covers a large proportion of a catchment, occurs over steep terrain and in the year prior to heavy rainfall events.

In the event of a major wildfire and heavy rainfall sequence within a catchment, there is potential for substantial ash deposition, runoff and soil erosion that would occur outside of and/or bypass mine sediment barriers, which would be limited to the portion of catchment subject to mining. Major wildfires can occur over tens of thousands of hectares in a single event, an area which is an order of magnitude greater than the area of mine pits open at any time or under early rehabilitation establishment. Accordingly, major wildfires may impact a much larger extent of land and not be subject to sediment barriers compared to mining and rehabilitation. Soil erosion from wildfire impacted areas under heavy rainfall is expected to be highest in areas of high slope. Steep landforms occur in portions of the Serpentine Main Dam and Pipehead Dam PDWSAs associated with incised valleys of the Serpentine River and hills in the vicinity of Mount Solus. Steep landforms also occur to a lesser extent within the South Dandalup Dam and Wungong Brook PDWSAs associated with valleys of the South Dandalup River and Upper Wungong Brook.

A major wildfire and heavy rainfall sequence may therefore result in widespread ash deposition, runoff and erosion that generate substantial discharges of ash and sediment into the catchment’s reservoir. Depending on the severity and location of fire and rainfall, there is potential for the scale of discharges to exceed the attenuating capacity of the reservoir and cause elevated contaminant levels at the offtake that exceed drinking water quality criteria.

9.3 Potential for future wildfires within the Northern Jarrah forest

There remains the potential for major wildfire events to occur throughout the Northern Jarrah Forest, irrespective of the Proposal. Previously, such events have included the 2003 Mount Cooke, 2005 Perth Hills and 2015 Boddington (Lower Hotham) fires which occurred away from bauxite mining and rehabilitation. The increased prevalence of wildfires over the past two decades is expected to have been in part due to a reduction in prescribed burning since the 1990s. The reduction in prescribed burning was due to a variety of reasons independent of bauxite mining and rehabilitation, including (CALM 1994, Burrows et al 2015):

– climate variability (e.g. increasing frequency of high fire risk days in which burning cannot be scheduled)
– land use changes and population growth (e.g. urban and rural air quality constraints, landowner objections)
– resource constraints.

Climate change is expected to extend the period at which vegetation is flammable, increasing the frequency and scale of forest fires in the Jarrah Forest, though drying may also reduce the rate of fuel accumulation (Burrows and Wardell-Johnson 2003). Analysis undertaken for south-east Australia, which is predicted to undergo similar drying and warming as is forecast for the South-West region, suggests a potential for increased cumulative forest fire danger index and increased number of high and very high fire risk days (Maher et al 2010). Accordingly, there is potential for the frequency of wildfires to increase in the future.

9.4 Potential for mining and rehabilitation to increase frequency or severity of wildfires

Alcoa engagement with the Water Corporation and DWER raised a number of concerns regarding the potential for mining and/or rehabilitation to affect the fire regime of the Northern Jarrah Forest and increase the risk to drinking water quality. The concerns included the following:

– fire behaviour interactions are by their nature complex and need to be investigated further to better establish risk profiles and nature and extent of uncertainty
  - established stream zone buffers may act as fire ‘wicks’ given they are largely not subject to fire controls and may over time become high fire fuel load areas
  - increased leaf area index (LAI) associated with rehabilitation on steep slopes may result in significant changes to fire behaviour
  - removal of the upper regolith may interact to result in significant post fire erosion / turbidity risk profile
  - interactions between climate change, area of impact, time since rehabilitation, land slope and changes to groundwater levels may result in significant changes to fire risk and fire behaviour in the future.

The effects of bauxite mining on soils and potential long term erosion are addressed in Section 10.

9.4.1 Increased leaf area index and fuel load with rehabilitation

Macfarlane et al (2017) report the leaf area index (LAI) in five un-mined catchments of Jarrah forest as ranging from approximately 1 to 2.2, with variation due to the stage of regrowth from timber harvesting and fire, and the effects of *Phytophthora* Dieback. Bradshaw (2015) reports the LAI of un-mined Jarrah forest as ranging from 1.6-2 when fully stocked. Fuel loads in un-mined Jarrah forest vary in accordance with the time since last fire. Burrows (1996) reports that fuel loads in upland Northern Jarrah Forest rise to approximately 20 t/ha at ten years from fire and thereafter vary from about 20 t/ha to 25 t/ha, with the majority of fuel load (about 15 t/ha) from accumulated litter and the remainder from scrub, trash and bark (Burrows 1996). The State Government has set a target of limiting litter fuel accumulation to 8 t/ha in the Jarrah forest, the threshold at which firefighting becomes problematic and damage occurs to young trees and crowns (CALM 1994, Burrows 1996). This target typically requires a fire interval of 5-7 years (CALM 1994). Climate change may result in a slower accumulation of fuel to previous recorded rates due to reduced rainfall, soil moisture and vegetation growth.

Fuel load accumulation may be greater in lowland Jarrah forest such as valley floors, stream zones and swamps that have higher soil moisture and more dense vegetation. In the past the higher soil moisture and live vegetation may have retarded the spread of fires through lowland areas. However, there has been a sustained decline in rainfall over the Northern Jarrah Forest since the 1970s and a consequent decline in groundwater levels in the regolith and disconnection of stream zones from the groundwater table. The drying out of stream zones and swamps due to climate change may result in the dense vegetation of streams and swamps becoming more fire prone.

The effects of bauxite mine rehabilitation on LAI and fuel loads have been reviewed by Grant et al (1998), Smith et al (2004), Daws and Koch (2015) and Macfarlane et al (2017).

Daws and Koch (2015) report LAI in rehabilitation as rising to approximately 2 after eight years and thereafter ranging from approximately 2-2.5. Macfarlane et al (2017) report LAI from mined catchments as rising to approximately 2-2.5. The reported LAI from these studies is for past rehabilitation prescriptions that included establishment targets of 3000 tree stems/ha in the 1990s. The past rehabilitation prescriptions were developed in agreement with Government and reflected the standards for timber production and knowledge of tree survival at the time. Since then the density of trees has been deliberately reduced and the current rehabilitation prescription, adopted since 2016, has an establishment target of 1000 stems/ha.

Figure 9.1 presents estimated data for the variation in LAI for the current rehabilitation prescription (Grigg, pers. comm.). As presented, the LAI of newly established rehabilitation is expected to reach approximately 2 after two decades from establishment, which is comparable to the range of LAI for un-mined Jarrah forest. Understorey LAI is expected to peak at about eight years and thereafter decline as the understorey senesces, with the canopy dominating the LAI after about 15 years.

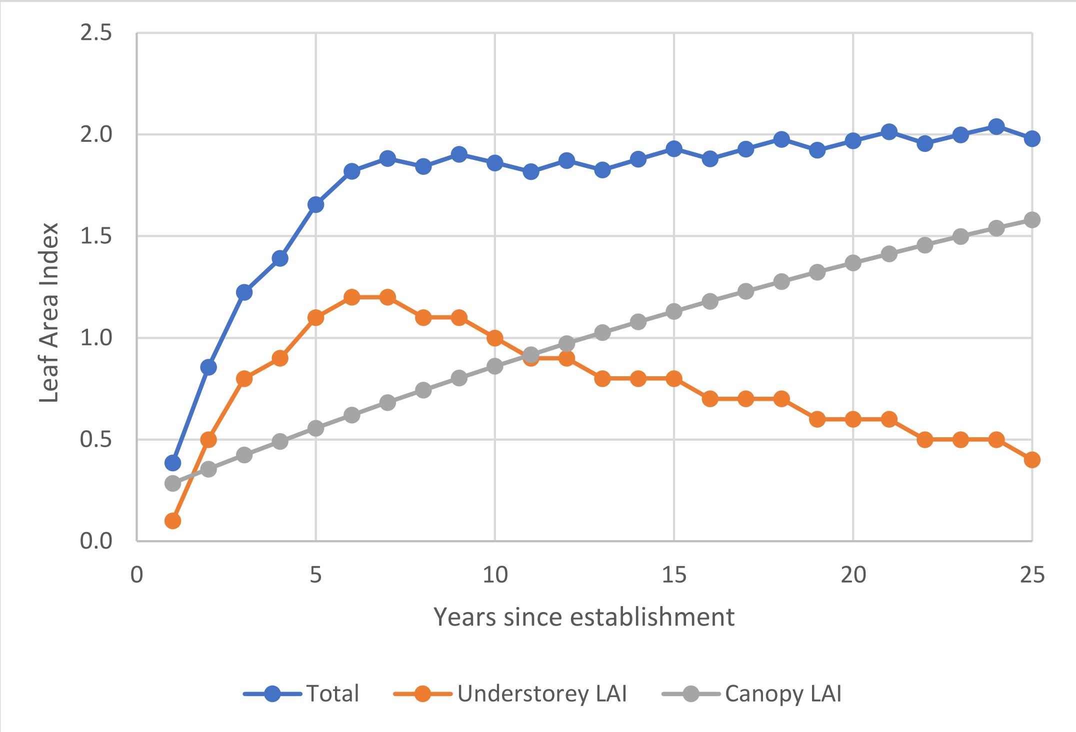

Figure 9.1 Estimated leaf area index of current rehabilitation prescriptions

Grant et al (1998) note that rehabilitation in the 1980s and 1990s seeded the understorey with legumes (e.g. Acacias) to prevent erosion and fix nitrogen. The legume species grew rapidly however they were short lived species and senescence led to accumulated fuel loads of 16-62 t/ha at 10 to 20 years from establishment. The accumulation of fuel in dead understorey/trash differs from that of un-mined Jarrah forest, in which fuel predominantly accumulates in the litter layer. Smith et al (2004) reported fuel loads ranging from 2.2-60.8 t/ha in rehabilitation, with an average of 15.0 t/ha at five years and 29.8 t/ha at eight years from establishment. Prescribed burns in the five year rehabilitation were of low intensity (< 250 kW/m) and in eight year rehabilitation were of very high intensity (> 7000 kW/m) (Smith et al 2004). The lower intensity at five years was due to lower fuel loads and a greater proportion of live plants which inhibited burns. While the fuel accumulation exceeds that of un-mined forest, Grant et al (1998) notes that fuel loads are highly variable and patchy.

Current rehabilitation prescriptions have reduced the seeding of legume species and application of fertiliser, which reduces the dominance of legume species and encourages greater floristic diversity (Daws et al 2013, Daws et al 2021). Current rehabilitation prescriptions are expected to result in less vigorous understorey development and a lower fuel accumulation in the shrub/trash layer compared to the measurements by Grant et al (1998) and Smith et al (2004).

9.4.2 Fire management in mining regions

Alcoa collaborates with DBCA in planning an annual prescribed burn program, and funds the DBCA burns conducted within and surrounding mining and rehabilitation areas. Prescribed burns are conducted by a combination of aerial and ground methods and occur adjacent to mining operations and infrastructure. Mining operations temporarily cease in the vicinity of burns during and for a period after prescribed burns, for safety reasons (i.e. heat, smoke, falling dead trees). Following DBCA inspection and clearance of burnt areas, mining operations recommence. Alcoa has operated in the Northern Jarrah Forest for over fifty years and has mature experience in managing operations during prescribed burning and collaborating with DBCA to plan prescribed burns around mine operations and infrastructure.

Alcoa's operations and infrastructure are less sensitive to smoke impacts compared to urban and rural land uses, which are a key constraint to DBCA's prescribed burn operations in the Northern Jarrah Forest. For example, Alcoa can temporarily suspend or relocate operations away from impacted areas, whereas urban and rural land uses are relatively fixed. Mine infrastructure and equipment are relatively resilient to smoke impacts compared to domestic properties, agricultural crops and stock animals. Accordingly, the Huntly Mine operations are able to accommodate smoke impacts from prescribed burns that would otherwise result in prescribed burns being delayed or cancelled due to public health risks or neighbouring landowner disputes. This provides more flexibility to DBCA in conducting prescribed burns within mining regions, subject to constraints posed by urban or rural land uses in the vicinity.

The integration of rehabilitation areas into forest prescribed burns utilises a fire risk matrix based on fuel ages in rehabilitated areas and adjacent unmined forest. Rehabilitation up to approximately six years of age has relatively low fuels with a discontinuous litter layer which provides opportunities to conduct prescribed burning in the surrounding un-mined forest. Rehabilitation from approximately six to 15 years requires fire exclusion to protect the crowns of young canopy tree saplings, which have not yet separated from the shrub layer. From approximately 15 years onwards, rehabilitation tends to form a two-tiered fuel structure, trees have developed a thick bark layer that provides greater protection and prescribed burning can be reintroduced within the rehabilitation and surrounding un-mined forest (Grant et al 1998, Grant et al 2007).

Though past rehabilitation prescriptions have generated high yet patchy fuel accumulation in the understorey, past prescribed burns conducted within mining regions have successfully reduced fuel levels and have not resulted in wildfires spreading outside of mining regions. This is in part due to the varying fuel loads in rehabilitation that occupy relatively small areas of the landscape and are interspersed by fire breaks created by open mine pits, mine infrastructure and the negligible fuel loads of newly established rehabilitation. Fire behaviour in prescribed burns is substantially affected by the fuel loads in the surrounding un-mined forest, which form the majority of the landscape.

Alcoa rehabilitation prescriptions require the reinstatement of forest access tracks and roads to DBCA approval, which enable forest management including prescribed burns and fire response activities. Alcoa's mine road network and the re-instated forest access tracks enable prescribed burn operations to be conducted within mine regions during mining and rehabilitation stages. During emergency fire events, Alcoa's mine road network and mine facilities can be used to provide access and emergency response management.

It is expected that the transition of mining into the Myara North and Holyoake regions will continue to enable DBCA's prescribed burning program to be effectively planned, funded and implemented, as has been demonstrated within the Huntly Mine to date. Accordingly, the Proposal is expected to maintain and support the State Government's program to limit fuel accumulation in the Northern Jarrah Forest, thereby reducing the likelihood of large wildfires occurring in the PDWSAs that lie within the mine regions.

10. Long term rehabilitation and erosion risks assessment

10.1 Effects of mining on Jarrah forest soils

Superficial soils on the Darling Plateau comprise a thin veneer of topsoil (typically less than 0.1 m thick), which contains sand, silt and the majority of the seedbank, over a sandy gravel overburden layer (Hickman et al 1992). The overburden ranges from about 0.2-4 m thick and averages about 0.5 m. The overburden is underlain by lateritic bauxite, which is approximately 4-6 m thick and comprises a caprock (duricrust) layer and underlying friable fragmental layer. The caprock layer is discontinuous and varies from absent to a thickness of a few metres. The friable fragmental layer contains nodules, pisoliths and weathered rock fragments in fine-grained, loose earths or sands. The friable fragmental layer is generally about 2 m thick but can be up to 10 m thick on the Darling Plateau (Hickman et al 1992). Beneath the bauxite layers lies mottled, pallid and saprolite clay layers that are typically 20-30 m thick, which transition into weathered saprock and then fresh bedrock (Hickman et al 1992).

The mine development stage involves stripping and stockpiling the superficial soils and blasting or ripping the caprock layer. Mining then involves removing the bauxite caprock and friable fragmental layers, which are transported to stockpiles, then crushed and conveyed to Pinjarra Alumina Refinery.

The mine floor remaining after mining contains a diverse range of lateritic regolith materials from the lower mottled, pallid clay and saprolite layers, which mostly comprise sandy loams and clays (Mengler et al 2005). In areas where the regolith is thin and has been mostly removed by mining, the mine floor may contain partly weathered material that retains the texture of the original bedrock. Other areas of the regolith have existing root channels, adequate structure and stable aggregates that support root exploration and plant re-establishment. The majority of pit floors require ripping to create macrostructure and alleviate high strength and high bulk density (Mengler et al 2005). Soils derived from dolerite bedrock tend to be more clay rich and have more pedal structure, whereas soils derived from granite typically contain macropores (Raper and Croton 1996).

Following the completion of mining, rehabilitation is undertaken including pre-ripping of compacted floors to at least 1.2 m, landscaping batters, spreading overburden and topsoil (typically 300 mm combined depth), then contour ripping to create a furrowed surface.

The net effect of bauxite mining of Jarrah forest soils is the removal of an approximately 4-6 m thick layer of caprock and friable fragmental material, and replacement of the seed rich topsoil and overburden over a ripped, friable substrate of sandy loams and clays. The total depth of friable material created is about 1.5 m, including topsoil, overburden and ripped substrate.

10.2 Vegetation use of Jarrah forest soils

The LAI of Jarrah forest vegetation is dominated by the predominant canopy tree Jarrah (*Eucalyptus marginata*), which comprises about 60 to 80 per cent of the LAI depending on the presence of other trees (Crombie 1992). Shallow rooted vegetation (i.e. small shrubs and groundcovers with roots confined to shallow soils above the caprock) is estimated to comprise less than 10 per cent of LAI and medium rooted vegetation (i.e. larger shrubs with roots that penetrate the caprock but not far into the underlying clays) approximately 10 per cent of LAI (Crombie 1992).

Jarrah has a dimorphic root system, comprising dense lateral roots in the topsoil and overburden above the caprock, from which ‘sinker’ roots extend vertically to penetrate cracks and fissures in the caprock and gain access to moisture bearing clay through ancient root channels (Dell et al 1983, Farrington et al 1996). Dell et al (1983) suggest that each tree may access 100-200 ancient root channels of up to 40 m from the surface. The root channels are permanent features of the profile and occupied by successive generations of trees (Dell et al 1983).

Carbon et al (1980) report that the bulk of Jarrah roots are in shallow soils (topsoil and overburden) above the caprock, which has the greatest potential to supply water in winter but dries over the summer and autumn. Measurements by Carbon et al (1980) indicate that the shallow soils have root density (root depth per area of ground surface) about an order of magnitude greater than the deeper sandy loam and clay layers. While trees have deeper roots, substantial groundwater use is limited to shallower depths, being recorded in Jarrah forest at sites with depths of 6 metres below ground level (mbgl) but not at 14 mbgl or 30 mbgl (Farrington et al 1996). Deeper rooted vegetation such as Jarrah and large shrubs can maintain higher photosynthetic activity into summer and autumn compared to shallow rooted vegetation (Crombie 1992). However, both deep and shallow rooted vegetation exhibit daily cycling of water potentials and stomatal conductance and a rapid response following rainfall during summer (Crombie 1992). This suggests that Jarrah forest vegetation remains physiologically active during summer and is tolerant of low water potentials, which would be necessary to enable deeper rooted vegetation to use water held in clayey subsoils (Crombie 1992).

The establishment of a 1.5 m thick friable layer of topsoil, overburden and ripped substrate provides a comparable, though generally thicker, stratum than the topsoil and overburden present above the caprock prior to mining. The friable layer enables development of a dense root structure of Jarrah forest vegetation as occurs in the topsoil and overburden present prior to mining. Deeper rooted vegetation establishing within the friable layer is expected to re-colonise ancient root channels present in the underlying regolith materials, as have been used by successive generations of trees prior to mining (Dell et al 1983). There is expected to be a partial loss of soil water capacity due to the removal of the bauxite friable fragmental layer, which comprised about 2 m of loamy soils that previously were accessed by deep and medium rooted vegetation. Loss of this layer represents approximately 10 per cent of the regolith thickness, however the loamy layer may have had a higher plant available water than that of the underlying mottled and pallid clays. Loss of the bauxite caprock layer is not expected to substantially reduce the soil water capacity, as the layer was primarily cemented material that provided discrete pathways for water and roots to enter the underlying un-cemented layers.

Loss of the bauxite friable fragmental layer has not been observed to result in impaired growth or health of rehabilitation. Monitoring of rehabilitation has demonstrated the successful establishment and persistence of an LAI of 2-2.5, comparable to that of un-mined Jarrah forest. Monitoring has also indicated a floristic diversity of about 80 to 100 per cent of un-mined forest, declining weed cover and sustained understorey coverage. During the 2010/11 drought and heat waves, Jarrah forest canopy die-off was observed at sites across the Northern Jarrah Forest, including un-mined forest and some areas of rehabilitation. Widespread die-off of rehabilitation did not occur nor was rehabilitation affected in greater proportion than un-mined forest. Browers et al (2012) report that canopy dieback was more frequent on:

– rocky soils with low water holding capacity
– sites that were close to rock outcrops
– areas that received a slightly higher amount of annual rainfall compared to the surrounding landscape
– sites at high elevations or on steep slopes
– in areas that were generally slightly warmer than their surroundings.

The results of monitoring collectively demonstrate that Alcoa's rehabilitation establishes and persists, including during drought and heat wave events, indicating that the 1.5 m thick friable substrate over regolith containing ancient root channels is an effective growth medium.

10.3 Erodibility of mine rehabilitation

Mengler et al (2006b) surveyed topsoil and overburden samples in rehabilitated mine pits at the Huntly Mine. The survey indicated predominantly sandy gravel texture, comprising an average of 60 per cent gravel (>2 mm diameter, range 38-78 per cent), 38 per cent sand (2-0.02 mm diameter, range 24-65 per cent) and 3 per cent silt and clay (<0.02mm diameters, range 0-6 per cent) for Huntly Mine. Due to the predominant sandy gravel texture, the soils had calculated low erodibility coefficients (RUSLE equation K factors) averaging 0.009 (range 0.000-0.019).

The skeletal topsoil and overburden materials are distinct to most agricultural soils and mining waste due to the low combined clay and silt contents and very high gravel contents, which develop with time a protective surface layer of gravel covering 70-80 per cent of the land surface. The high porosity and coarse texture also enable rapid infiltration of rainfall within the topsoil, overburden and ripped regolith material. However, thinly applied topsoil and overburden can be mixed with finer grained pit floor materials during contour ripping, which can introduce more erodible (and potential dispersive) clayey material into the shallow subsurface surface. The regolith beneath the ripped zone typically comprises low permeability saprolite clays, therefore rainfall infiltration is limited to the water storage in the overburden and ripped zoned, accordingly surface runoff occurs following extended rainfall periods that fill up the permeable materials.

Gullies form in the rehabilitated landform through an erosion sequence (Mengler et al 2006). The fine grained content is displaced from the coarser topsoil/overburden, depositing within the furrows and filling their volume such that surface water overflows and erodes through the fine grained materials in downslope furrows. The gully that is initially created in the fine grained materials concentrates flow and creates knickpoints that enable erosion of the coarser topsoil/overburden and underlying ripped regolith materials.

Analysis of gully erosion at the Huntly, Willowdale and Boddington bauxite mines suggested a minimum catchment of 0.3 ha for gully development, with gully volumes typically remaining small (20-100 m3) but potentially increasing for higher slopes (> 10°) and shallower topsoil/overburden placement (< 200 mm). Erosion was highest in the first two to three years following rehabilitation completion until rehabilitation establishes, though there was a lack of long term data with which to compare the erodibility of rehabilitation to that of un-mined Jarrah forest (Mengler et al 2006). For the period at higher risk of erosion, the major triggers for gully erosion were identified as:

– directing excessive off-site runoff into the rehabilitation
– poor surface completion (e.g. ripping that does not adhere to contours) that concentrates flow or impairs infiltration
– insufficient depth of returned topsoil and overburden (< 200 mm combined)

11. Major diesel spill assessment

11.1 Potential for diesel exposure

GHD (2021) examined the effect of mining activity-related cryptosporidium and diesel spill incidents in the catchments. This included simulated diesel spill incidents, with the assumption that a 15 m^3 tanker load was directly discharged into a stream at a haul road crossing. The modelled processes leading to decreased diesel concentrations were river dilution, reservoir mixing and dispersion, and withdrawals from the dams. These were simulated to occur in three catchments of Serpentine Main Dam and South Dandalup Dam catchments, and both of the two Pipehead Dam catchments, with existing (Serpentine Main Dam, South Dandalup Dam) and proposed (Serpentine Main Dam, South Dandalup Dam) mining scenarios. No losses due to volatilisation, degradation, adsorption and settling were included in the simulation, so the modelled outputs are regarded as conservative.

The simulation results included the following:

– Serpentine Main Dam - predicted peak diesel concentrations of up to 1 µg/L, with all levels below 0.2 µg/L within 6-7 months of the spill.
– South Dandalup Dam - predicted peak diesel concentrations of up to 1 µg/L, with all levels below 0.4 µg/L within 6-7 months of the spill.
– Pipehead Dam catchment 24 (mid reservoir) - predicted peak diesel concentrations of up to 5 µg/L, and levels were predicted to fall to ~0 µg/L within ~10-12 months of the spill, because of SPD's relatively small volume and high outflow.
– Pipehead Dam catchment 23 (upper reservoir) - predicted peak diesel concentrations in withdrawals of up to 1.5 µg/L, and levels were predicted to fall to ~0 µg/L within ~10-12 months of the spill.

It is recommended that some monitoring of the concentrations of diesel and other hydrocarbons is performed prior to the proposed mining transition, so as to establish baseline concentrations in the storages. Such monitoring will support the assumptions of background concentrations used in the simulation.

11.2 Interpretation of diesel exposure

Diesel itself is a complex mixture of chemicals, primarily hydrocarbons, which can separate and behave uniquely in the environment. Although there are numerous contaminants in diesel fuel, it is practical to consider a selection as part of this assessment. This selection focuses on the most prevalent light fraction component (benzene) and the most prevalent heavy fraction component (xylene) with guideline values recommended in the ADWG.

The ADWG recommends a health based guideline limit for benzene of 1 µg/L, consistent with WHO guidance for this parameter. Additionally, health based limit for xylenes of 600 µg/L and an aesthetic based limit of 20 µg/L are included in the ADWG.

Heath et al (1993) and Friebl and Nadebaum (2010) describe the component characteristics of diesel fuel. Benzene constitutes 0.5 per cent of the mass of fuel diesel, and xylene 0.03 per cent.

From the diesel spill incident modelling, the largest predicted peak diesel concentration was up to 5 µg/L. With <1 per cent of diesel constituted by benzene and xylene, the ADWG health-based limits for these parameters are not exceeded for the modelled incidents. The xylene aesthetic limit of 20 µg/L is also not exceeded.

The ADWG notes that diesel contamination in drinking water has a taste and odour threshold of 5 µg/L. This could be reached with the largest predicted peak diesel concentration of up to 5 µg/L.

12. PFAS and minor discharges of hazardous materials

12.1 PFAS

Alcoa have committed to using PFAS-free firefighting foams for the Myara North and Holyoake regions. All water supplies to construction and operations in the Myara North and Holyoake regions will be sourced from public drinking water sources, captured onsite stormwater or from licensed onsite water treatment facilities where approved for reuse within the drinking water catchment. PFAS would be limited to minor quantities in materials such as workforce clothing, paper packaging, carpets or wire insulation, which are unlikely to be discharged to the environment as all wastes will be recycled or disposed off-site at licensed waste facilities. Accordingly, the direct discharge of PFAS from construction and mining is expected to pose a low risk to drinking water quality.

The existing land uses and baseline monitoring program (GHD 2021) do not indicate the presence of substantial PFAS contamination within the Myara North or Holyoake regions. PFAS are relatively persistent and water-soluble compounds which readily mobilise through the unsaturated zone and into groundwater, which discharges into streams. It is therefore expected that any existing substantial PFAS contamination of the catchments would be detectable in stream flows. Due to the absence of existing substantial contamination, any hydrological changes from construction and mining (i.e. the clearing of vegetation causing groundwater mounding and increased stream flows) are not expected to mobilise substantial quantities of PFAS into reservoirs. Accordingly, the indirect mobilisation of historical PFAS from catchments due to construction and mining is expected to pose a low risk to drinking water quality.

12.2 Minor discharges of hazardous materials

Diesel is the predominant hazardous material used at the Huntly Mine, and to a lesser extent hydraulic and lubricating oils. Minor quantities of other hazardous materials include solvents, adhesives and other chemicals are used for vehicle and equipment maintenance or water treatment.

Haul trucks, some wheeled earthmoving equipment and light vehicles are refuelled at fuel bays. Planned maintenance of haul trucks, light vehicles and some earthmoving equipment is undertaken at workshops. The fuel bay and workshop buildings are located at mine facilities and have roofs and sealed floors, which are expected to capture spills or leaks during refuelling or maintenance. Diesel and oil storage tanks are located at mine facilities and are double-lined and above ground to minimise and detect leaks. Smaller quantities of hazardous materials stored at mine facilities inside buildings or on sealed floors.

Excavators, bulldozers and other earthmoving equipment are refuelled and maintained in the field. Refuelling and maintenance in the field have potential to cause spills and leaks that contaminate soils. There is also potential for ongoing, low level oil leaks from vehicles and equipment, and rare collisions that result in fuel or oil spills.

The majority of spills and leaks, particularly those from major incidents and involving large volumes, are expected to be identified quickly and the contaminated soils excavated and disposed off-site at a licensed waste facility. Smaller spills and leaks may potentially be missed and the contaminants leach through the unsaturated zone. The smaller spills and leaks are expected to remain predominantly adsorbed to soil particles beneath the spill site. Diesel and particularly oil contain larger chain hydrocarbons that are weakly water soluble and readily adsorb to soils with organic matter and clay content. Accordingly small volumes of diesel and oil that escape detection and remediation are unlikely to result in substantial migration of hydrocarbons that reach streams and can be transported into the reservoirs.

13. Risk Assessment

13.1 Definitions

13.1.1 Likelihood

Likelihood is defined as the chance that the risk event and associated consequences will occur. The likelihood definitions used by Water Corporation (2018) match those used by ADWG (2011), and are reproduced in Table 13.1 below. At Water Corporations request, the Water Corporation likelihood definitions have been adopted for this report.

Table 13.1 Likelihood ratings

Descriptor	ADWG example description	Water Corporation Corporate Description	Water Corporation Corporate Frequency
Almost Certain	Is expected to occur in most circumstances	The event is expected or known to occur more than once per year	Will occur more than once a year
Likely	Will probably occur in most circumstances	Known to re-occur approximately annually. Known to occur across like industries or within corporation.	Will occur once per year
Possible	Might occur or should occur at some time	The event should occur at some time. Has occurred several times across like industries.	Will occur once every 5 years
Unlikely	Could occur at some time	The event could occur at some time. Known to have occurred once or twice within industry.	Will occur once in 10 years
Rare	May occur only in exceptional circumstances	The event may occur in exceptional circumstances. An example of this has occurred historically, but is not anticipated.	Will occur once in 30 years or less

13.1.2 Consequence

Water Corporation (2018) define consequence as the outcome of an event affecting objectives expressed qualitatively or quantitatively, being a loss, injury, disadvantage or gain. The severity of the consequence is the most plausible, (credible) outcome should the risk manifest into an event, not the most severe/worst case. They note that consequences are typically measured after a consideration of the barriers in place. Any variation on this (e.g. inherent risk) needs to be clearly specified 'in context' for the risk assessment being undertaken.

At Water Corporations request, the Water Corporation consequence definitions have been adopted for this report, where relevant. The definitions that relate to employee consequences have been ignored.

Table 13.2 Consequence ratings

Rating	Descriptor	ADWG example description	Water Corporation People and Public	Water Corporation Customer Service Interruption
5	Catastrophic	Major impact for large population, complete failure of systems	Multiple fatalities, and/or Onset of life shortening illness for multiple persons	Significant widespread degradation of operations or services, and Long, sustained, loss of operations or services for residential customers or key, sensitive and unregulated customers

Rating	Descriptor	ADWG example description	Water Corporation People and Public	Water Corporation Customer Service Interruption
4	Major	Major impact for small population, systems significantly compromised and abnormal operation if at all, high level of monitoring required	Single fatality, and/or Injury/illness resulting in significant permanent disability or life shortening illness	Widespread degradation of operations or services, and Sustained service cessation for residential customers (>24 hours) or key, sensitive and unregulated customers
3	Moderate	Minor impact for large population, significant modification to normal operation but manageable, operation costs increased, increased monitoring	Injury/illness, requiring specialist medical treatment, or hospitalisation, resulting in loss of functional ability (Restricted Work Injury (RWI)), or time off work (Lost Time Injury (LTI))	Wide-spread customer impacts or inconvenience – entire regional centre or country scheme, multiple metropolitan suburbs, and Temporary loss of operations and services for residential customers (<24 hours) or key, sensitive and unregulated customers
2	Minor	Minor impact for small population, some manageable operation disruption, some increase in operating costs	Injury/illness requiring medical treatment, nil loss of functional ability (Medical Treatment Injury (MTI))	Localised operations or service interruption/ inconvenience for customers, and Temporary, short term service cessation for residential customers (<6 hours) or key, sensitive and unregulated customers Multiple occurrences in one location
1	Insignificant	Insignificant impact, little disruption to normal operation, low increase in normal operation costs	Injury/illness requiring no treatment or first aid treatment only (Minor Injury (MI))	Brief loss of local services, or inconvenience for customers, and No measurable operational impact

13.1.3 Risk

Risk is the combination of likelihood and consequence. The risk matrix used by Water Corporation differs to the ADWG (2011) matrix. At Water Corporations request, the Water Corporation risk matrix has been adopted for this report.

Table 13.3 Risk matrix

Likelihood Consequence	Rare E	Unlikely D	Possible C	Likely B	Almost Certain A
Catastrophic 5	High	High	Extreme	Extreme	Extreme
Major 4	Medium	High	High	Extreme	Extreme
Moderate 3	Low	Medium	High	High	High
Minor 2	Low	Low	Medium	High	High
Insignificant 1	Low	Low	Low	Medium	Medium

13.2 Residual risks *(unmitigated)*

The hazardous events defined between Sections 7 and 12 have been summarised in Table 13.4. Each hazardous event has been assigned likelihood and consequence ratings, and the resultant residual risk (*unmitigated*) from that rating. These have been assigned subjectively from within the defined risk framework, and the residual risk is the risk present without mitigation measures being in place, apart from existing intrinsic barriers such as decay and dilution.

Table 13.4 Residual risks (unmitigated) from defined hazardous events

Residual risk event	Likelihood	Consequence	Risk (*unmitigated*)
Raw sewage overflow in STP located within any catchment area, followed by heavy rainfall	Unlikely	Moderate	Medium
Treated effluent accumulates at surface of irrigation site within any catchment, followed by heavy rainfall resulting in washout	Unlikely	Moderate	Medium
Treated effluent accumulates in shallow perched aquifer, transferred to creek or downslope seepage face, and then into any reservoir	Unlikely	Moderate	Medium
Staff member with asymptomatic cryptosporidiosis in Pipehead Dam catchment area defecates in gully or riparian zone, followed by heavy rainfall	Possible	Major	High
Staff member with asymptomatic cryptosporidiosis in Serpentine or South Dandalup Dam catchment area defecates in gully or riparian zone, followed by heavy rainfall	Possible	Moderate	High
Mining-related inputs in reservoir results in 5 NTU or greater turbidity of source waters	Possible	Moderate	High
Substantial diesel fuel spill into Pipehead Dam reservoir	Unlikely	Moderate	Medium
Substantial diesel fuel spill into Serpentine or South Dandalup Dam reservoir	Unlikely	Minor	Low

14. Barriers and preventive measures

This section includes discussion of the existing and proposed barriers to identified water quality hazards, related to Alcoa's current and future activities in the study area. As defined in the ADWG section 3.3, barriers and preventive measures are those actions, activities and processes used to prevent hazards from occurring or reduce them to acceptable levels. Many preventive measures may control more than one hazard, while, as prescribed by the multiple barrier approach, effective control of some hazards may require more than one preventive measure.

These barriers and preventive measures are summarised in Appendix I.

14.1 Pathogen barriers - workforce in the field

Demountable ablution block (existing): A crib room and ablution block are provided within the mine region at a location closer to active mine pits, so as to provide support to the field workforce working away from the mine facilities. The ablution block drains into a tank, which is periodically pumped out by a tanker for disposal at a licenced facility.

Mandated work breaks (existing): Work breaks provide an opportunity for field staff to access the ablutions block or mine facilities.

Haul truck refuelling at mine facilities (existing): Haul truck refuelling provides an opportunity for field staff to access ablutions at mine facilities.

Workforce education (existing): Inductions for all staff and contractors at commencement, with regular refresher training. The inductions are proposed to include education about drinking water catchment sensitivity, the risks from pathogens to the catchment, and mandatory procedures to minimise those risks.

Workforce health monitoring (existing): Employees and contractors are encouraged, and required, to not attend the workplace if unwell, particularly if experiencing specific gastrointestinal symptoms, or contact with individuals with gastrointestinal symptoms. This requirement is communicated in the inductions and regular refresher training.

Waste bagging and removal (proposed): A procedure where human waste will be bagged and disposed of appropriately is proposed.

Incident reporting and response (proposed): It is proposed that all accidental human waste discharges are to be reported and cleaned up consistent with a hazardous material spill.

Drinking water protection signs (proposed): It is proposed that hazard signs are installed at active mine pits, with a warning statement on drinking water protection and mandatory off-site waste disposal.

Workforce access restrictions (proposed): It is proposed that access within designated buffers from streams and reservoirs, is only permitted to those employees and contractors that have completed the appropriate training package, to understand the drinking water catchment sensitivity, and mandatory procedures to minimise those risk. Refresher training is to occur annually with acknowledgement of employee and contractor obligations.

Riparian reservoir buffers – overland flow attenuation (existing): In the event of failure of the earlier described barriers, some attenuation of pathogen load is expected during overland flow, due to filtration in Jarrah forest understorey vegetation and litter layer.

Seasonal stream attenuation (existing): Streams flow seasonally for several months of the year and then are dry. Some attenuation of pathogen loads will occur if discharging to a dry stream, when there is no flow for a few to several months. Limited attenuation may occur in flowing streams, however travel time is likely to be in the order of minutes to hours until discharge into the reservoir.

Reservoir attenuation (existing): Serpentine Dam is the downstream reservoir for the Myara and Myara North mine facilities. South Dandalup Dam is the downstream reservoir for the Holyoake mine facilities. Some dilution and inactivation of pathogens is expected due to natural mixing and retention processes in the reservoir.

In addition to the above barriers, Alcoa have opted not to mine withing the Serpentine Pipehead catchment, thus eliminating field activities in this particular PDWSA and RPZ.

14.2 Pathogen barriers – workforce at mine facilities

Reservoir protection zone (existing): Mine facilities are located outside of the RPZ, increasing travel pathways and attenuation for pathogens prior to discharge into the reservoir.

Sewage treatment and disinfection (existing and proposed): Sewage at mine facilities is treated in a sewage treatment plant, with primary and secondary treatment followed by chlorine disinfection. Consideration will be given to additional treatment with advanced processes such as ultraviolet disinfection and filtration to provide additional pathogen removal, including of *Cryptosporidium* as the key pathogen of concern in the drinking water catchments.

Treated sewage effluent irrigation (existing): Drip irrigation of treated effluent over Jarrah forest vegetation is performed within the mine facilities complex. Water is lost to evapotranspiration, with some leaching of effluent to prevent the salt build-up. Pathogens are captured in the shallow soil layer and die-off through natural processes.

Overland flow attenuation (existing): In the event of failure in the sewage treatment or irrigation barriers, effluent may travel downslope of the STP or irrigation area. Some pathogen attenuation during overland flow is expected due to filtration in the Jarrah forest understorey vegetation and litter layer. Overland flow is unlikely to reach streams or reservoirs, unless heavy rainfall or wet catchment conditions are present.

Subsurface flow attenuation (existing): In the event of failure in the sewage treatment or irrigation barriers, pathogens may be transported with infiltration through the unsaturated zone and then transported downslope with groundwater. Some pathogen attenuation during subsurface flow is expected due to filtration in the subsurface matrix.

Seasonal stream attenuation (existing): Stream flows within the drinking water catchments are seasonal for several months of the year, and are then dry. Some pathogen attenuation is expected with discharge to a dry stream bed, where there is no flow for a few to several months. Limited attenuation may occur in flowing streams however travel time is likely to be in the order of minutes to hours until discharge into the reservoir.

Reservoir attenuation (existing): Serpentine Dam is the downstream reservoir for the Myara and Myara North mine facilities. South Dandalup Dam is the downstream reservoir for the Holyoake mine facilities. Some dilution and inactivation of pathogens is expected due to natural mixing and retention processes in the reservoir.

14.3 Turbid discharge barriers

No mining in areas of high slope (existing): Slope is a demonstrated key factor in the generation of channelised flow, higher runoff velocities and volumes, and higher soil erosion. Mine planning to reassess the slope (or slope-length) at which clearing and/or mining is excluded.

Staged and seasonal approach to development and clearing (existing): Mine development, mining and rehabilitation occurs in a staged manner within a mine region. The average timeframe between clearing and completion of mine rehabilitation is 3-4 years.

Clearing contour windrows (existing): Cleared wood waste is arranged in windrows on the contour, prior to burning or reuse. Windows intercept runoff to prevent flow concentration and subsequent erosion of mine pit and overflow of drainage protection shots. Clearing contour windrows are a temporary, seasonal barrier applied as cleared wood waste is available.

In-pit drainage (existing): Engineered and maintained mine drainage bunds and trenches intercept and convey runoff and sediment to in-pit sumps, preventing uncontrolled discharge.

In-pit drainage protection shots (existing): Drainage shots, also called water shots, comprise shallow (~1.8 m) blasted or ripped ground on the downslope perimeter of each mine pit. Drainage shots capture and infiltrated surface runoff within the blasted voids.

In-pit sumps (existing): Some mine pits have in-pit sumps that collect runoff from pit floors and/or in-pit drainage. In-pit sumps are designed to retain runoff from major storm events.

Interception sumps (existing): All paved areas at mine facilities and all haul roads drain to interception sumps. Paved areas upstream of major rivers (e.g. Big Brook) drain to triple interceptor sumps. All sumps are designed to retain rainfall from major storm events.

Rehabilitation revegetation prescription (existing): Revegetation establishes a native understorey and overstorey with more than 80 per cent of the floristic diversity of un-mined forest. Substantial establishment of understorey coverage within five years.

Rehabilitation substrate prescription (existing): Rehabilitation substrate includes deep ripping of regolith, application of minimum 200 mm overburden/topsoil and ripping on the contour. Deep ripping promotes infiltration of runoff into the regolith. Application of minimum overburden provides a gravel-sand layer that protects finer grained regolith materials from erosion. Contour ripping creates a furrowed surface that promotes retention and infiltration of runoff.

Rehabilitation landscape prescription (existing): Rehabilitation prescription limits final landform to slopes less than 16 degrees. Downslope toe of rehabilitated pits can have a reverse batter that creates a 'sunken' landform that retains surface runoff and prevents discharge.

Overland flow attenuation (existing): In the event of failure in above barriers, overflows from mine pits or haul road sumps will travel via overland flow downslope. Sediment will attenuate during overland flow due to filtration in Jarrah forest understorey vegetation and litter layer.

Stream attenuation (existing): In the event of failure of above barrier, sediment laden runoff will discharge into streams. Sediment in stream flow is subject to deposition, filtration and dilution prior to discharge into the reservoir.

Reservoir attenuation (existing): Serpentine Dam is the downstream reservoir for the Myara and Myara North mine facilities. South Dandalup Dam is the downstream reservoir for the Holyoake mine facilities. Dilution and settlement of sediment in the reservoir.

In addition to the above barriers, Alcoa have opted not to mine withing the Serpentine Pipehead catchment, thus eliminating turbidity risk in this particular PDWSA and RPZ.

14.4 Risk assessment with barriers

The hazardous events summarised in Table 13.4 have been re-assessed based in consideration of the multiple preventative barriers described above and detailed in Appendix I. In Table 14.1, the multiple barriers affect the likelihood ratings, whilst the consequence are unchanged.

Table 14.1 Mitigated risk assessment

Residual risk event	Likelihood	Consequence	Risk
Raw sewage overflow in STP located within any catchment area, followed by heavy rainfall	Unlikely	Moderate	Medium
Treated effluent accumulates at surface of irrigation site within any catchment, followed by heavy rainfall resulting in washout	Unlikely	Moderate	Medium
Treated effluent accumulates in shallow perched aquifer, transferred to creek or downslope seepage face, and then into any reservoir	Unlikely	Moderate	Medium
Staff member with asymptomatic cryptosporidiosis in Pipehead Dam catchment area defecates in gully or riparian zone, followed by heavy rainfall	Rare	Major	Medium
Staff member with asymptomatic cryptosporidiosis in Serpentine or South Dandalup Dam catchment area defecates in gully or riparian zone, followed by heavy rainfall	Unlikely	Moderate	Medium
Mining-related inputs in reservoir results in 5 NTU or greater turbidity of source waters	Unlikely	Moderate	Medium
Substantial diesel fuel spill into Pipehead Dam reservoir	Rare	Moderate	Low
Substantial diesel fuel spill into Serpentine or South Dandalup Dam reservoir	Unlikely	Minor	Low

At the catchment scale, the proposed multiple barriers are more robust than the existing barriers, result in a lower risk of contamination than the present land use. Further opportunities to improve reliability of barriers and reduce uncertainty are detailed in Appendix I.

15. Conclusion

A public drinking water risk assessment was conducted, relating to bauxite mining operations proposed for the Serpentine Main Dam, Serpentine Pipehead Dam, and South Dandalup Dam drinking water catchment areas. The risk assessment considered potential contaminants arising from mining activities and infrastructure, as well as mobilisation of existing contaminants from past catchment activities.

Water quality risks from multiple hazards were assessed for their potential to impact human health, including pathogenic microorganisms, turbidity, fuel spills, bushfires, long-term rehabilitation, and contamination from PFAS.

The major conclusions reached from the risk assessment included the following:

– The most hazardous tested event, of direct faecal deposition in the Pipehead Dam catchment, was elevated above the threshold of acceptable risk for pathogen exposure. As an elevated risk, this hazard requires attention during detailed design, so as to define how to reduce the risk to an acceptable level.

– In addition to the averaged annual concentration of *Cryptosporidium* resulting from the examined hazards, GHD (2021) predicted the peak concentrations of this organism resulting the hazards. For the highest risk hazards presented in the Serpentine Pipehead Dam catchment, these included concentrations of ~0.00001 oocysts/L and ~0.01 oocysts/L, based on the location of faecal deposition within that catchment area. From these calculated concentrations, the latter hazard presents an unacceptable short-term high risk of cryptosporidiosis, in addition to the annualized risk. This observation supports the conclusion that the mitigation of this hazard to a level of acceptable risk requires attention during detailed design.

– Serpentine Main Dam turbidity concentrations were sensitive to changes in sump failure suspended solids concentrations, as mining comprises a sufficient proportion of the catchment landscape to do so. This contrasted with South Dandalup Dam sump failure suspended solids concentrations, as the proposed mining area is a small proportion of the overall catchment area, and there is no existing mining in that catchment and previous mining areas are assumed to be fully rehabilitated.

– In the case of the examined catchments, turbidity challenges were modelled in GHD (2021) in the form of inorganic clay and silt particles, simulating turbidity inputs associated with natural waterways and mining sumps. It is noted that these inorganic particles would not be expected to affect disinfection efficacy. Where organic particles capable of impacting efficacy are present in source waters, they can still be effectively disinfected for chlorine-resistant viruses, but require longer chlorine contact times to factor in the chlorine demand from wastewater particulates. In practice, challenge testing can be performed to validate and optimise virus disinfection, where a source water is outside the tested range for disinfection parameters such as turbidity.

– The modelled diesel spill incidents in Serpentine Main Dam and South Dandalup Dam were predicted to peak at up to 1 µg/L, whilst a mid-reservoir spill in Pipehead Dam was predicted to peak at up to 5 µg/L. These concentrations did not exceed the ADWG health based guideline limits for components of diesel fuel. The ADWG notes that diesel contamination in drinking water has a taste and odour threshold of 5 µg/L. This could be reached, with the largest predicted peak diesel concentration of up to 5 µg/L. It is recommended that some monitoring of the concentrations of diesel and other hydrocarbons is performed prior to the proposed mining transition, so as to establish baseline concentrations in the storages.

– After application of multiple barriers, all risk events were deemed to have a risk rating of Medium or less.

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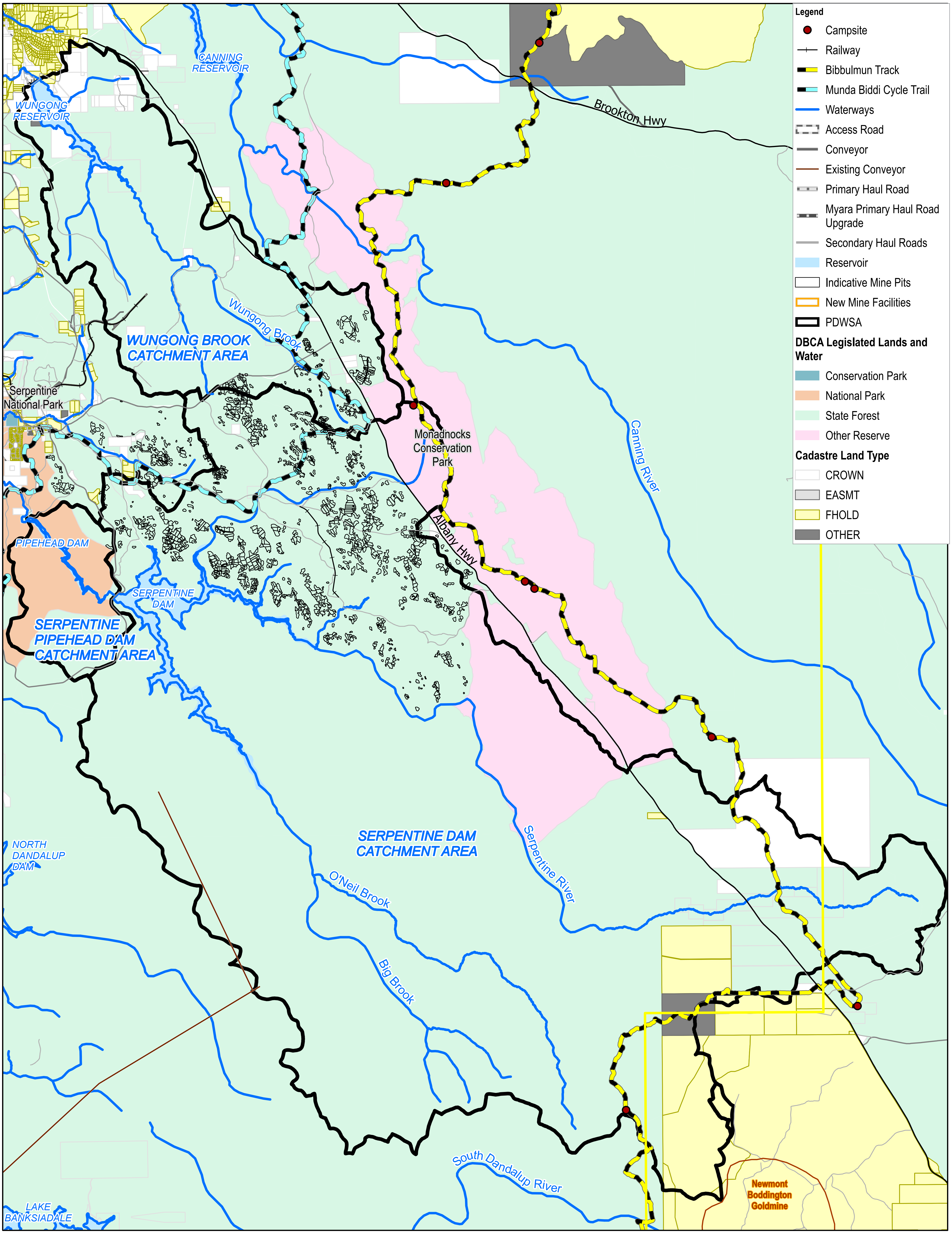
Appendices

Appendix A

Myara North and Holyoake regions



Alcoa of Australia

Drinking Water
Risk Assessment

Myara North
Land Use and Tenure

Project No. 12520591
Revision No. -
Date 15/10/2021

FIGURE A-1

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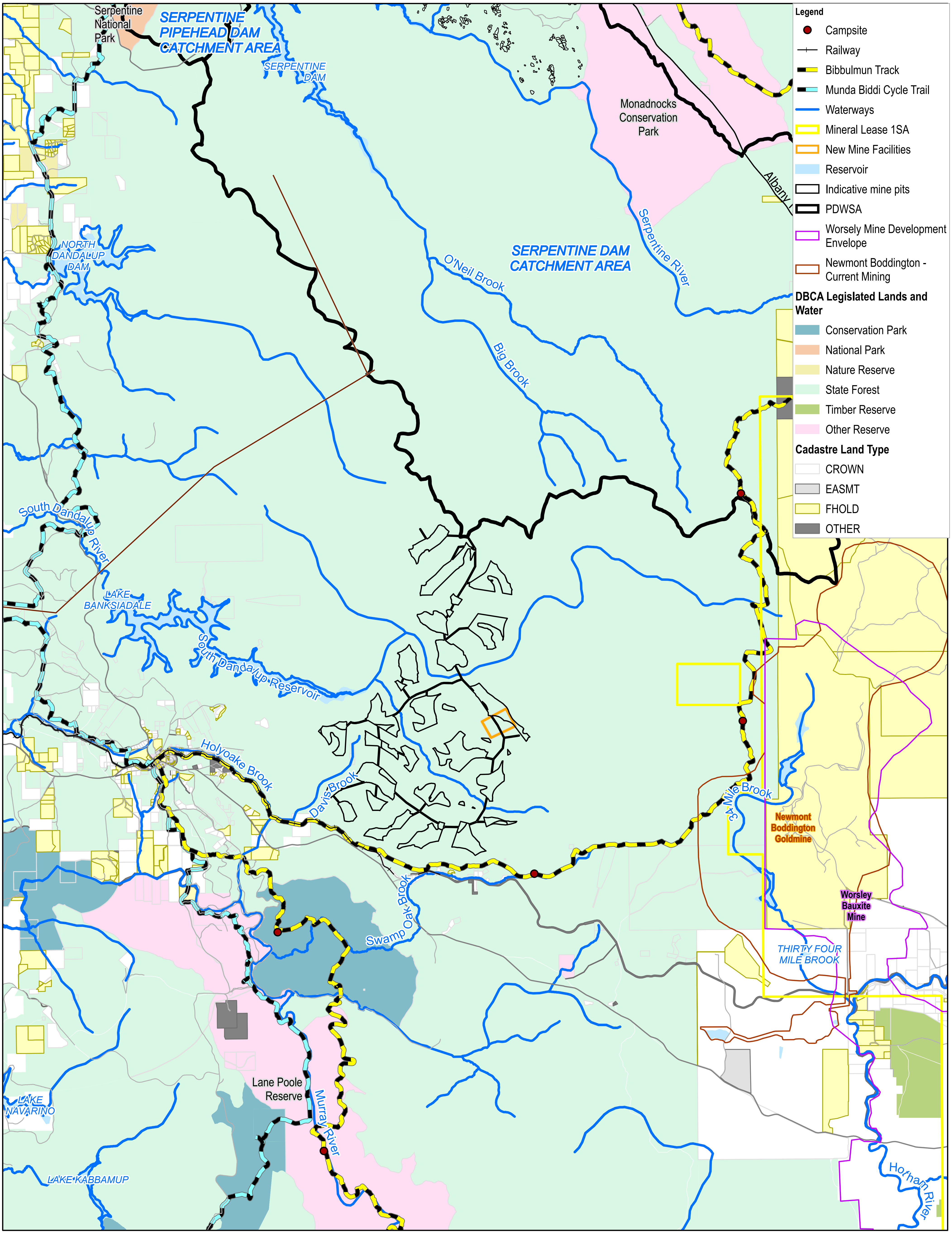

Paper Size ISO A3

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Kilometers

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 50

N

Alcoa of Australia

Drinking Water Risk Assessment

Holyoake
Land Use and Tenure

Project No. 12520591
Revision No. -
Date 15/10/2021

FIGURE A-2

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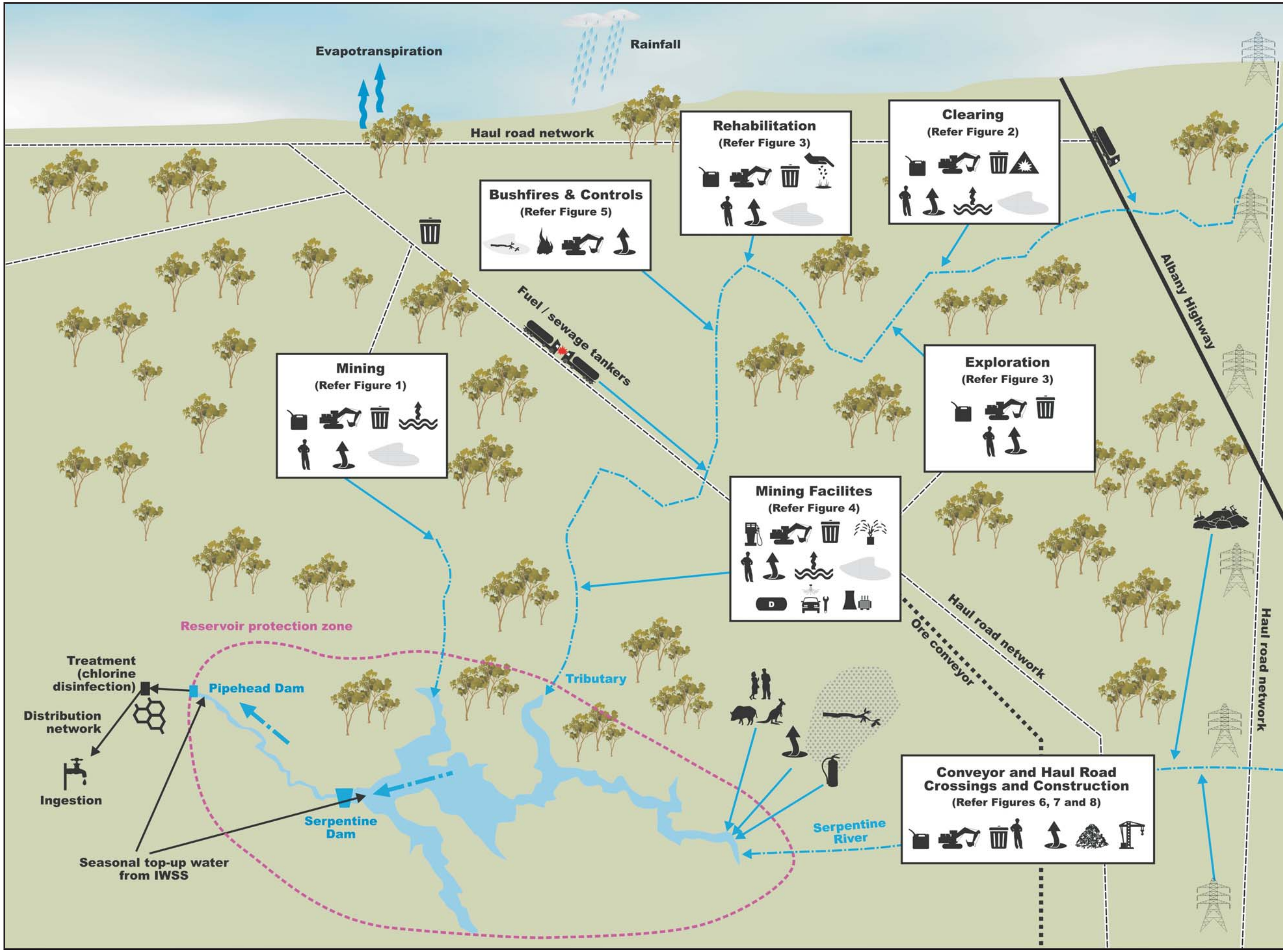
Appendix B

Conceptual Site Models



LEGEND

Source types	Contaminant
Mining sources	
Surface water and sediment releases	Suspended solids
Workers (toileting / vomiting)	Pathogens
Fuel storage / use (leaks and spills)	Hydrocarbons
Vehicles / heavy machinery (fuel/oil leaks and spills, tyre wear)	Hydrocarbons, metals, microplastics, suspended solids, nutrients, metals
Hazardous chemicals storage	Hydrocarbons, organic solvents, surfactants, PFAS
Treated wastewater irrigation	Nutrients
Diesel power plant and transformers	Hydrocarbons
Washbay and vehicle maintenance	Hydrocarbons, microplastics, suspended solids, nutrients, metals
Fertiliser / herbicide application	Fertilisers and herbicides
Diesel fuel storage	Hydrocarbons
THM formation via disinfection, organic carbon deposition	Trihalomethanes, organic carbon
Waste disposal	Nutrients, hydrocarbons, metals, pathogens
Rising groundwater table	Salts / contaminants in soils
Material stockpile	Suspended solids
Cleared area (clearing, mining)	Suspended solids
Existing land uses	
Existing fauna	Pathogens
Feral amimals	Suspended solids, pathogens
Human presence from recreation and other land uses	Pathogens
Rubbish dumping	Nutrient, chemicals, heavy metals, hydrocarbons
Cleared area (timber harvesting)	Suspended solids
Power / telephone lines (maintenance)	Herbicides, suspended solids
Legacy fire fighting foams	PFAS
Vehicles (associated with most existing land uses)	Hydrocarbons, metals, microplastics, suspended solids, nutrients, metals
Roads and tracks	Herbicides

CONTAMINANT PATHWAYS

- Overland flow and / or infiltration and subsurface flow
- Seasonal flow path
- Perennial flow path
- Gravity / pump fed flow path

Conceptual diagram only - not to scale

GHD

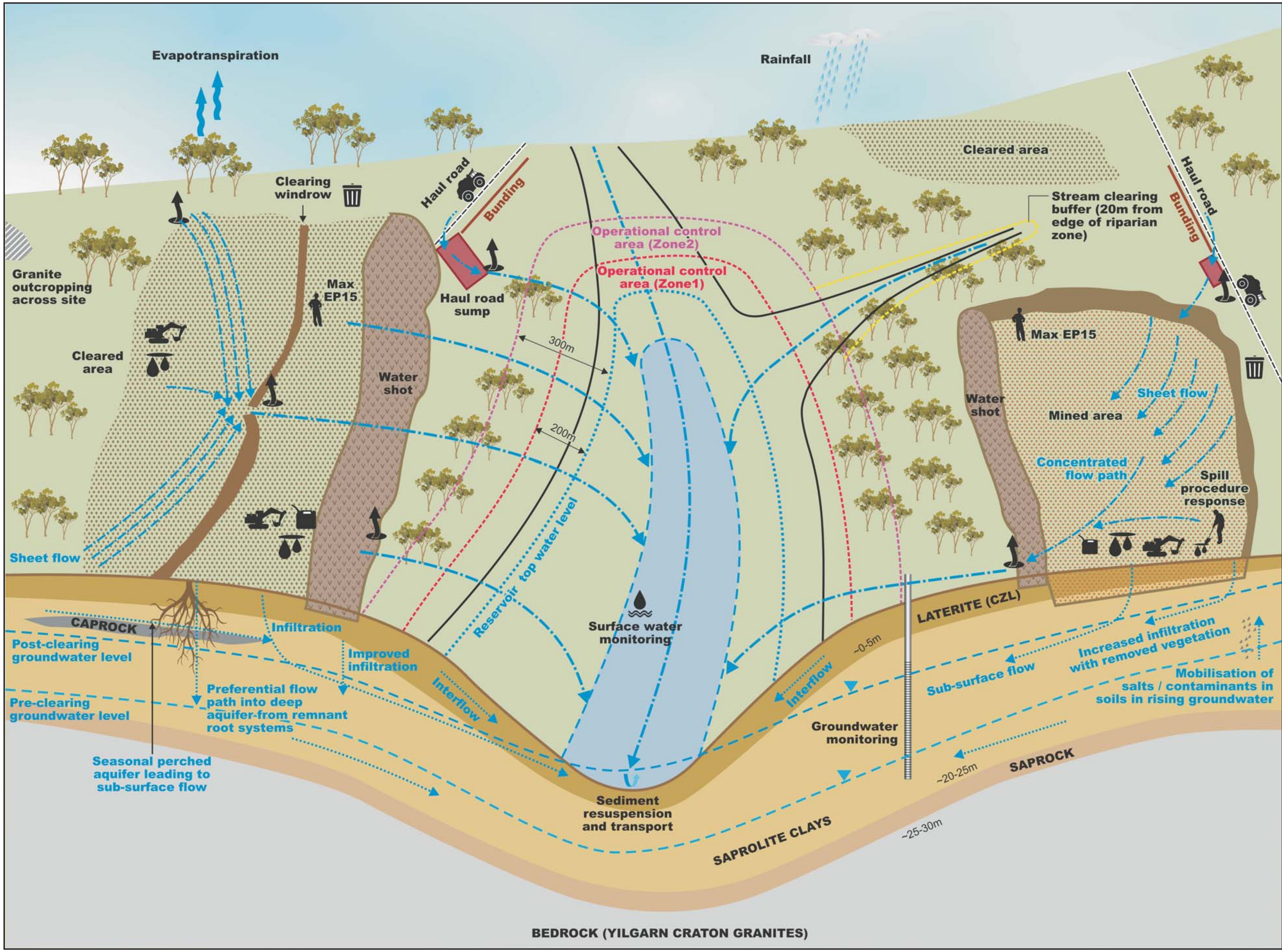
Alcoa of Australia Pty Ltd
Huntly Mine Expansion
Drinking Water Quality Risk Assessment

Conceptual model overview

Job Number	12542267
Revision	A
Date	18 Oct 2021

Figure B-1

999 Hay Street Perth WA 6000 **T** 61 8 6222 8222 **F** 61 8 6222 8555 **E** permail@ghd.com **W** www.ghd.com



LEGEND

Source types	Contaminant
Surface water and sediment releases	Suspended solids
Workers (toileting / vomiting)	Pathogens
Fuel storage / use (leaks and spills)	Hydrocarbons
Vehicles / heavy machinery (fuel/oil leaks and spills, tyre wear)	Hydrocarbons, metals, microplastics, suspended solids, nutrients, metals
Waste disposal	Nutrients, hydrocarbons, metals, pathogens
Cumulative undetected leaks and spills	Hydrocarbons

CONTAMINANT PATHWAYS

- Overland flow path
- Seasonal flow path
- Infiltration and subsurface flow

Conceptual diagram only - not to scale

GHD

Alcoa of Australia Pty Ltd
Huntly Mine Expansion
Drinking Water Quality Risk Assessment

Clearing / mining conceptual model

Job Number	12542267
Revision	A
Date	18 Oct 2021

Figure B-2

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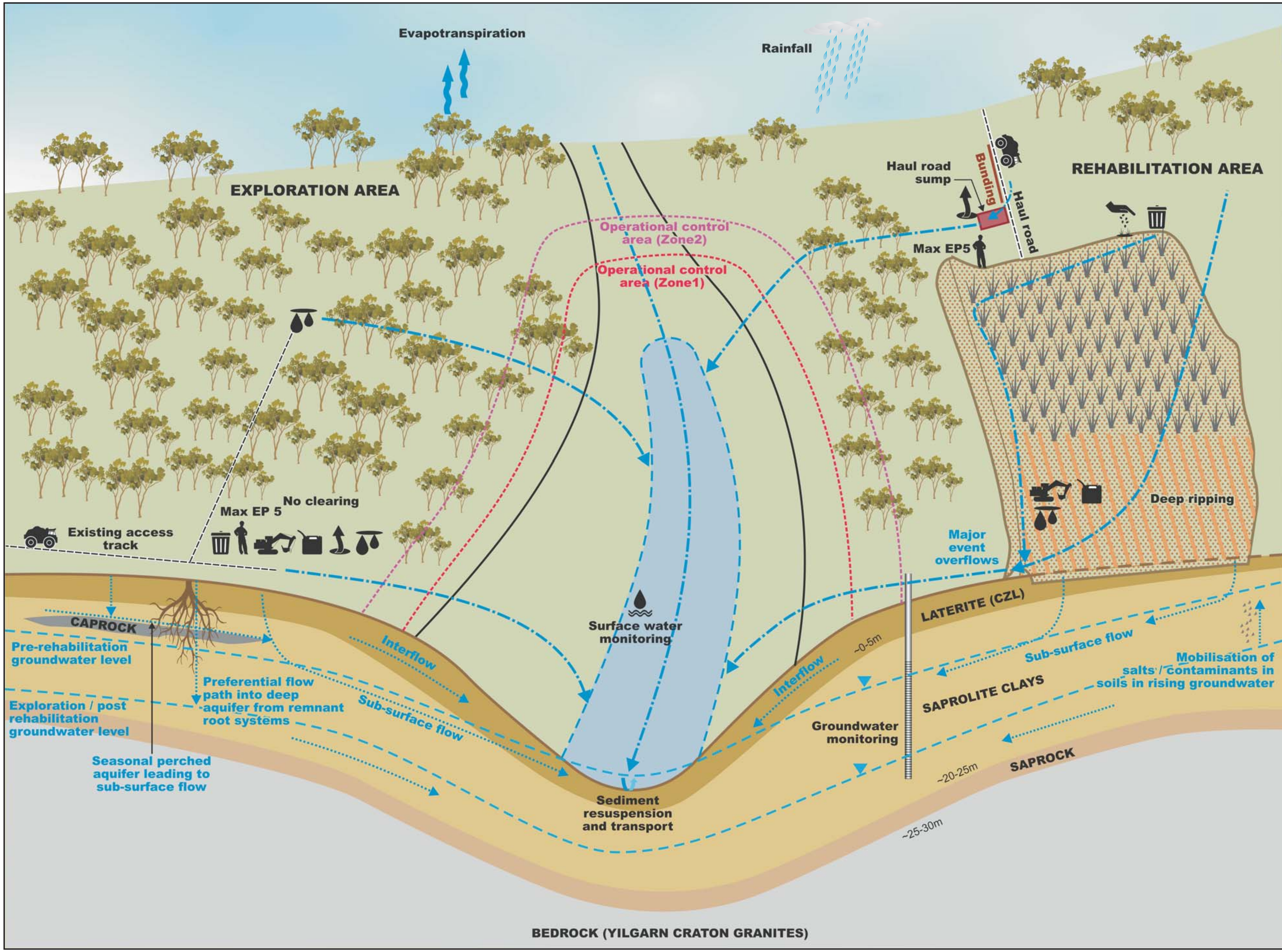

LEGEND

Source types		Contaminant
	Surface water and sediment releases	Suspended solids
	Workers (toileting / vomiting)	Pathogens
	Fuel storage / use (leaks and spills)	Hydrocarbons
	Vehicles / heavy machinery (fuel/oil leaks and spills, tyre wear)	Hydrocarbons, metals, microplastics, suspended solids, nutrients, metals
	Waste disposal	Nutrients, hydrocarbons, metals, pathogens
	Cumulative undetected leaks and spills	Hydrocarbons
	Fertiliser and herbicide application	Nutrients, herbicides

CONTAMINANT PATHWAYS

Overland flow path

Seasonal flow path

Infiltration and subsurface flow

Conceptual diagram only - not to scale

GHD

Alcoa of Australia Pty Ltd
Huntly Mine Expansion
Drinking Water Quality Risk Assessment

Job Number 12542267
Revision A
Date 18 Oct 2021

Exploration / rehabilitation conceptual model

Figure B-3

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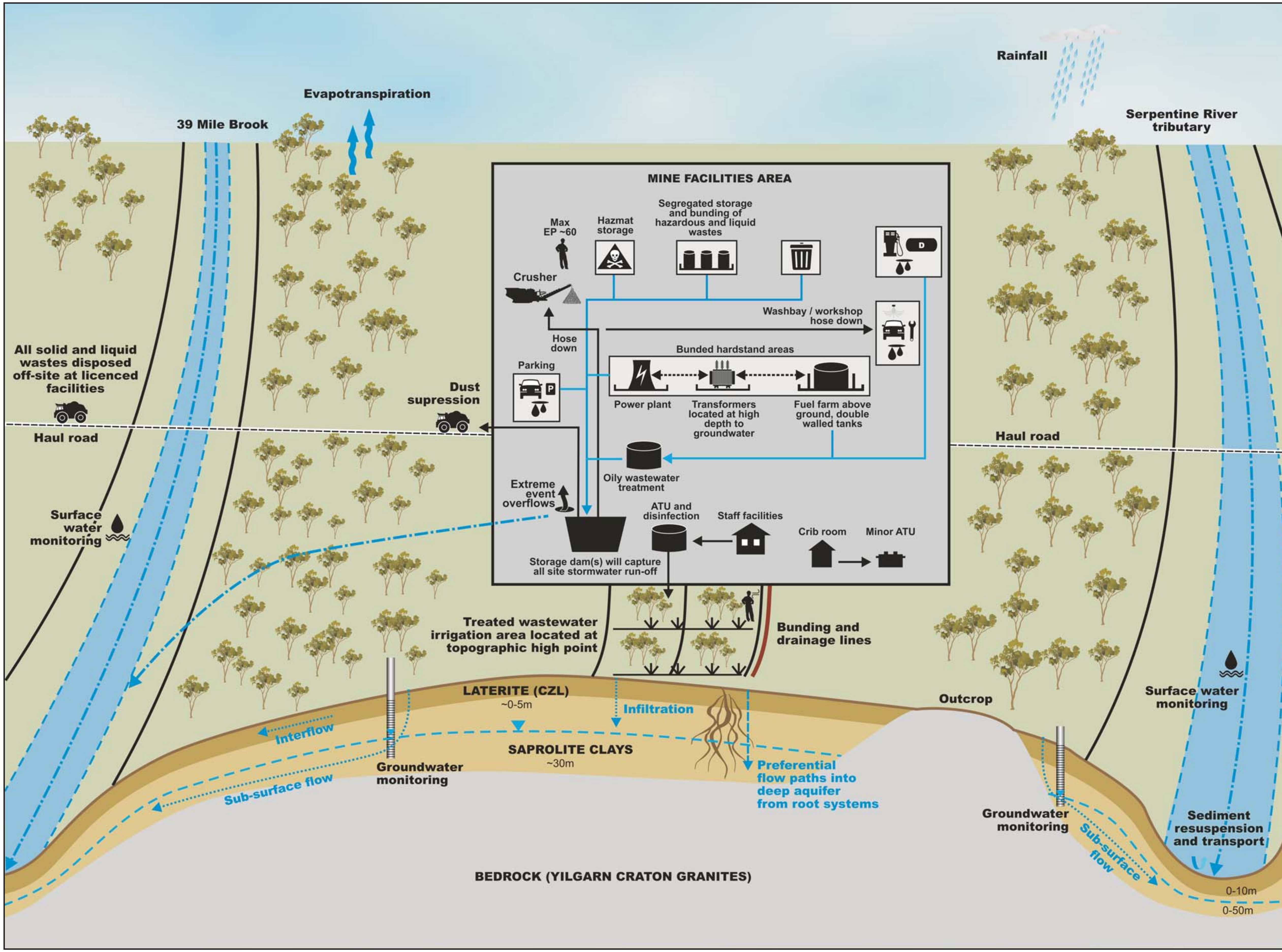

LEGEND

Source types	Contaminant
Surface water and sediment releases	Suspended solids
Workers (toileting / vomiting)	Pathogens
Fuel storage / use (leaks and spills)	Hydrocarbons
Vehicles / heavy machinery (fuel/oil leaks and spills, tyre wear)	Hydrocarbons, metals, microplastics, suspended solids, nutrients, metals
Waste disposal	Nutrients, hydrocarbons, metals, pathogens
Cumulative undetected leaks and spills	Hydrocarbons
Washbay water, vehicle maintenance (spills / leaks)	Hydrocarbons, metals, microplastics, suspended solids, nutrients, metals
Refuelling bay	Hydrocarbons
Power plant	Hydrocarbons
Treated wastewater irrigation	Nutrients, pathogens

CONTAMINANT PATHWAYS

- Overland flow path
- Infiltration and subsurface flow
- Seasonal flow path

Controls

- Direct inhalation
- Gravity / pump fed flow
- Bunded hardstand areas to control spills / leaks

Conceptual diagram only - not to scale

Alcoa of Australia Pty Ltd
Huntly Mine Expansion
Drinking Water Quality Risk Assessment

Mine facilities conceptual model

Job Number 12542267
Revision A
Date 31 Mar 2021

Figure B-4

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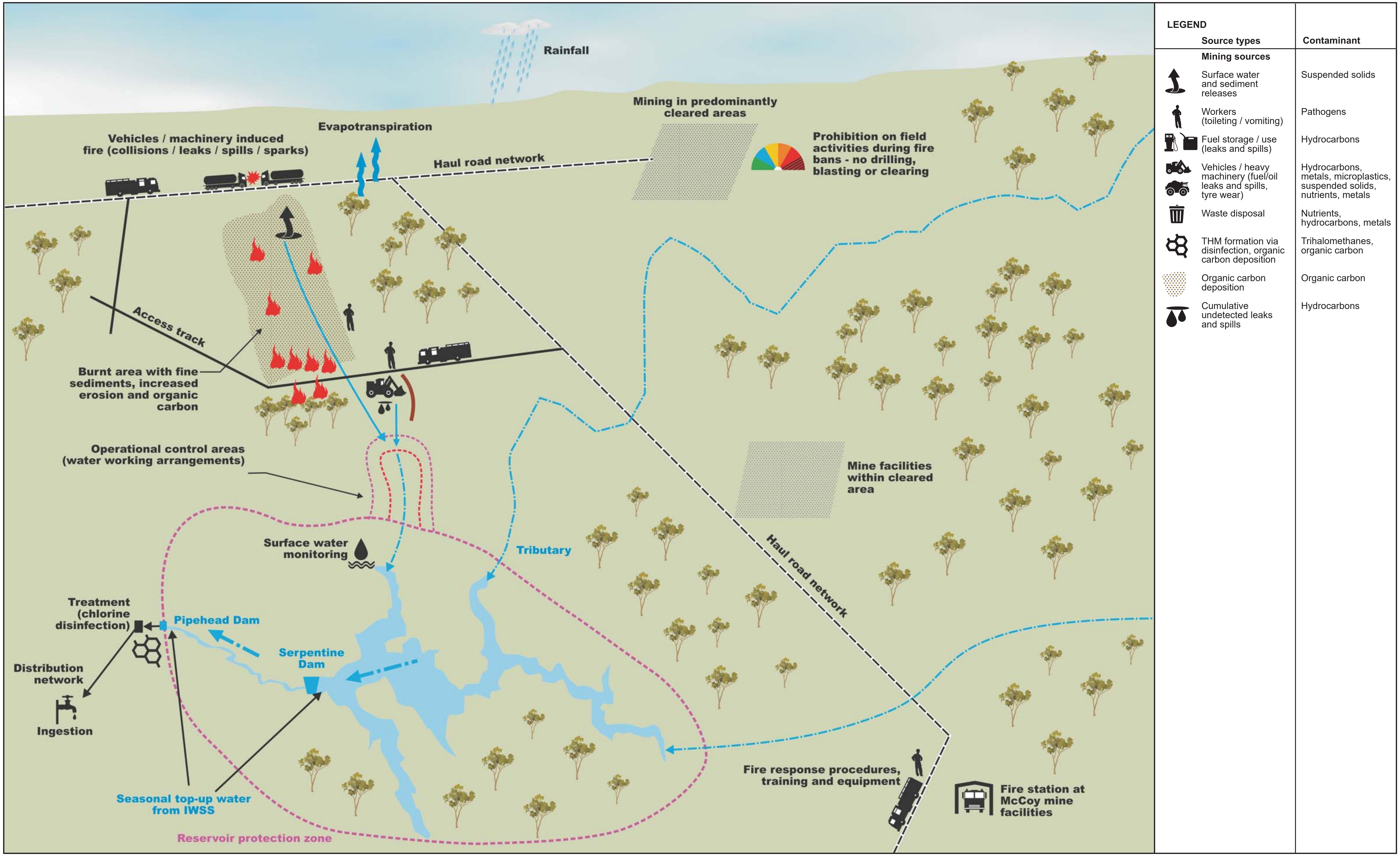

CONTAMINANT PATHWAYS

- Overland flow and / or infiltration and subsurface flow
- Seasonal flow path
- Perennial flow path
- Gravity / pump fed flow path

Conceptual diagram only - not to scale

GHD

Alcoa of Australia Pty Ltd
Huntly Mine Expansion
Drinking Water Quality Risk Assessment

Job Number 12542267
Revision A
Date 18 Oct 2021

Bushfire and controls conceptual model overview

Figure B-5

GHD\Launceston\Projects\12\542267\12542267_LST_05.cdr

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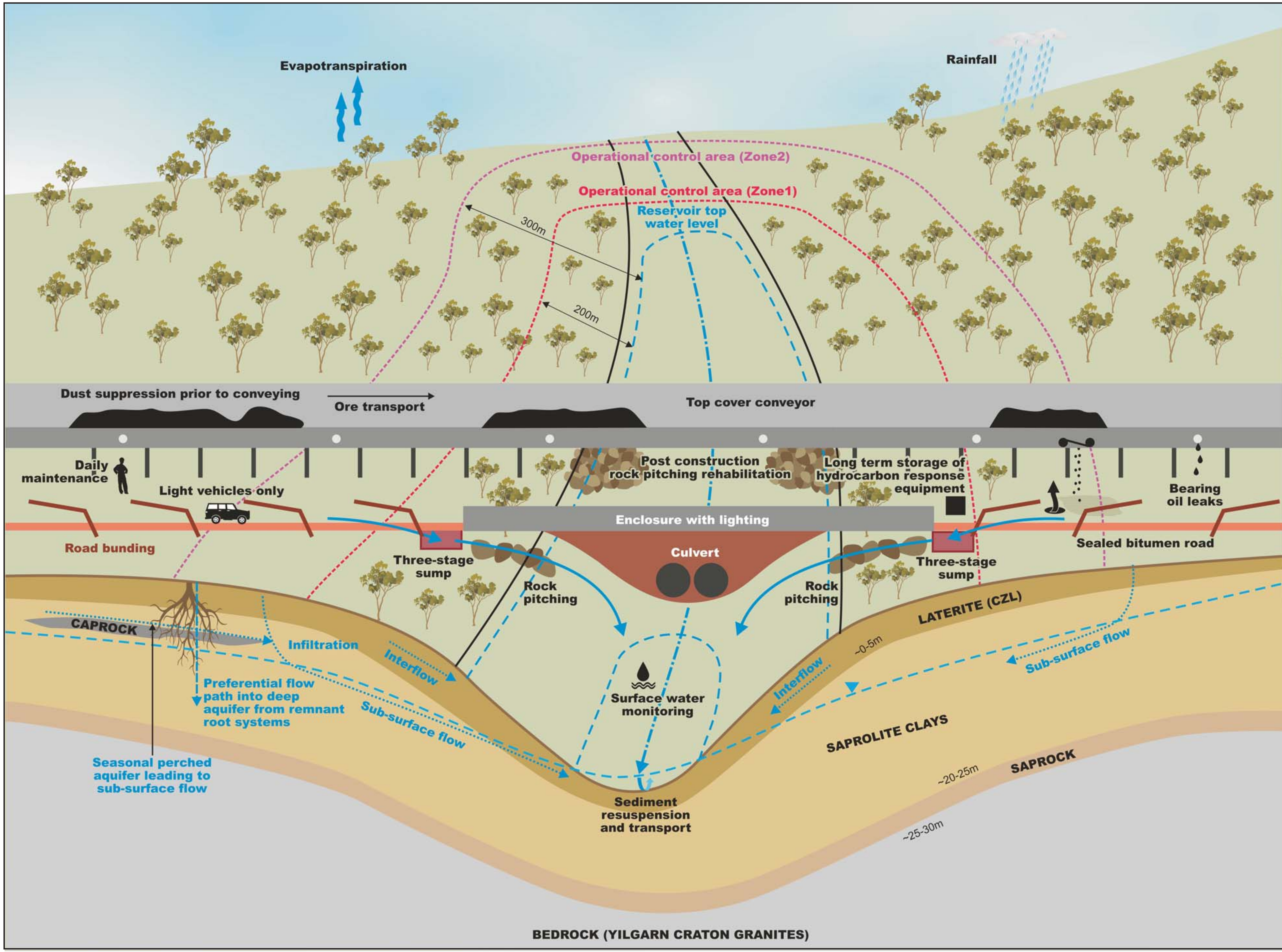

LEGEND

Source types		Contaminant
	Surface water and sediment releases	Suspended solids
	Workers (toileting / vomiting)	Pathogens
	Vehicles (fuel/oil leaks and spills, tyre wear)	Hydrocarbons, metals, microplastics, suspended solids, nutrients, metals
	Spilled ore / sediment from damaged equipment, belt abrasion or dusting	Suspended solids, plastics, metals, plastic additives

CONTAMINANT PATHWAYS

Overland flow path

Seasonal flow path

Infiltration and subsurface flow

Conceptual diagram only - not to scale

GHD

Alcoa of Australia Pty Ltd
Huntly Mine Expansion
Drinking Water Quality Risk Assessment

Job Number 12542267
Revision A
Date 6 Apr 2021

Conveyor operation conceptual model

Figure B-6

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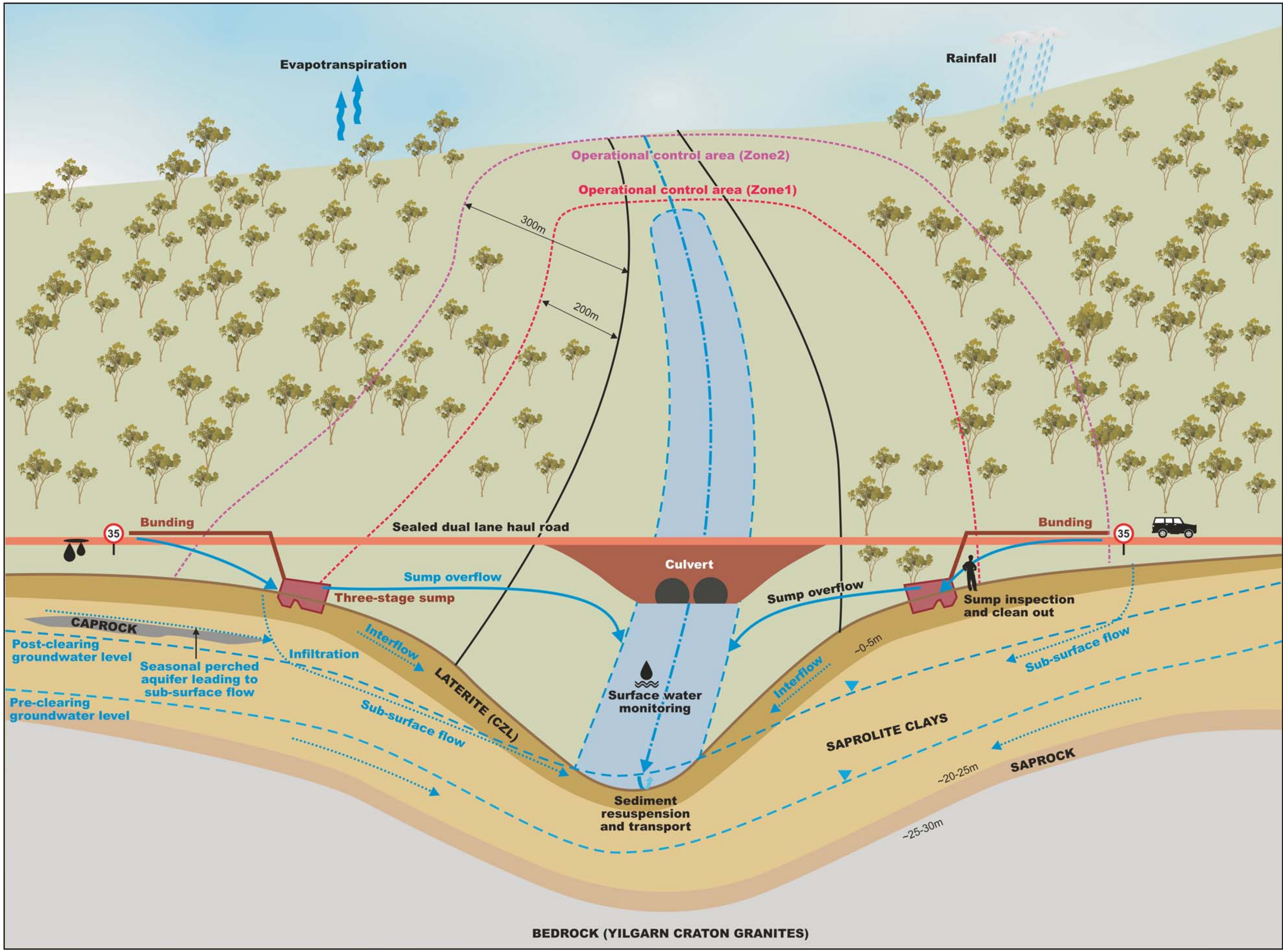

LEGEND

Source types		Contaminant
	Workers (toileting / vomiting)	Pathogens
	Vehicles (fuel/oil leaks and spills, tyre wear)	Hydrocarbons, metals, microplastics, suspended solids, nutrients, metals
	Cumulative / undetected leaks and spills	Hydrocarbons

CONTAMINANT PATHWAYS

- Overland flow path
- Seasonal flow path
- Infiltration and subsurface flow

Conceptual diagram only - not to scale

Alcoa of Australia Pty Ltd
Huntly Mine Expansion
Drinking Water Quality Risk Assessment

Haul road operation conceptual model

Job Number 12542267
Revision A
Date 31 Mar 2021

Figure B-7

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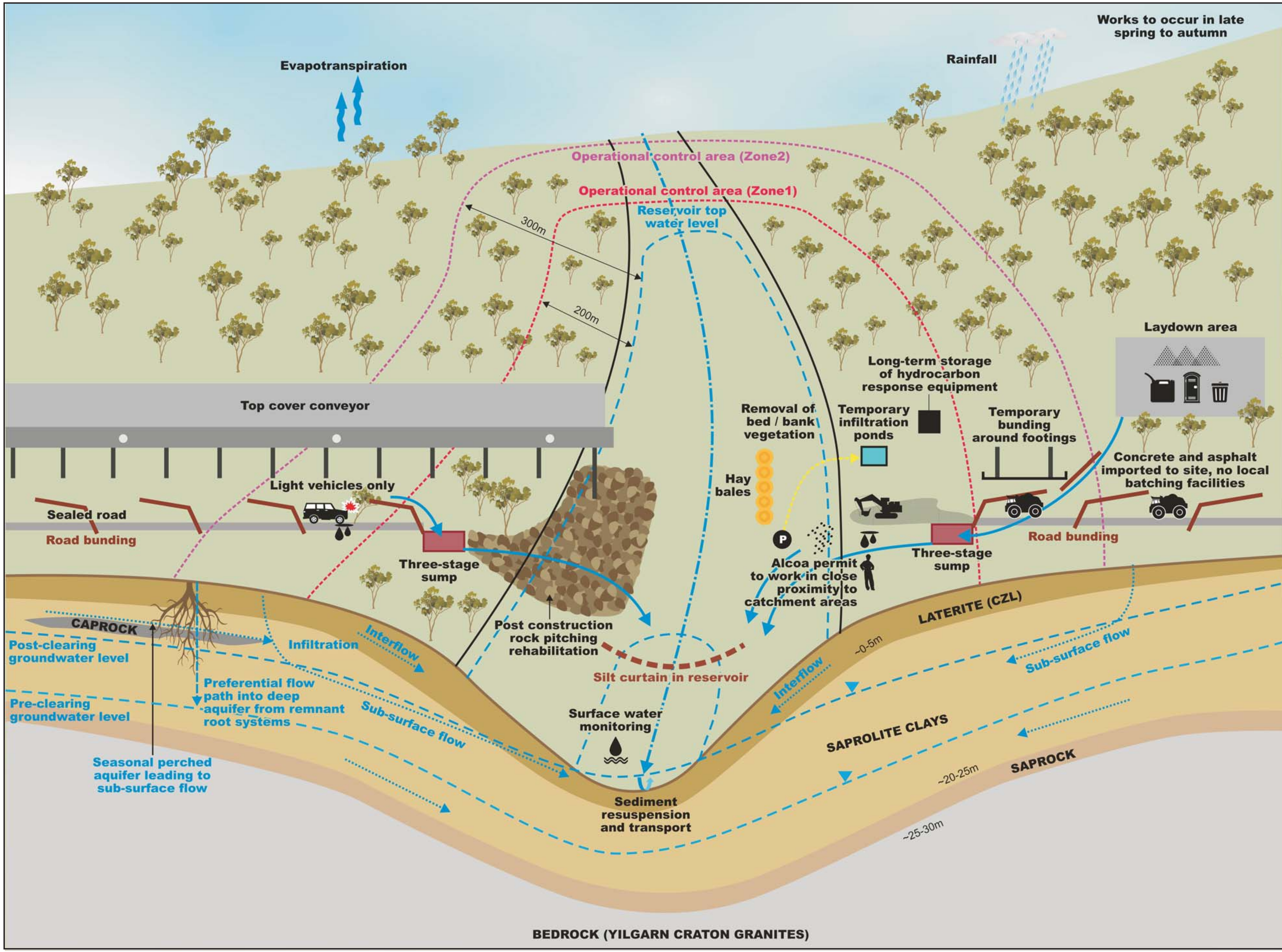

LEGEND

Source types		Contaminant
	Workers (toileting / vomiting)	Pathogens
	Vehicles (fuel/oil leaks and spills, tyre wear)	Hydrocarbons, metals, microplastics, suspended solids, nutrients, metals
	Refuelling	Hydrocarbons
	Bed and bank erosion	Suspended solids
	Cumulative undetected leaks and spills	Hydrocarbons
	Temporary material stockpiling	Suspended solids
	Waste disposal	Nutrients, hydrocarbons, metals, pathogens
	Cleared area	Suspended solids

CONTAMINANT PATHWAYS

- Overland flow path
- Infiltration and subsurface flow
- Seasonal flow path
- Pump-fed flow path

Conceptual diagram only - not to scale

Alcoa of Australia Pty Ltd
Huntly Mine Expansion
Drinking Water Quality Risk Assessment

Job Number 12542267
Revision A
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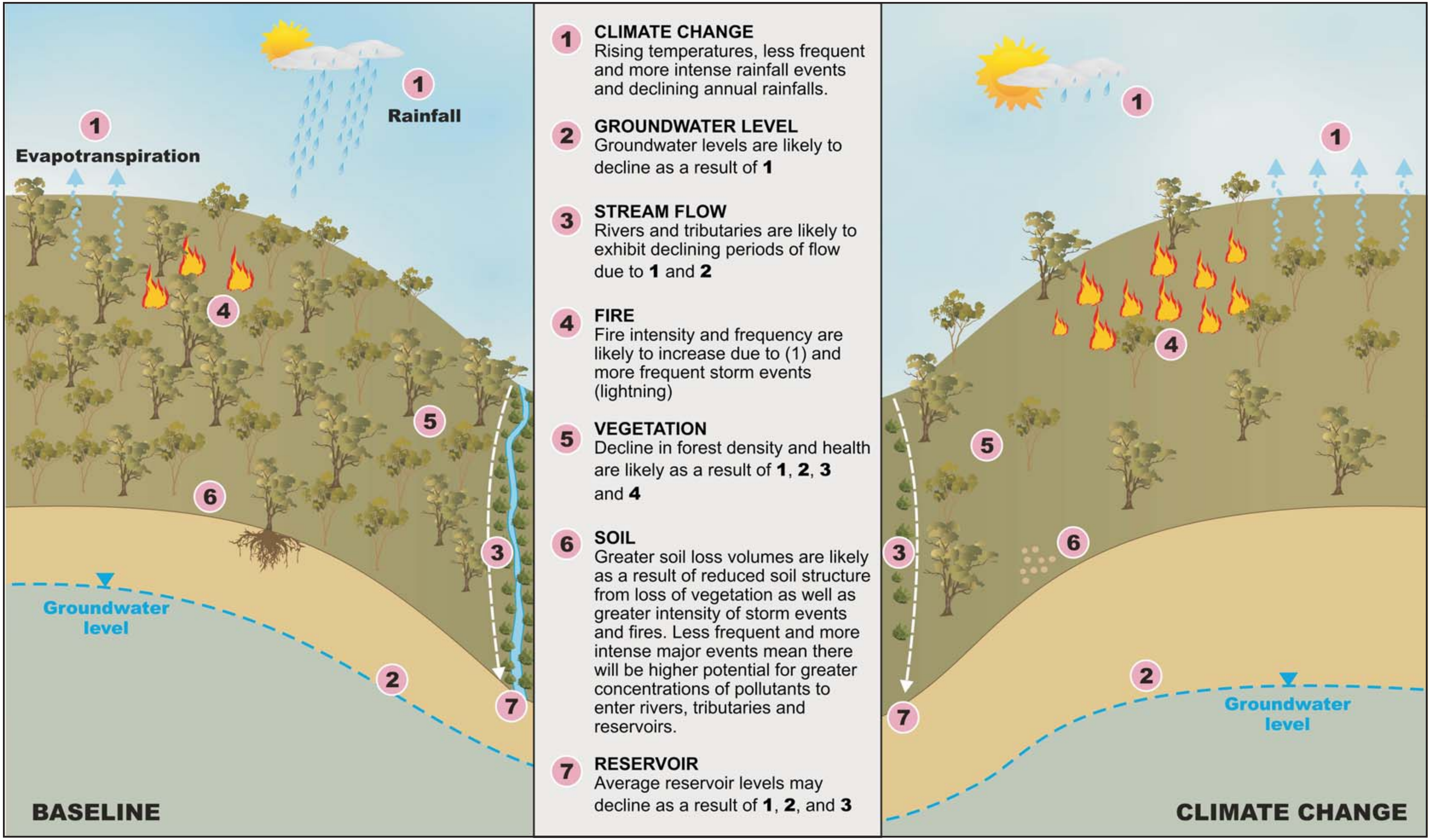
Linear infrastructure stream crossing conceptual model

Figure B-8



Conceptual diagram only - not to scale

Alcoa of Australia Pty Ltd
Huntly Mine Expansion
Drinking Water Quality Risk Assessment

Job Number	12542267
Revision	A
Date	31 Mar 2021

Conceptual site model - climate change considerations

Figure B-9

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Appendix C

Model sources, pathways, and receptors

Activity	Source	Contaminants	Pathway	Preventive measures / barriers - prior to discharge to reservoir Excludes dilution, settling, attenuation in reservoir, or treatment by Water Corporation
Exploration	1) Exploration workforce in catchment and RPZ 2) Use of bushland for toileting and vomiting	Pathogenic microorganisms	1) Overland flow during heavy rainfall and wet ground conditions, discharging into stream or direct to reservoir 2) Transport along stream during winter / spring flow period, discharging into reservoir	1) Operational Control Area between reservoir and streams (Water Working Arrangements) - vegetated surface filtration/infiltration 2) Dieback controls prohibit site access during/after heavy rainfall and wet ground conditions - reduce likelihood of overland flow 3) Seasonal stream flows, pathogen die-off over summer/autumn 4) Zero contact policy with water 5) Drinking water catchment signage 6) Limit on size of exploration teams
Construction Clearing Mining Mining support Rehabilitation	1) Operational workforce in RPZ (mine pits and haulage) and catchment (mine pits, haulage, mine facilities) 2) Construction workforce in RPZ (haul roads, conveyors) and catchment (haul roads, conveyors, mine facilities) 3) Use of bushland for toileting and vomiting	Pathogenic microorganisms	1) Overland flow during heavy rainfall and wet ground conditions, discharging into stream or direct to reservoir 2) Transport along stream during winter / spring flow period, discharging into reservoir	1) Ablution facilities provided outside of RPZ, reducing potential for toileting/vomiting in bushland 2) Operational Control Area between reservoir and streams (Water Working Arrangements) - vegetated surface filtration/infiltration 3) Dieback controls prohibit site access during/after heavy rainfall and wet ground conditions - reduce likelihood of overland flow 4) Seasonal stream flows, pathogen die-off over summer/autumn 5) Zero contact policy with water 6) Drinking water catchment signage
Construction Clearing Mining Mining support Rehabilitation	1) Construction and operational workforce in the catchment 2) Treatment of workforce sewage 3) Irrigation of treated effluent at construction compound and mine facilities	Pathogenic microorganisms	1) Irrigation of treated sewage effluent over bushland 2) Process upsets / failure resulting in reduced treatment efficacy / higher contaminant loading 3) Overland flow during heavy rainfall and wet ground conditions, discharging into stream 4) Infiltration through soils into groundwater, subsurface flow discharging into stream or direct to reservoir 5) Transport along stream during winter / spring flow period, discharging into reservoir	1) Mine facilities / WWTP sited outside of RPZ 2) Operational Control Area between irrigation area and streams - vegetated surface filtration/infiltration 3) Cutoff drains to intercept overland flow 4) Irrigation area located with high depth to groundwater - maximise unsaturated zone flow distance/attenuation 5) Single sewage treatment plant approved by Health Department 6) Single sewage treatment plant maintenance, flow metering and discharge monitoring 7) Seasonal stream flows, pathogen die-off over summer/autumn
Construction Clearing Mining Mining support Rehabilitation	1) Construction and operational workforce in the catchment 2) Mobile ablutions facilities 3) Pump out and transport of raw sewage for off-site disposal 4) Raw sewage leaks during tanker collisions	Pathogenic microorganisms	1) Overland flow, discharging into stream or direct to reservoir 2) Infiltration through soils into groundwater, subsurface flow discharging into stream or direct to reservoir 3) Transport along stream during winter / spring flow period, discharging into reservoir	1) Mobile ablutions sited outside of RPZ 2) Mobile ablutions use dead end tanks for pump out, no site discharge 3) Mobile ablutions have bunding, to capture spills in immediate vicinity 4) Haul road/road design and sump design to prevent collisions and prevent spills from discharging outside haul roads 5) Sewage tanker movements restricted to between ablutions and public roads, no sewage tanker crossing of RPZ, Serpentine River or South Dandalup River. 6) Collision avoidance system 7) Training and fatigue management for drivers 8) Spill response procedures, equipment and training

Activity	Source	Contaminants	Pathway	Preventive measures / barriers - prior to discharge to reservoir Excludes dilution, settling, attenuation in reservoir, or treatment by Water Corporation
Construction Clearing Mining Mining support Rehabilitation	1) Exploration, construction and operational vehicles and equipment in the RPZ and catchment 2) Fuel leaks during refuelling 3) Oil leaks during vehicle/equipment maintenance 4) Fuel or oil leaks during vehicle collisions	Hydrocarbons	1) Overland flow during heavy rainfall and wet ground conditions, discharging into stream or direct to reservoir 2) Surface runoff from haul roads and other paved/compacted areas, discharging into stream or direct to reservoir 3) Infiltration through soils into groundwater, subsurface flow discharging into stream or direct to reservoir 4) Transport along stream during winter / spring flow period, discharging into reservoir	1) Diesel only site - not petrol that contains higher BTEX/soluble fractions 2) In-situ refuelling limited to excavators and large equipment, all haul trucks and light vehicles refuelled at mine facilities outside RPZ 3) In-situ equipment maintenance limited to unplanned/emergencies, all planned maintenance at mine facilities at McCoy outside RPZ 4) Operational Control Area between reservoir and streams (Water Working Arrangements) 5) Haul road/road design and sump design to prevent collisions and prevent spills from discharging outside haul roads 6) Restrictions on fuel transport across Serpentine River and South Dandalup river - max 15 kL. All bulk fuel deliveries from public roads direct to mine facilities, no bulk fuel crossing of Serpentine River or South Dandalup River. 7) Collision avoidance system 8) Training and fatigue management for drivers 9) Spill response procedures, equipment and training 10) Triple sump design at haul road river crossings
Construction Clearing Mining Mining support Rehabilitation	1) Exploration, construction and operational workforce, vehicles and equipment in the RPZ and catchment 2) Bushfire due to machinery or electrical sparks	Suspended solids, organic carbon loading, trihalomethanes, haloacetic acids, haloacetonitriles and halonitromethanes.	1) Bushfire reduces soil cover and increases organic carbon loading 2) Increased erosion and sediment / organic carbon runoff from burnt areas, discharging into stream or direct to reservoir 3) Transport of sediment / organic carbon along stream during winter / spring flow period, discharging into reservoir 4) Generation of disinfection by-products, such as trihalomethanes, haloacetic acids, haloacetonitriles and halonitromethanes.	1) Prohibition on field activities during fire bans - no drilling, blasting or clearing 2) Mining and facilities activities in predominantly cleared areas 3) Operational Control Area between reservoir and streams (Water Working Arrangements) 4) Fire response procedures, equipment and training - Firestation at McCoy mine facilities 5) Prescribed burning by DBCA
Exploration Clearing and construction Roads and infrastructure Mining support Mining Rehabilitation	1) Exploration, construction and operational vehicles and equipment in the RPZ and catchment 2) Fires caused by leaks or spills during refuelling or vehicle collisions	Hydrocarbons, metals	1) Overland flow during heavy rainfall and wet ground conditions, discharging into stream or direct to reservoir 2) Infiltration through soils into groundwater, subsurface flow discharging into stream or direct to reservoir 3) Transport along stream during winter / spring flow period, discharging into reservoir	1) Diesel only site - not petrol that contains higher BTEX/soluble fractions 2) In-situ refuelling limited to excavators and large equipment, all haul trucks and light vehicles refuelled at mine facilities outside RPZ 3) Operational Control Area between reservoir and streams (Water Working Arrangements) 4) Haul road/road design and sump design to prevent collisions and prevent spills from discharging outside haul roads 5) Restrictions on fuel transport across Serpentine River and South Dandalup river - max 15 kL. All bulk fuel deliveries from public roads direct to mine facilities, no bulk fuel crossing of Serpentine River or South Dandalup River. 6) Collision avoidance system 7) Training and fatigue management for drivers 8) Fire response procedures, equipment and training - Firestation at McCoy mine facilities 9) Spill response procedures, equipment and training 10) Triple sump design at haul road river crossings
Rehabilitation	1) Use of fertiliser for revegetation	Nutrients	1) Overland flow during heavy rainfall and wet ground conditions, discharging into stream or direct to reservoir 2) Infiltration through soils into groundwater, subsurface flow discharging into stream or direct to reservoir 3) Transport along stream during winter / spring flow period, discharging into reservoir	1) Operational Control Area between reservoir and streams (Water Working Arrangements) 2) Aerial application of fertilisers, no surface transport or storage on site 3) Low application rates based on research 4) Seasonal application in spring

Activity	Source	Contaminants	Pathway	Preventive measures / barriers - prior to discharge to reservoir Excludes dilution, settling, attenuation in reservoir, or treatment by Water Corporation
Construction Clearing Mining Mining support Rehabilitation	1) Solid and liquid waste generation from construction and operational activities 2) On-site waste disposal	Nutrients, hydrocarbons, metals	1) Overland flow during heavy rainfall and wet ground conditions, discharging into stream or direct to reservoir 2) Surface runoff from haul roads and other paved/compacted areas, discharging into stream or direct to reservoir 3) Infiltration through soils into groundwater, subsurface flow discharging into stream or direct to reservoir 4) Transport along stream during winter / spring flow period, discharging into reservoir	1) All solid and liquid wastes (apart from cleared vegetative materials and sewage effluent) disposed off-site at licensed facilities 2) Cleared vegetation salvaged by FPC and Simcoa, salvaged for fauna habitats, or else burnt 3) Sewage treated and disposed via irrigation at mine facilities 4) Concrete and asphalt will be imported to site, no local batching facilities 5) Temporary storage of solid and liquid waste at designated facilities (construction compound, mine facilities) outside of RPZ 6) Segregated storage and bunding of hazardous wastes and liquid wastes 7) Construction environmental management plan 8) Spill response procedures, equipment and training
Construction Clearing Mining Mining support Rehabilitation	1) Use of aqueous film forming foam (AFFF) to respond to fire events 2) Presence of perflouro-alkyated substances (PFAS) in AFFF	PFAS	1) Overland flow during heavy rainfall and wet ground conditions, discharging into stream or direct to reservoir 2) Infiltration through soils into groundwater, subsurface flow discharging into stream or direct to reservoir 3) Transport along stream during winter / spring flow period, discharging into reservoir	1) Phasing out of PFAS in fire suppressants prior to commencement of construction and operations 2) All construction and operational fire response systems to use PFAS free fire suppressants
Construction Clearing Mining Mining support Rehabilitation	1) Water use for pavement construction, dust suppression, vehicle washing and other site uses 2) PFAS detected in existing mine water supply	PFAS	1) Surface runoff from treated haul roads, discharging into stream or direct to reservoir 2) Infiltration through soils into groundwater, subsurface flow discharging into stream or direct to reservoir 3) Transport along stream during winter / spring flow period, discharging into reservoir	1) All water supplied to mine region will be from uncontaminated catchments/sources or treated to remove PFAS to below detection limits 2) PFAS investigation into existing mine water supply, informing remediation as appropriate
Clearing Mining	1) Removal of vegetation and caprock 2) Change in hydrological regime 3) Rising groundwater mobilising salts in soils	Salinity	1) Rising groundwater following clearing of vegetation 2) Salts mobilise into groundwater and flow into streams	1) Research into hydrological changes and salinity 2) Hydrological modelling to identify areas at risk and inform mining planning, scheduling and management 3) Majority of catchment in high rainfall zone 4) Groundwater monitoring 5) Scheduling of clearing and rehabilitation
Clearing Mining	1) Removal of vegetation and caprock 2) Change in hydrological regime 3) Rising groundwater mobilising pre-mining contaminants	Hydrocarbons, PFAS	1) Rising groundwater following clearing of vegetation 2) Contaminants mobilise into groundwater and flow into streams	1) Catchment assessment to identify potential contaminating land uses 2) Catchment baseline monitoring of groundwater and surface water to identify any areas at risk 3) Catchment land use predominantly State Forest, PDWSA prevents contaminating uses 4) Groundwater monitoring 5) Scheduling of clearing and rehabilitation

Activity	Source	Contaminants	Pathway	Preventive measures / barriers - prior to discharge to reservoir Excludes dilution, settling, attenuation in reservoir, or treatment by Water Corporation
Clearing	1) Clearing of vegetation for construction and mining	Suspended solids	1) Overland flow during heavy rainfall and wet ground conditions, discharging into stream or direct to reservoir 2) Surface runoff from haul roads and other paved/compacted areas, discharging into stream or direct to reservoir 3) Infiltration through soils into groundwater, subsurface flow discharging into stream or direct to reservoir 4) Transport along stream during winter / spring flow period, discharging into reservoir	1) Construction water management plan 2) Operational Control Area between reservoir and streams (Water Working Arrangements) 3) 'Water shots' (mechanical fracturing of ground) to minimise runoff from mine pits infiltration and prevent runoff 4) Provision of engineering designed sumps downstream of haul roads and cleared areas 5) Schedule rehabilitation as early as practicable to minimise period of uncovered soil 6) Turbidity monitoring 7) Clearing windrow along contour 8) Haul road design and drainage management manual upgraded 9) Dedicated water crew undertaking sump cleaning program 10) Red alert checklist process 11) Changing of operational strategy to open fewer concurrent sites (big blend process in Myara North) 12) Mine pit analysis and sump design
Ore transport	1) Conveyor crossing over reservoir. 2) Spilling ore and/or sediment from damaged equipment or dusting off the belt. 3) Abrasion of the belt discharging pollutants. 4) Oil leaks from bearings on conveyor idlers 5) Fuel or oil leaks from accidents of maintenance/inspection vehicles along conveyor corridor.	Sediments, suspended solids Plastics, metals, plastic additives Hydrocarbons	1) Direct discharge from conveyor/road into reservoir. 2) Surface runoff from conveyor maintenance road, discharging into reservoir	1) Top cover conveyor 2) Maintenance road causeway is bunded (secondary bunding) to contain vehicles and spills. 3) Bitumen on causeway. 4) Drainage channel on length of causeway. 5) Daily maintenance/inspection/condition monitoring. 6) Dust suppression on ore prior to conveying. 7) Light vehicles used for inspections, diesel only site. 8) Spill response procedures, equipment and training
Exploration Clearing and construction Roads and infrastructure Mining support Mining Rehabilitation	1) Construction and operational vehicles and equipment in catchment and RPZ 2) Tyre wear releasing microplastics and other tyre additives (metals, plasticisers, antioxidants, antimicrobials, lubricants, and vulcanisers) via runoff	Metals, microplastics	1) Overland flow during heavy rainfall and wet ground conditions, discharging into stream or direct to reservoir 2) Surface runoff from haul roads and other paved/compacted areas, discharging into stream or direct to reservoir 3) Infiltration through soils into groundwater, subsurface flow discharging into stream or direct to reservoir 4) Transport along stream during winter / spring flow period, discharging into reservoir	1) Construction water management plan 2) Operational Control Area between reservoir and streams (Water Working Arrangements) 3) 'Water shots' (mechanical fracturing of ground) to minimise runoff from mine pits infiltration and prevent runoff 4) Provision of engineering designed sumps downstream of haul roads and cleared areas 5) Schedule rehabilitation as early as practicable to minimise period of uncovered soil 6) Turbidity monitoring 7) Clearing windrow along contour 8) Haul road design and drainage management manual upgraded 9) Dedicated water crew undertaking sump cleaning program 10) Red alert checklist process 11) Changing of operational strategy to open fewer concurrent sites (big blend process in Myara North) 12) Mine pit analysis and sump design

Activity	Source	Contaminants	Pathway	Preventive measures / barriers - prior to discharge to reservoir Excludes dilution, settling, attenuation in reservoir, or treatment by Water Corporation
Mine power supply	1) Construction and operations power supply 2) Diesel power plant fuel farm leak or spill 3) Substations transformer oil leak or spills	Hydrocarbons	1) Infiltration through soils into groundwater, subsurface flow discharging into stream or direct to reservoir 2) Transport along stream during winter / spring flow period, discharging into reservoir	1) Construction compound and mine facilities located outside of RPZ 2) Operational Control Area between power plant fuel farm/transformers and streams 3) Power plant fuel farm/transformers located at high depth to groundwater 4) Power plant fuel farm comprises above ground, double walled tanks 5) Hazardous material segregation / distance from fuel farm 6) Fire suppression system at fuel farm 7) Fire response equipment, procedures and training - McCoy fire station 8) Spill response equipment, procedures and training 9) Monitoring bores upstream and downstream of fuel farm
Mine facilities	1) Construction and operational vehicles and equipment in catchment and RPZ 2) Vehicle and equipment washdowns 3) Washbay washwater generation	Suspended solids Hydrocarbons Surfactants Nutrients Metals	1) Overland flow during heavy rainfall and wet ground conditions, discharging into stream or direct to reservoir 2) Infiltration through soils into groundwater, subsurface flow discharging into stream or direct to reservoir 3) Transport along stream during winter / spring flow period, discharging into reservoir	1) All vehicle and equipment washing undertaken at construction compound and mine facilities, located outside of RPZ 2) Heavy vehicle washway located at McCoy mine facilities 3) Operational Control Area between washbays/wastewater system and streams 3) Isolated drainage system to contaminated wastewater treatment system 4) Contaminated wastewater treatment to remove sediment and hydrocarbons 5) Treated effluent tested prior to reuse 6) Monitoring and maintenance of contaminated wastewater treatment system
Mine facilities	1) Construction and operational vehicles and equipment in catchment and RPZ 2) Fuel storage and handling at mine facilities 3) Vehicle parking at mine facilities 4) Vehicle and equipment maintenance at mine facilities	Suspended solids Hydrocarbons Surfactants Metals	1) Overland flow during heavy rainfall and wet ground conditions, discharging into stream or direct to reservoir 2) Infiltration through soils into groundwater, subsurface flow discharging into stream or direct to reservoir 4) Transport along stream during winter / spring flow period, discharging into reservoir	1) All planned vehicle and equipment maintenance undertaken at construction compound and mine facilities, located outside of RPZ 2) Operational Control Area between fuel delivery areas, refuelling bays, carparks, maintenance areas and streams 3) Refuelling bays and vehicle/equipment maintenance in roofed buildings with sealed concrete floors to prevent rainfall ingress and contain spills 4) Isolated drainage system to contaminated wastewater treatment system 5) Contaminated wastewater treatment to remove sediment and hydrocarbons 6) Treated effluent tested prior to reuse 7) Monitoring and maintenance of contaminated wastewater treatment system 8) Speed limits apply within the mine area, with lower limits (35 km/hr) near stream crossings.
Mine facilities	1) Overflow of contaminated water ponds	Suspended solids Hydrocarbons Surfactants Nutrients	1) Overland flow during heavy rainfall and wet ground conditions, discharging into stream or direct to reservoir 2) Infiltration through soils into groundwater, subsurface flow discharging into stream or direct to reservoir 3) Transport along stream during winter / spring flow period, discharging into reservoir	1) Wastewater system located outside of RPZ 2) Operational Control Area between wastewater ponds and treatment system and streams 3) Raw wastewater pond located in roofed area to prevent ingress of rain 4) Provision of freeboard in raw and treated wastewater ponds to prevent overflow during major storm events
Mine facilities	1) Construction and operation vehicles and equipment 2) Bulk diesel fuel storage for vehicle and equipment fleet	Hydrocarbons	1) Infiltration through soils into groundwater, subsurface flow discharging into stream or direct to reservoir 2) Transport along stream during winter / spring flow period, discharging into reservoir	1) Construction compound and mine facilities located outside of RPZ 2) Operational Control Area between diesel fuel farm and streams 3) Fuel farm located at high depth to groundwater 4) Fuel farm comprises above ground, double walled tanks 5) Hazardous material segregation / distance from fuel farm 6) Fire suppression system at fuel farm 7) Fire response equipment, procedures and training - McCoy fire station 8) Spill response equipment, procedures and training 9) Monitoring bores upstream and downstream of fuel farm

Activity	Source	Contaminants	Pathway	Preventive measures / barriers - prior to discharge to reservoir Excludes dilution, settling, attenuation in reservoir, or treatment by Water Corporation
Mine facilities	1) Construction and operational vehicles and equipment 2) Hazardous materials / package chemical storage and use for vehicle and equipment maintenance	HydrocarbonsOrganic solvents SurfactantsPFAS	1) Infiltration through soils into groundwater, subsurface flow discharging into stream or direct to reservoir 2) Transport along stream during winter / spring flow period, discharging into reservoir	1) Construction compound and mine facilities located outside of RPZ 2) Operational Control Area between hazmat/chemical store and streams 3) Hazmat/chemicals stored in flammable lockers or bunded pallets, within roofed buildings with sealed concrete floor 4) Hazmat segregation 5) Fire suppression system at hazmat/chemical store 6) Fire response equipment, procedures and training - McCoy fire station 7) Spill response equipment, procedures and training 8) Phase out of PFAS materials, no PFAS containing AFFF to be used in Myara North or Holyoake
Construction	1) Haul road construction over/near waterways 2) Disturbance to bed and banks of waterways	Sediment	1) Erosion of bed and banks causing elevated sediment 2) Transport along stream during winter / spring flow period, discharging into reservoir	1) Haul road crossings limited to above 100% reservoir water level. 2) Haul road crossings minimised to the extent practical and aligned at perpendicular angle to minimise disturbance at crossing sites. 3) Construction timed outside of flow periods as far as practicable. 4) If occurring during flow periods, use of upstream/downstream coffer dams to divert water around construction site. 5) Disturbed bed and banks around crossings rehabilitated/stabilised at completion of construction to prevent erosion.
Construction	1) Conveyor / causeway construction over/near streams 2) Disturbance to bed and banks of streams 3) Conveyor / causeway construction over reservoir 4) Disturbance to bed and banks of reservoir	Sediment	1) Erosion of bed and banks of streams causing elevated sediment 2) Transport along stream during winter / spring flow period, discharging into reservoir 3) Erosion of bed and banks of reservoir	1) Conveyor and causeway crossings minimised to the extent practical and aligned at perpendicular angle to minimise disturbance at crossing sites. 2) Conveyors constructed by spans over Serpentine River and Big Brook, avoiding earthworks or footings within or adjacent to the reservoir. 3) Construction to be undertaken in periods when risk of significant rainfall events occurring is low (November to April). 4) Works will be suspended during significant rainfall events. This will depend on the frequency of rainfall during the summer period. 5) Weather forecasts will be used to assess if construction operations should continue when rainfall events are predicted, following the Alcoa Red Alert process, and/or cease when a major storm event is predicted by these forecasts. 6) Installation and maintenance of temporary erosion and sediment control measures for all works within streams. 7) Disturbed streams around crossings stabilised at completion of construction to prevent erosion. 8) Lay down yard will be provided away from the stream. Ablutions will be provided here by means of portable toilets ensuring they are more than 100 m from drainage lines and the Top Water Level (TWL) of the dam.

Appendix D

Site Images

Figure D-1 Erosion control measures (watershots, blasted drainage lines) on cleared hillside

Figure D-2 Erosion control measures (watershots, blasted drainage lines) on cleared hillside #2

Figure D-3 Temporary facilities, overhead view

Figure D-4 Temporary facilities, angle view

Figure D-5 Effluent discharge area, signage

Figure D-6 Effluent discharge area, metering

Figure D-7 **Effluent discharge area, purple dripper pipe dispersing to leaf litter on ground surface**

Figure D-8 **Effluent discharge area, overland piping prior to discharge area**

Figure D-9 *20-year jarrah and marri rehabilitation at Banya*

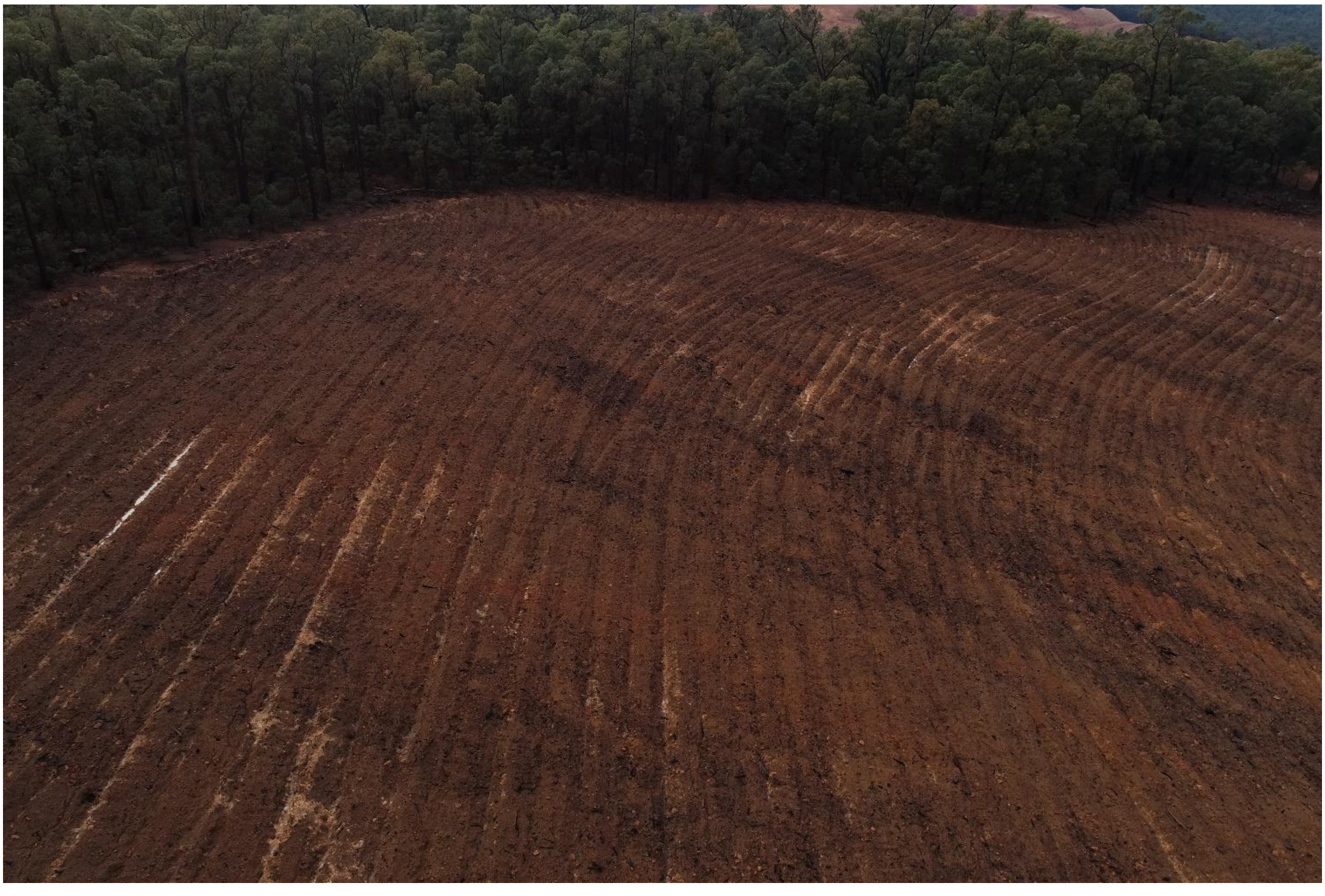

Figure 10 *0-year rehabilitation at Kisler*

Appendix E

Hydrologic modelling

Catchments

The reservoir receives inflow from major and minor streams, overland flow paths and as direct rainfall on the water surface. For modelling purposes, minor inflows are consolidated into the main inflow locations depicted in Figures E.1 and E.2 below. Where hydrodynamic model water levels are too low to match inflow locations, the inflow is applied at the nearest wet cell in the model. Catchments were defined in greater detail in areas subject to mining.

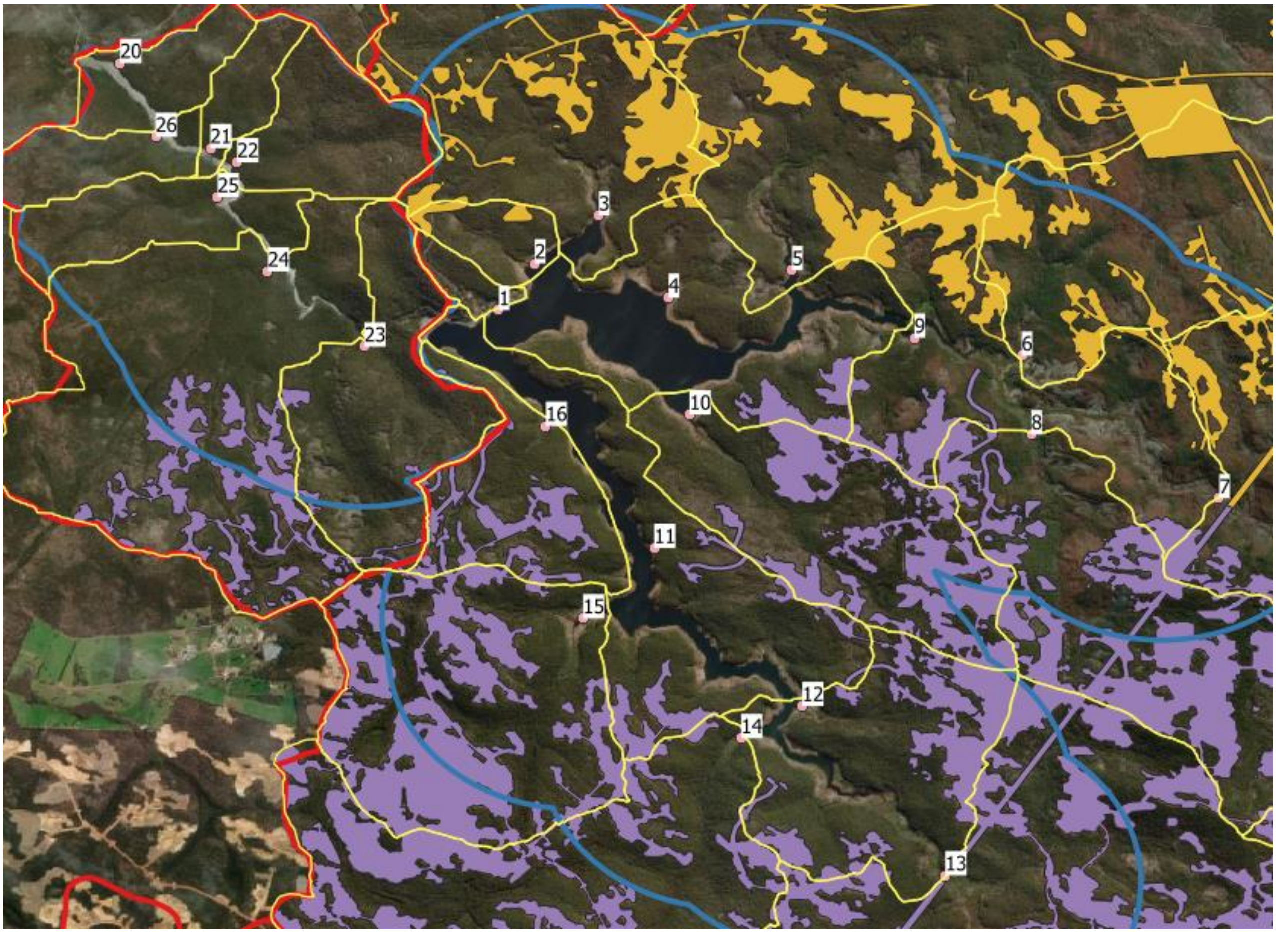

Figure E.1 Serpentine and Serpentine Pipehead catchment breakdown and hydrodynamic model input locations

Table E.1 Serpentine catchment areas (clockwise from dam wall)

Label	Total Area (ha)	Current approved mining (ha)	Proposal clearing (ha)	Total clearing (ha)
1	54	0	0	0
2	117	0	15	15
3	1064	0	243	243
4	740	49	7	56
5	6618	0	1130	1130
6	1059	0	249	249
7	29454	783	645	1428
8	982	449	0	449
9	734	67	90	157
10	718	274	0	274
11	758	74	0	74
12	664	179	0	179

Label	Total Area (ha)	Current approved mining (ha)	Proposal clearing (ha)	Total clearing (ha)
13	20889	1587	0	1587
14	1269	494	0	494
15	955	459	0	459
16	387	103	0	103

Table E.2 Serpentine Pipehead catchment areas (clockwise from dam wall)

Label	Area (ha)	Current approved mining (ha)	Propoal clearing (ha)	Total clearing (ha)
20	183	0	0	0
21	113	0	0	0
22	297	0	0	0
23	564	21	0	21
24	1295	199	0	199
25	271	0	0	0
26	163	0	0	0

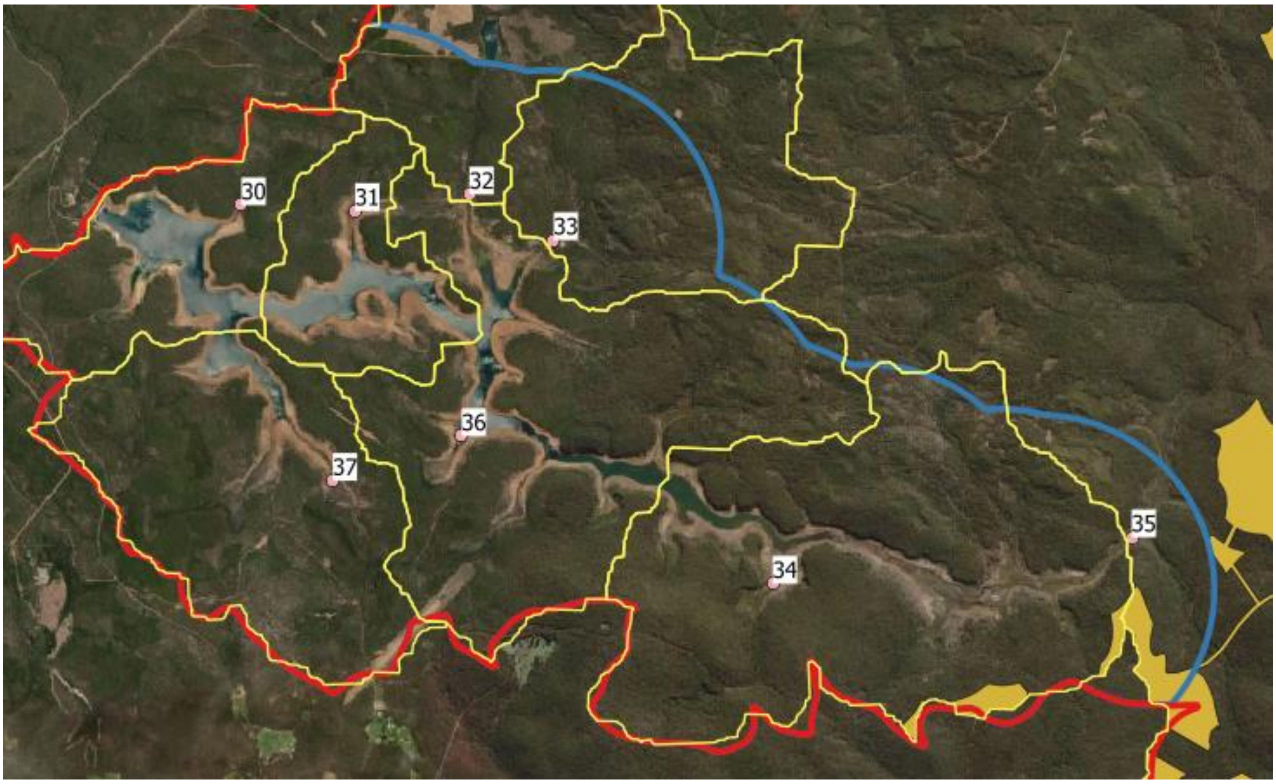

Figure E.2 South Dandalup catchment breakdown and hydrodynamic model input locations

Table E.3 South Dandalup catchment areas (clockwise from dam wall)

Label	Area (ha)	Current approved mining (ha)	Future clearing (ha)	Total clearing (ha)
30	648	0	0	0
31	458	0	0	0
32	615	0	0	0
33	903	0	0	0
34	1854	0	35	35
35	23943	0	1440	1440
36	1573	0	0	0
37	1073	0	0	0

Rainfall

Rainfall Intensity Frequency Duration (IFD) data has been obtained for the centroids of each PDWSA from the Bureau of Meteorology (Rainfall 2016 IFD Data System, 2016).

Hydrology

Approach

Referring to GHD (2021), baseflow represents between 45 and 80 per cent of streamflow. Baseflow represents a higher proportion of streamflow for long duration events compared to short duration events. For reasons explained in the Turbidity section, long duration events are critical for barriers to turbidity failure scenarios. Based on the nature of the catchment, requirements of the turbidity modelling, and standard hydrologic practices, it is proposed to analyse baseflow and mining generated quick flow separately. A conceptual runoff model is illustrated in Figure E.3. For the baseflow and interflow components of all surfaces, and the quick flow component of un-mined surfaces, streamflow is best estimated using stream gauge data, scaled relative to design rainfalls and observed runoff coefficients. The surface runoff component of mined surfaces is represented using a hydrologic event-based model.

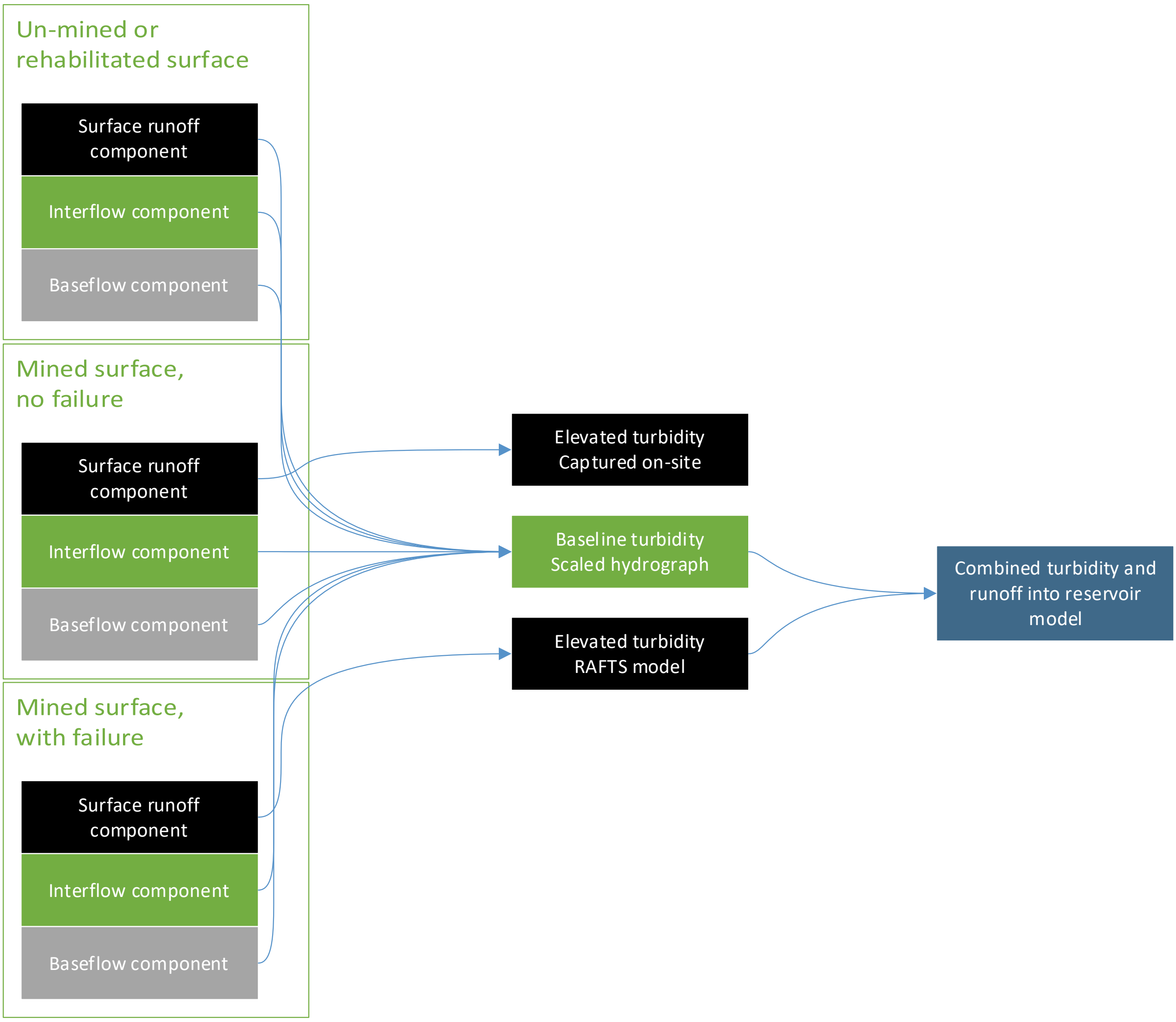

Figure E.3 Conceptual runoff model

Hydrograph scaling

Data analysis

Inspection of stream gauge data indicates that the majority of runoff (stormflow and interflow) occurs within 7-days of a rainfall event. To estimate the 14-day runoff volume for a 7-day rainfall event, the 14-day runoff coefficient was calculated for each of the gauged catchments. To understand if there is any relationship between the runoff coefficient and the magnitude of the rainfall event, a runoff coefficient was calculated for all gauged runoff events, together with magnitude of the runoff event.

Daily, spatially gridded rainfall data was analysed for the period 1970 to 2020 for each of the gauged catchments using data from SILO (2021). Rainfall IFD data was obtained for each stream gauge catchment and adjusted by an Aerial Reduction Factor (ARF) equation obtained from the Australian Rainfall and Runoff data hub (Babister, 2016). The table below summarises the frequency that the SILO data exceeded the 7-day IFD data.

Table E.4 7-Day rainfall event frequency 1970-2020 by stream flow gauging station

Rainfall AEP	614007 Del Park	614031 Jack Rocks	614035 River Rd	614037 O'Neil Rd	614059 Skeleton Road	614060 Gordon Catchment
> 1%	0	0	0	0	0	0

Rainfall AEP	614007 Del Park	614031 Jack Rocks	614035 River Rd	614037 O'Neil Rd	614059 Skeleton Road	614060 Gordon Catchment
1% to 2%	0	0	0	0	0	0
2% to 5%	8	3	0	0	0	0
5% to 10%	2	7	0	0	2	0
10% to 20%	24	7	1	2	4	7
20% to 50%	90	21	14	29	19	36
maximum recorded	204.7	229.4	178.2	170.1	195.8	176.1

The 14-day runoff coefficient was calculated for a range of 7-day rainfall events, illustrated below. The runoff coefficient increases as the frequency of the event increases. The larger catchments (614031, 614035, and 614037) have similar runoff coeffects for similar storm events, however the other smaller catchments show greater variation. To address uncertainty, the catchment weighted runoff coefficient for the 4EY event is conservatively adopted (3.50 per cent) for the 1EY, 10 per cent AEP, and 1 per cent AEP design storms.

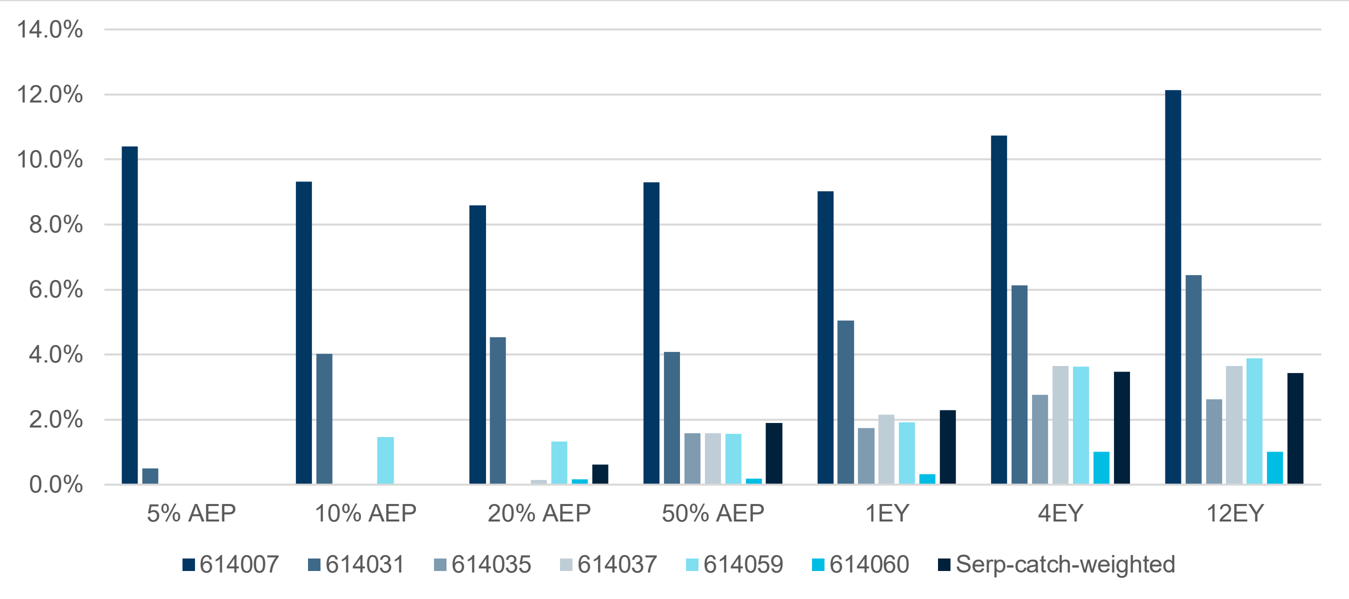

Figure E.4 14-day runoff as a percentage of 7-day rainfall

Unit hydrograph

A 14-day duration unit hydrograph was obtained from the largest recorded event at the Serpentine gauge, commencing 29th July 1996. This runoff event was assessed as a 2.4 per cent AEP (1 in 42-year) event. The hydrograph was scaled to suit the volume of runoff for each design storm (table below), using a 3.5 per cent runoff coefficient.

Table E.5 Adopted rainfall depths for each PDWSA

Catchment	1EY 7-day	10% AEP 7-day	1% AEP 7-day
Serpentine	126	183	252
Serpentine Pipehead	124	182	251
South Dandalup	118	166	228

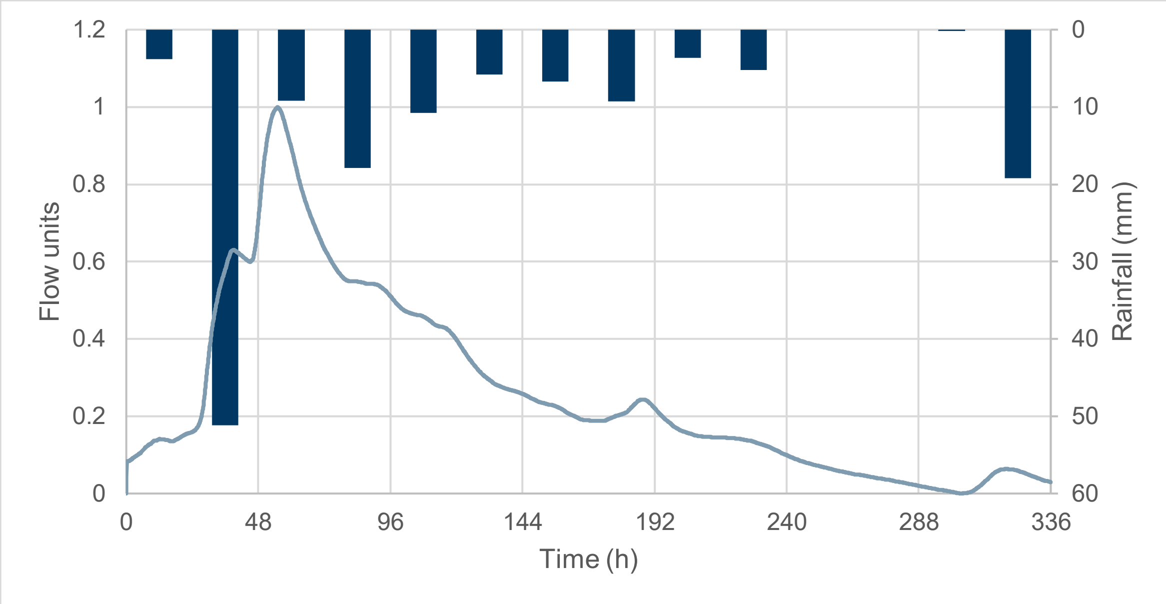

Figure E.5 Unit hydrograph

Mine surface runoff

Storm runoff rates vary according to the runoff surface, with mine pits and haul roads providing the greatest runoff. For simplicity, it will be assumed that surfaces are either undisturbed or actively mined as detailed in Table E.6.

Table E.6 Storm runoff rates by surface

Runoff surface	Runoff rates	Initial and continuing loss
Un-mined forest	Low	Modelled using scaled gauge data
Rehabilitated mining	Low-Moderate	Classified as un-mined surface
Recently rehabilitated mining	Moderate	Classified as mined surface
Cleared with topsoil	Moderate	Classified as mined surface
Cleared without topsoil	Moderate-High	Classified as mined surface
Active or recent mining, or haul road	High	15 mm, 2 mm/hr

Initial and continuing loss rates are adopted for actively mined areas in accordance with procedures detailed in Australian Rainfall and Runoff (Ball, et al., 2019). Values are estimated from anecdotal evidence and engineering judgement, taking into consideration factors such as:

- Geotechnical properties of exposed materials.
- Absence of interception loss (except for areas undergoing rehabilitation).
- Depression storage on rough mining surfaces.
- Prescence of formal and informal barriers such as deep ripping, contour ripping, and mine pits.

An XP-Rafts hydrologic model was used to represent mined runoff surfaces. For simplicity and as a means of treating uncertainty, mine runoff surfaces were assumed to be directly connected to the reservoir without any loss or attenuation associated with the overland flow paths and streams between the mine pits and the water surface. Catchment slopes were based on the topography at the date of the lidar survey.

Table E.7 summarises the areas assumed to be actively or recently mined, or haul roads.

Table E.7 Mining catchment areas

PDW SA	Mining region	Historical, current, and future clearing area within catchment (Ha)	Status	Adopted active mining catchment area (Ha)
Serpentine	O'Neil	1,153	Predominantly rehabilitated	0 (all scenarios)
	McCoy	2,140	Predominantly rehabilitated	0 (all scenarios)
	East Murray	Unknown	Rehabilitated	0 (all scenarios)
	Myara	4,517	Predominantly mined	0 (un-mined scenarios) 4,517 (existing and future scenarios)
	Myara North	2,379	Un-mined	0 (un-mined and existing scenarios) 2,379 (future scenarios)
SPH	Myara	220	Partially rehabilitated	0 (un-mined scenarios) 220 (existing scenarios) 0 (future scenarios)
South Dandalup	White	1,143	Predominantly rehabilitated	0 (all scenarios)
	Del Park	363	Predominantly rehabilitated	0 (all scenarios)
	Huntly 1&2	529	Predominantly rehabilitated	0 (all scenarios)
	Holyoake	1,475	Un-mined	0 (un-mined and existing scenarios) 1,475 (future scenarios)

Barrier failure rates

Existing and proposed turbidity barriers include sedimentation sumps, infiltration sumps, water shots, bunds, deep ripping, contour ripping, windrows, mulching, operational controls, and other ad-hoc measures. Sump failures are more likely to occur during long duration storm events where runoff volumes exceed sump volumes. Sumps are currently designed for a range of events ranging from the 10 per cent AEP 24-hour event in low risk areas to the 1 per cent AEP 7-day event in high risk areas.

Table E.8 Mine drainage design risk rating

Design Risk Rating Guide				
Location	**Facility Design Life**			
	<2-year	**2 to 5-years**	**5 to 10 years**	**10 + years**
OCA1	5	5	5	5
OCA2	5	5	5	5
RPZ	3	4	4	5
P1 Catchment	2	3	4	4
Non P1	2	2	3	4
Elsewhere	1	2	3	3

Table E.9 Mine drainage design storm event criteria

Risk Rating	Sedimentation Sump	Infiltration Sump	Conveyance (channel, drain, chute, etc.)
1	5% AEP storm of 24-hr duration	5% AEP storm of 24-hr duration	10% AEP storm of 24-hr duration
2	1% AEP storm of 24-hr duration	5% AEP storm of 24-hr duration	5% AEP storm of 24-hr duration
3	0.5% AEP storm of 24-hr duration	0.5% AEP storm of 24-hr duration	1% AEP storm of 24-hr duration
4	0.2% AEP storm of 24-hr duration	0.2% AEP storm of 24-hr duration	1% AEP storm of 72-hr duration

Risk Rating	Sedimentation Sump	Infiltration Sump	Conveyance (channel, drain, chute, etc.)
5	1% AEP storm of 168-hr duration	1% AEP storm of 72-hr duration	0.2% AEP storm of 72-hr duration

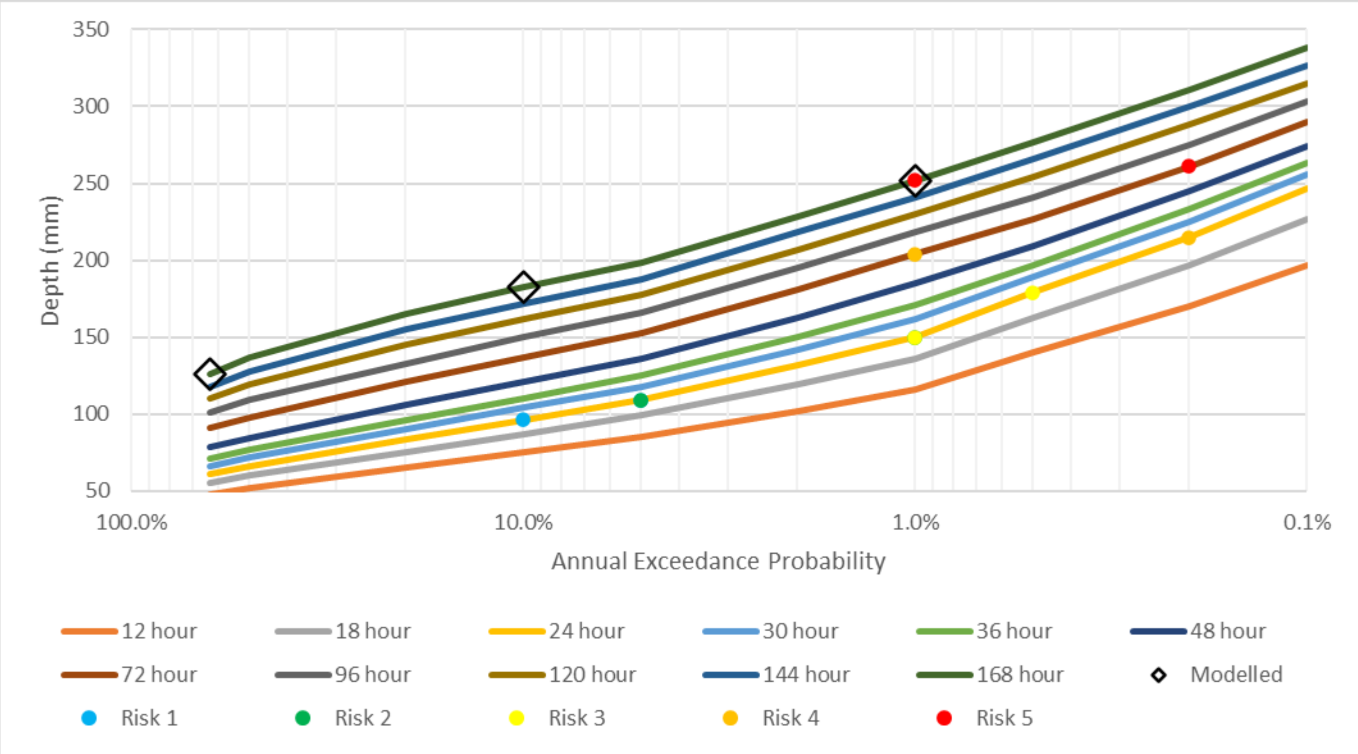

Figure E.6 Serpentine rainfall IFD

Referring to Figure E.6 in relation to Table E.9, sumps with a risk rating of 5, located in the Serpentine catchment, will cater for up to 252 mm of rainfall (1 per cent AEP 168-hour). However, all sumps with a risk rating of 4 or less will spill in this event. This event is therefore selected as the conceivable worst case failure event.

Referring to Figure E.6 in relation to Table E.9, sumps with a risk rating of 3 or above, located in the Serpentine catchment, will cater for up to 179 mm of rainfall (0.5 per cent AEP 24-hour). In a more frequently occurring 10 per cent AEP 168-hour event, 183 mm of rain will fall, causing all sumps with a risk rating of 3 or less to spill.

Referring to Figure E.6 in relation to Table E.9, sumps with a risk rating of 1 or above, located in the Serpentine catchment, will cater for up to 109 mm of rainfall (5 per cent AEP 24-hour). In a more frequently occurring 1EY 168-hour event, 126 mm of rain will fall, causing all sumps with a risk rating of 1 to spill, and infiltration sumps with a risk rating of 2 to spill.

When a sump spills, it won't necessarily fail catastrophically and release the entire content of the sump and the entire catchment runoff. However, given the uncertainty in predicting the failure behavior, and to cater for mine catchments not serviced by sumps, it has been conservatively assumed that all runoff from the mined catchment discharges to the reservoir.

Based on the number of sumps servicing the Myara mining region, it is estimated that up to 800 sumps will be active at the peak of future mining activity in the Serpentine catchment. Whilst it is not known which risk category will apply to each sump, a conservative estimate is presented in Table E.10. This is converted into a catchment proportion for each storm event.

Table E.10 Serpentine sump failure rates

Storm Event	Sump failure risk rating	Estimated number of active sumps meeting this criterion	Estimated total number of active sumps	Proportion of mined catchment
1 EY	=1 or 2 (inf.)	40	800	5%

Storm Event	Sump failure risk rating	Estimated number of active sumps meeting this criterion	Estimated total number of active sumps	Proportion of mined catchment
10% AEP	<=3	240	800	30%
1% AEP	<=4	600	800	75%

It is important to note that events shorter than 7-days will produce higher peak flows in the main streams, however, are less likely to cause a turbidity failure. The volume of runoff and the volume of turbid water is of primary concern to this assessment.

Failure likelihood

The likelihood of the design event has been assessed against Water Corporation and ADWG criteria.

Table E.11 Turbidity barrier failure likelihood

Storm event	Water Corporation Corporate Description	Water Corporation Corporate Frequency	ADWG Likelihood Rank and Descriptor
1 EY	Known to re-occur approximately annually. Known to occur across like industries or within corporation.	Will occur once per year	B – Likely
10% AEP	The event could occur at some time. Known to have occurred once ortwice within industry.	Will occur once in 10 years	D – Unlikely
1% AEP	The event may occur in exceptional circumstances. An example of this hasoccurred historically, but is not anticipated.	Will occur once in 30 years or less	E – Rare

Turbidity and Total Suspended Solids

Turbidity occurs naturally and because of clearing activities. Naturally occurring turbidity spikes are associated with large storm events. Where clearing and mining has occurred, exposed soils are subject to erosive action, mobilising sediment and suspended solids. The amount of erosion is a factor of soil properties (erodibility), catchment slope and length, rainfall intensity (erosivity), and vegetative cover.

Data analysis

The following turbidity data has been analysed:

– Water Corporation stream, reservoir, and offtake grab samples for period 2000 to 2020.
– Alcoa stream compliance monitoring continuous readings, located downstream of cleared, mined, or rehabilitated regions
– Department of Water and Environmental Regulation Water Information Reporting (WIR) measurements at stream gauges and other locations, for period 1975 to 2000

Baseline turbidity

To estimate in-stream turbidity from un-mined catchments, 4589 historical WIR turbidity measurements from the subject PDWSA's were analysed. Of this data, 1762 measurements were collected across six gauging stations at a time when flow was non-zero. These measurements were compared to flow rate for the purpose of identifying if there is a relationship between flow rate and turbidity. Where hourly streamflow data was available, streamflow was obtained for the same hour that the turbidity measurement was taken, otherwise the daily average streamflow was adopted. Given that the average daily flow readings are within ±17 per cent of the daily range, 80 per cent of the time, this is an acceptable estimate of the flow rate on these occasions. Discharge rates were converted to specific discharge to account for the varying catchment areas between gauges.

Referring to the figure below, turbidity has negligible relationship with flow rate. Measurements were also checked for hysteresis by classifying the measurement as being collected during the rising or falling limb of the hydrograph. The rising limb turbidity was, on average, 1.2 per cent higher than the falling limb readings, indicating no statistically significant hysteresis.

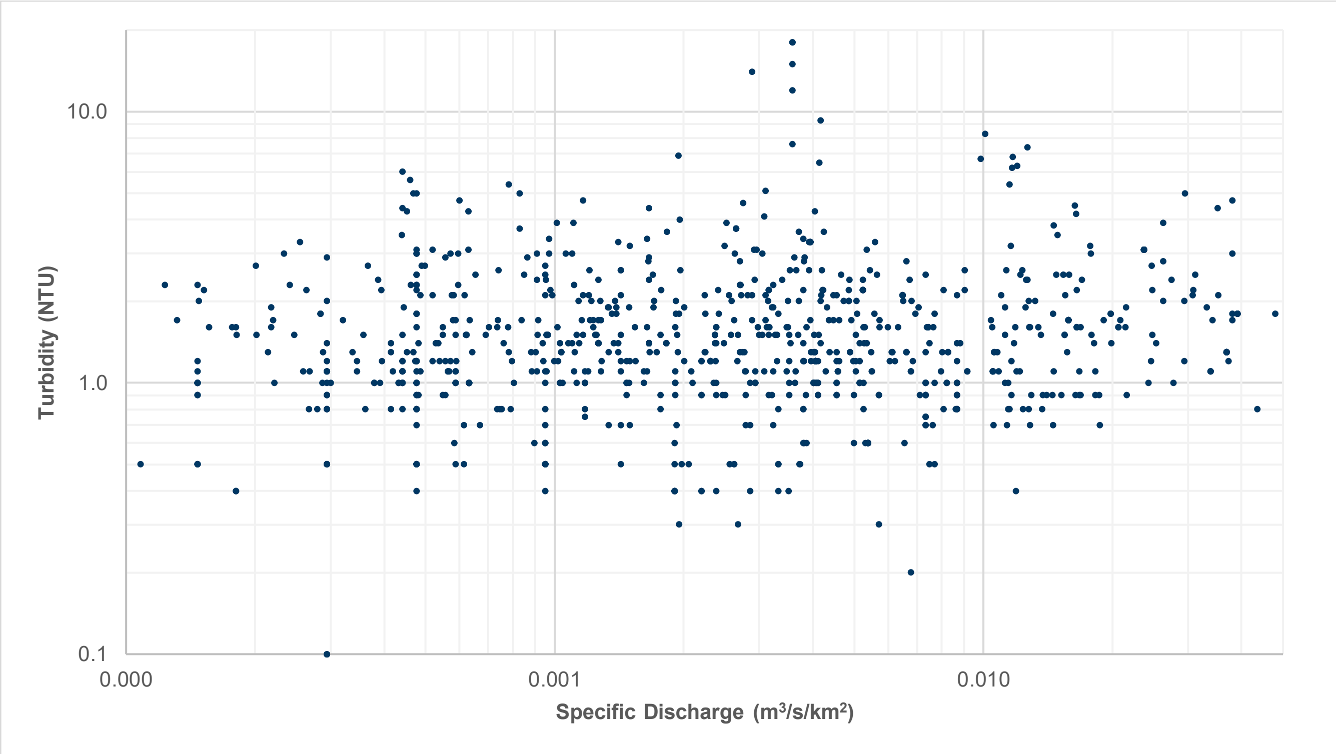

Figure E.7 ***Turbidity-flow relationship***

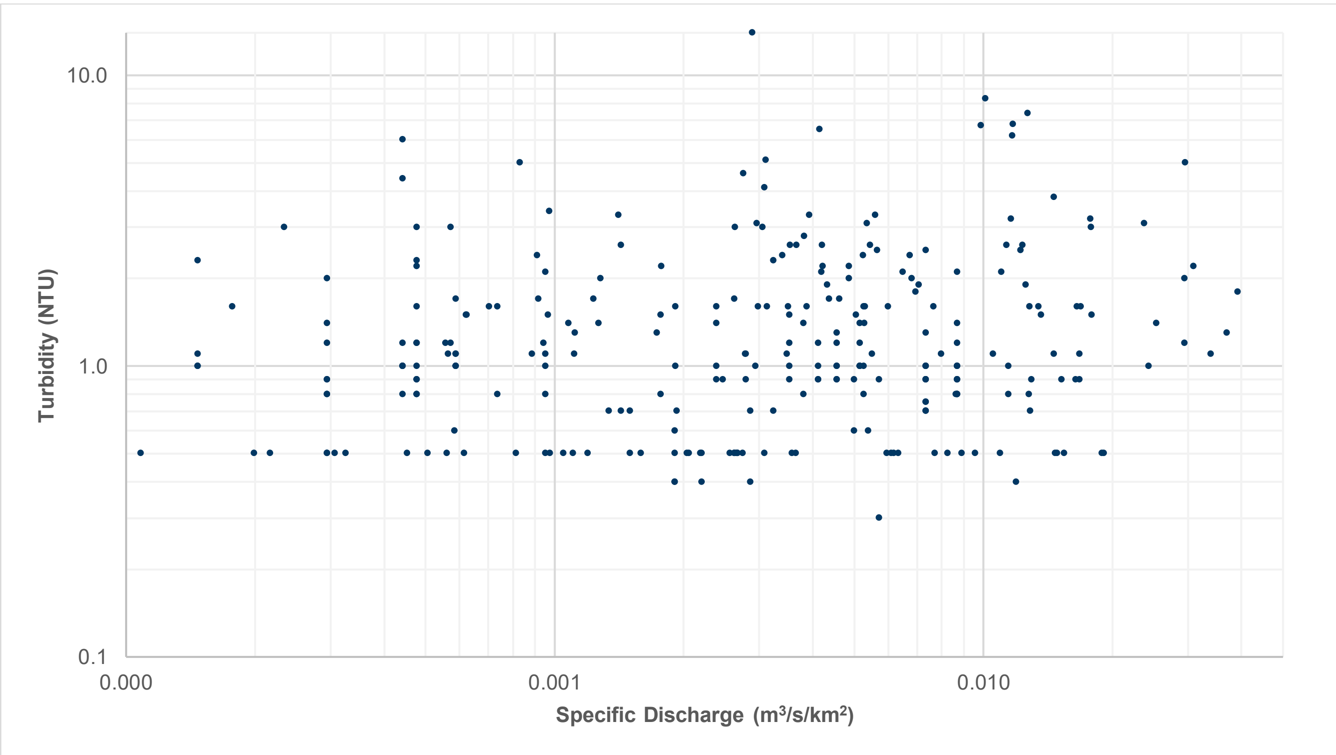

Figure E.8 ***Rising limb turbidity-flow relationship***

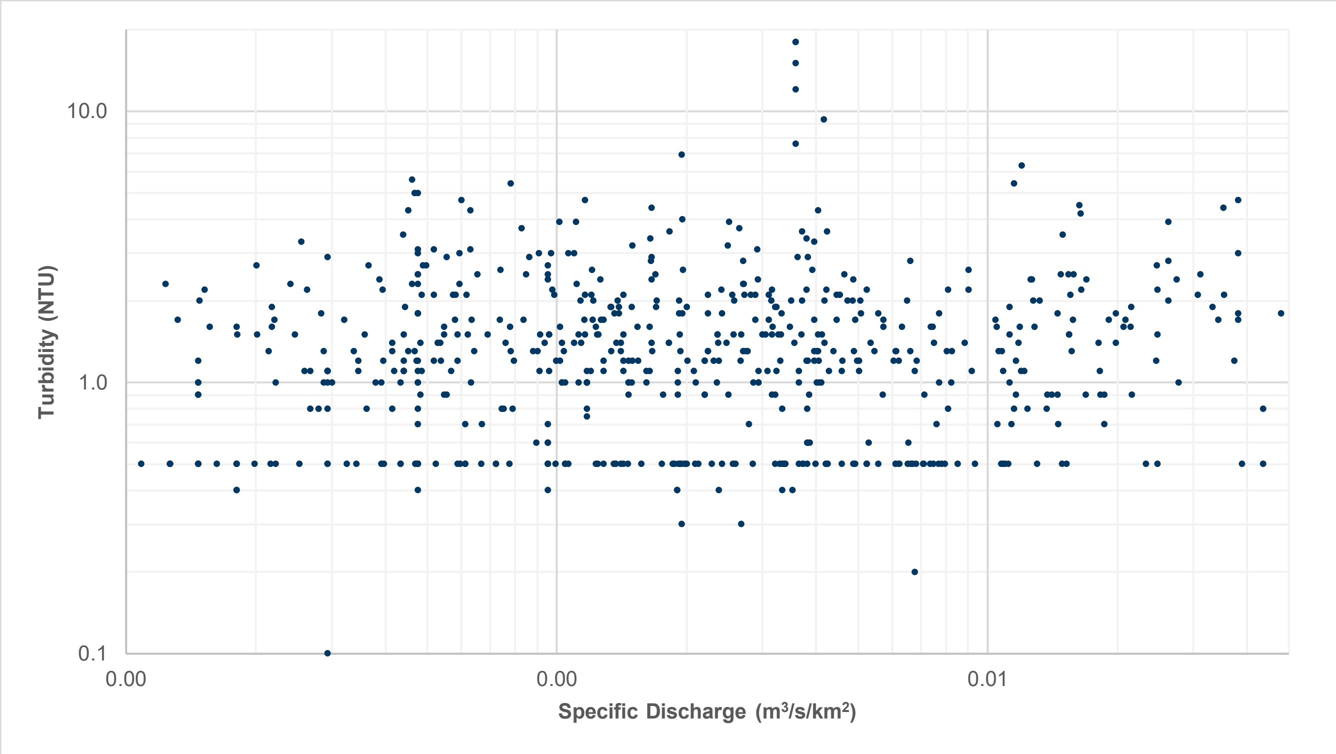

Figure E.9 *Falling limb turbidity-flow relationship*

In the absence of a relationship between turbidity and flow, an average turbidity of 1.6 NTU is adopted for hydrodynamic modelling of un-mined catchment discharge.

Mining turbidity

The Alcoa turbidity compliance monitoring data was used to estimate turbidity from mined catchments under a barrier failure scenario. Data from 54 monitoring stations covering a combined duration of 394-years was analysed. Despite the large volume of monitoring data and detailed incident reporting system, there is little monitoring data that corresponds to the time and location of known failures. It is understood that incident turbidity data was captured but could not be located. The monitoring stations also lack flow rate data to derive turbidity loads from concentrations.

An attempt was made to adopt a statistical analysis of the data to estimate turbidity levels following a failure event. Prior to the analysis, the data required the following cleaning and filtering steps to remove erroneous data associated with faulty instrumentation:

– Instruments appear to become dirty over time, with a gradual increase in the minimum reading. Spot readings were adjusted by a local minimum to correct this.
– Turbidity of flow months with <2 per cent annual runoff (Dec-May) was assumed to be zero due to high prevalence of erroneous readings during dry periods.
– Periods of constant and very high turbidity lasting more than 14 days presumed to be erroneous and excluded.
– Non-zero readings that are identical for 14-days or longer are assumed to erroneous and are excluded.

Figure E.0 illustrates that despite a month of zero rainfall, 16 of 36 active gauges are recording non-zero turbidity readings, with many turbidity readings extremely high.

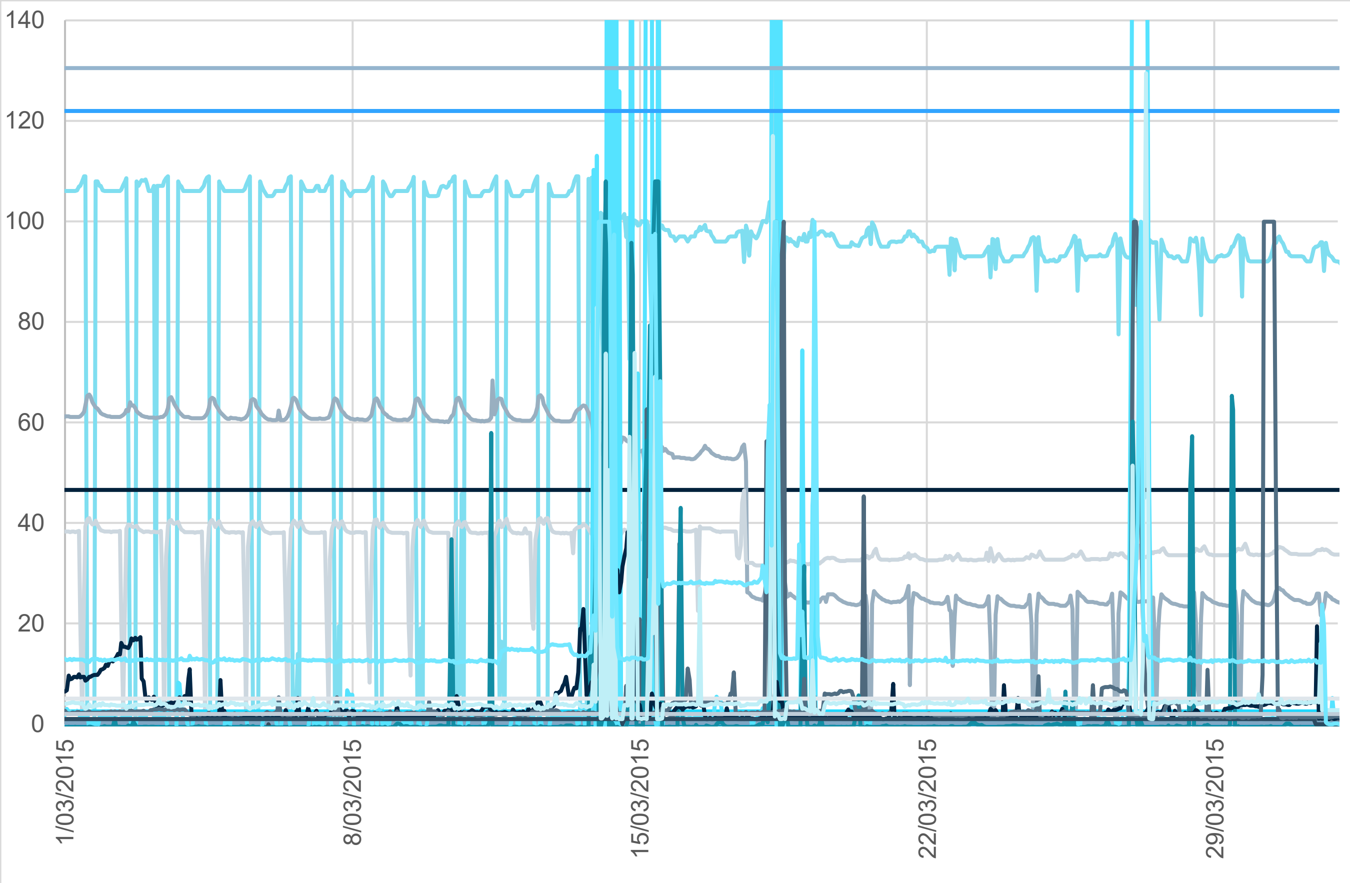

Figure E.0 Example raw turbidity data

Whilst the data cleaning removed some erroneous data, it is clear from inspection of the cleaned data that copious residual errors remain. This approach is therefore deemed unsuitable to establish turbidity levels from uncontrolled mine catchment discharge.

Turbidity readings from known failures with error-free corresponding turbidity data have been adopted as a guide to turbid discharge from mined catchments (Figure E.10). A constant sump failure turbidity of 31.5 NTU was assumed in the case of effective sump turbidity management. This is conservative in terms of the current operational stream limit in mined catchments of 25 NTU for no more than 1 hour. For the case of ineffective sump turbidity management, the continuous turbidity levels during drainage failures was doubled to 63 NTU.

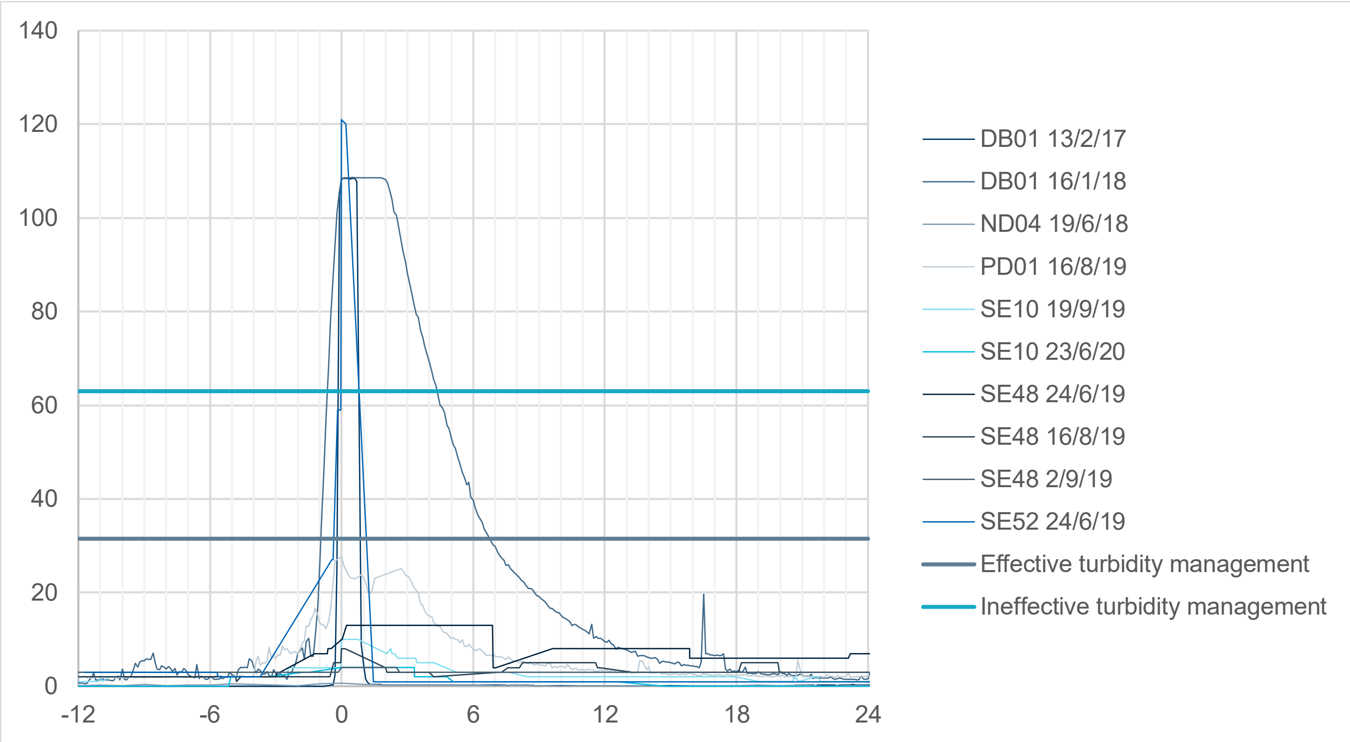

Figure E.10 *Known turbidity events*

TSS relationship to turbidity

Turbidity is a construct of Total Suspended Solids (TSS), used for measurement purposes. The hydrodynamic modelling requires TSS input. In the absence of continuous TSS monitoring for mined and un-mined catchments, GHD has undertaken soil sampling of three natural waterways and three mining sumps to quantify potential TSS loads mobilised during runoff events. By mixing and diluting these samples in a laboratory, a relationship between TSS and turbidity is established. Referring to Figure E.11, the natural baseline TSS is 1.42 times the turbidity value, whilst the sump failure TSS is 0.63 times the turbidity value.

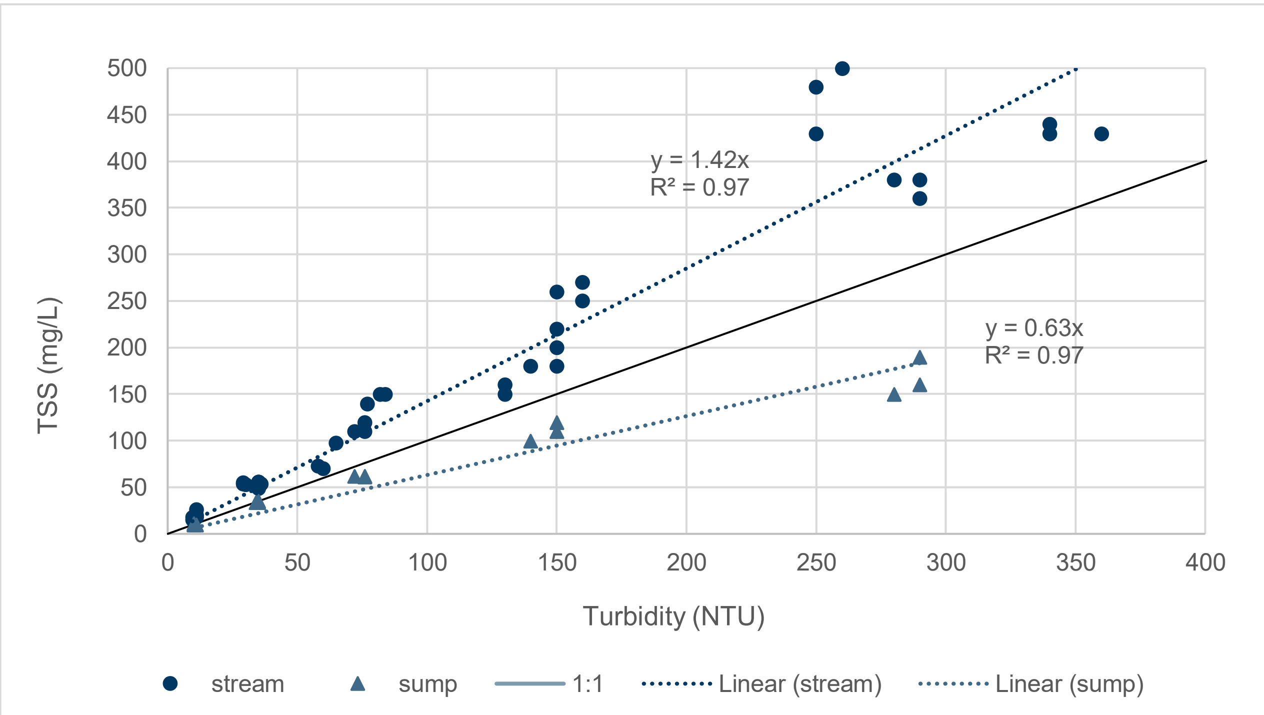

Figure E.11 *Turbidity and TSS relationship*

Total Suspended Solids is made up of a range or particle diameters, described by the Particle Size Distribution (PSD). Monitoring data shows that this varies depending on the runoff surface characteristics, with mined surfaces having a higher clay proportion than un-mined surfaces. Preliminary monitoring data from three sumps and one un-mined stream suggests the breakdowns listed in Table E.12.

Table E.12 Runoff surface Particle Size Distribution

Runoff surface	Clay	Silt	Sand
Mined	41%	47%	12%
Un-mined	20%	60%	20%

A TSS of 5 mg/L for the clay component was established during verification of the hydrodynamic model with available turbidity measurements in Serpentine Main Dam.

Referring to Table E.13, each runoff surface draining into the reservoir will be assigned with either:

– Zero surface runoff (and therefore zero TSS) for mined catchments with functioning sumps;
– Baseline TSS concentrations for un-mined catchments or rehabilitated catchments; or
– Sump failure TSS concentrations for mined catchments with failing sumps.

Baseflow and interflow, as distinct from stormflow, is assumed to occur at the same rate from each surface type.

Scenarios

A summary of the key input variables is tabulated below, resulting in a combination of 18 scenarios. For three reservoirs, this equates to 54 simulations. For modelling purposes, STP discharge and fuel spill will be simulated in all scenarios. The addition of another starting reservoir water level will double the number of scenarios and simulations.

Table E.13 Scenario matrix

Scenario	Catchment clearing	Reservoir starting level	Season	Storm	Sump failure rate
1	Un-mined	Historical minimum	Summer	1% AEP	Nil
2				10% AEP	Nil
3				1 EY	Nil
4			Winter	1% AEP	Nil
5				10% AEP	Nil
6				1 EY	Nil
7	Existing	Historical minimum	Summer	1% AEP	High
8				10% AEP	Moderate
9				1 EY	Low
10			Winter	1% AEP	High
11				10% AEP	Moderate
12				1 EY	Low
13	Future	Historical minimum	Summer	1% AEP	High
14				10% AEP	Moderate
15				1 EY	Low
16			Winter	1% AEP	High
17				10% AEP	Moderate
18				1 EY	Low

Table E.14 Reservoir details

Reservoir	Operating capacity (at spillway level) (GL)	Operating (spillway) level (mAHD)	30-year minimum water level (mAHD)	Total catchment area (km^2)
Serpentine	138	212.39	192.45 (~15%)	664
Serpentine Pipehead	2.63	165.51	153.00 (~0%)	28
South Dandalup	138	252.82	236.20 (~7%)	311

Uncertainty

The modelling scenarios are defined to minimise uncertainty. For example, extreme runoff and sump failure scenarios are included to understand uncertainty limits. Where there is parameter uncertainty, the more conservative value is adopted. Whilst there is uncertainty in runoff rates and inflow turbidity levels, there is low uncertainty in the hydrodynamic modelling.

Results

Peak flows and runoff volumes are tabulated below, together with an example of the combined hydrograph used for input into the hydrodynamic model. Compared to the unit hydrograph, spikes in discharge can be observed representing mine surface turbid runoff from individual storm bursts within the 7-day event.

Table E.15 Peak flow by catchment, method, event, and scenario (m^3/s)

Catchment	1EY unit hydrograph	1EY existing stormflow	1EY future stormflow	10% AEP unit hydrograph	10% AEP existing stormflow	10% AEP future stormflow	1% AEP unit hydrograph	1% AEP existing stormflow	1% AEP future stormflow
1	0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.01
2	0.01	0.00	0.00	0.02	0.00	0.05	0.03	0.00	0.23
3	0.13	0.00	0.04	0.19	0.00	0.82	0.27	0.00	3.41
4	0.09	0.01	0.01	0.13	0.19	0.19	0.18	0.81	0.81
5	0.82	0.00	0.07	1.19	0.00	3.69	1.65	0.00	7.54
6	0.13	0.00	0.05	0.19	0.00	0.85	0.26	0.00	3.68
7	3.65	0.03	0.04	5.31	2.32	4.02	7.36	3.69	5.96
8	0.12	0.09	0.09	0.18	1.54	1.54	0.25	6.73	6.73
9	0.09	0.02	0.03	0.13	0.23	0.53	0.18	1.04	2.28
10	0.09	0.06	0.06	0.13	0.94	0.94	0.18	4.16	4.16
11	0.09	0.00	0.00	0.14	0.10	0.10	0.19	0.14	0.14
12	0.08	0.04	0.04	0.12	0.62	0.62	0.17	2.75	2.75
13	2.59	0.06	0.06	3.77	4.74	4.74	5.22	7.64	7.64
14	0.16	0.07	0.07	0.23	1.65	1.65	0.32	5.92	5.91
15	0.12	0.08	0.08	0.17	1.55	1.54	0.24	6.48	6.48
16	0.05	0.03	0.03	0.07	0.37	0.37	0.10	1.64	1.64
20	0.03	0.00	0.00	0.04	0.00	0.00	0.05	0.00	0.00
21	0.02	0.00	0.00	0.02	0.00	0.00	0.03	0.00	0.00
22	0.04	0.00	0.00	0.06	0.00	0.00	0.08	0.00	0.00
23	0.08	0.01	0.01	0.11	0.08	0.08	0.16	0.34	0.34

Catchment	1EY unit hydrograph	1EY existing stormflow	1EY future stormflow	10% AEP unit hydrograph	10% AEP existing stormflow	10% AEP future stormflow	1% AEP unit hydrograph	1% AEP existing stormflow	1% AEP future stormflow
24	0.18	0.05	0.05	0.26	0.70	0.70	0.36	3.17	3.17
25	0.04	0.00	0.00	0.05	0.00	0.00	0.08	0.00	0.00
26	0.02	0.00	0.00	0.03	0.00	0.00	0.05	0.00	0.00
30	0.08	0.00	0.00	0.12	0.00	0.00	0.16	0.00	0.00
31	0.06	0.00	0.00	0.08	0.00	0.00	0.12	0.00	0.00
32	0.08	0.00	0.00	0.11	0.00	0.00	0.16	0.00	0.00
33	0.12	0.00	0.00	0.17	0.00	0.00	0.23	0.00	0.00
34	0.24	0.00	0.00	0.34	0.00	0.12	0.47	0.00	0.42
35	3.13	0.00	0.03	4.40	0.00	3.70	6.04	0.00	4.99
36	0.21	0.00	0.00	0.29	0.00	0.00	0.40	0.00	0.00
37	0.14	0.00	0.00	0.20	0.00	0.00	0.27	0.00	0.00

Table E.16 Runoff volume by catchment, method, event, and scenario (m^3)

Catchment	1EY unit hydrograph	1EY existing stormflow	1EY future stormflow	10% AEP unit hydrograph	10% AEP existing stormflow	10% AEP future stormflow	1% AEP unit hydrograph	1% AEP existing stormflow	1% AEP future stormflow
1	2,128	0	2	3,097	0	84	4,294	0	230
2	4,601	0	81	6,697	0	3,192	9,285	0	8,633
3	41,690	0	1,330	60,673	0	52,631	84,124	0	142,478
4	28,989	302	302	42,189	11,981	11,981	58,495	32,431	32,431
5	259,415	0	6,191	377,541	0	244,638	523,462	0	662,409
6	41,527	0	1,363	60,437	0	53,917	83,796	0	145,957
7	1,154,604	4,290	7,816	1,680,362	169,566	309,124	2,329,826	459,213	837,217
8	38,500	2,456	2,456	56,032	97,111	97,091	77,688	262,874	262,819
9	28,757	366	859	41,851	14,521	33,983	58,027	39,303	91,998
10	28,156	1,497	1,497	40,977	59,202	59,187	56,815	160,262	160,218
11	29,703	386	386	43,228	15,928	15,928	59,936	43,189	43,189
12	26,023	978	979	37,873	38,697	38,741	52,511	104,757	104,875
13	818,853	8,692	8,692	1,191,724	343,580	343,580	1,652,329	930,471	930,471
14	49,747	2,705	2,704	72,399	106,976	106,923	100,382	289,607	289,458
15	37,431	2,512	2,512	54,475	99,353	99,333	75,529	268,947	268,895
16	15,160	561	561	22,063	22,218	22,209	30,590	60,138	60,114
20	7,951	0	0	11,670	0	0	16,094	0	0
21	4,892	0	0	7,181	0	0	9,903	0	0
22	12,909	0	0	18,948	0	0	26,131	0	0
23	24,465	115	115	35,909	4,560	4,560	49,523	12,339	12,339
24	56,191	1,089	1,089	82,474	43,089	43,089	113,741	116,644	116,644
25	11,749	0	0	17,245	0	0	23,783	0	0
26	7,069	0	0	10,375	0	0	14,309	0	0
30	26,778	0	0	37,671	0	0	51,741	0	0
31	18,917	0	0	26,612	0	0	36,551	0	0
32	25,394	0	0	35,723	0	0	49,066	0	0
33	37,295	0	0	52,465	0	0	72,061	0	0
34	76,566	0	190	107,711	0	7,582	147,940	0	20,535
35	988,853	0	7,862	1,391,098	0	311,441	1,910,665	0	843,596
36	64,981	0	0	91,413	0	0	125,556	0	0
37	44,332	0	0	62,365	0	0	85,658	0	0

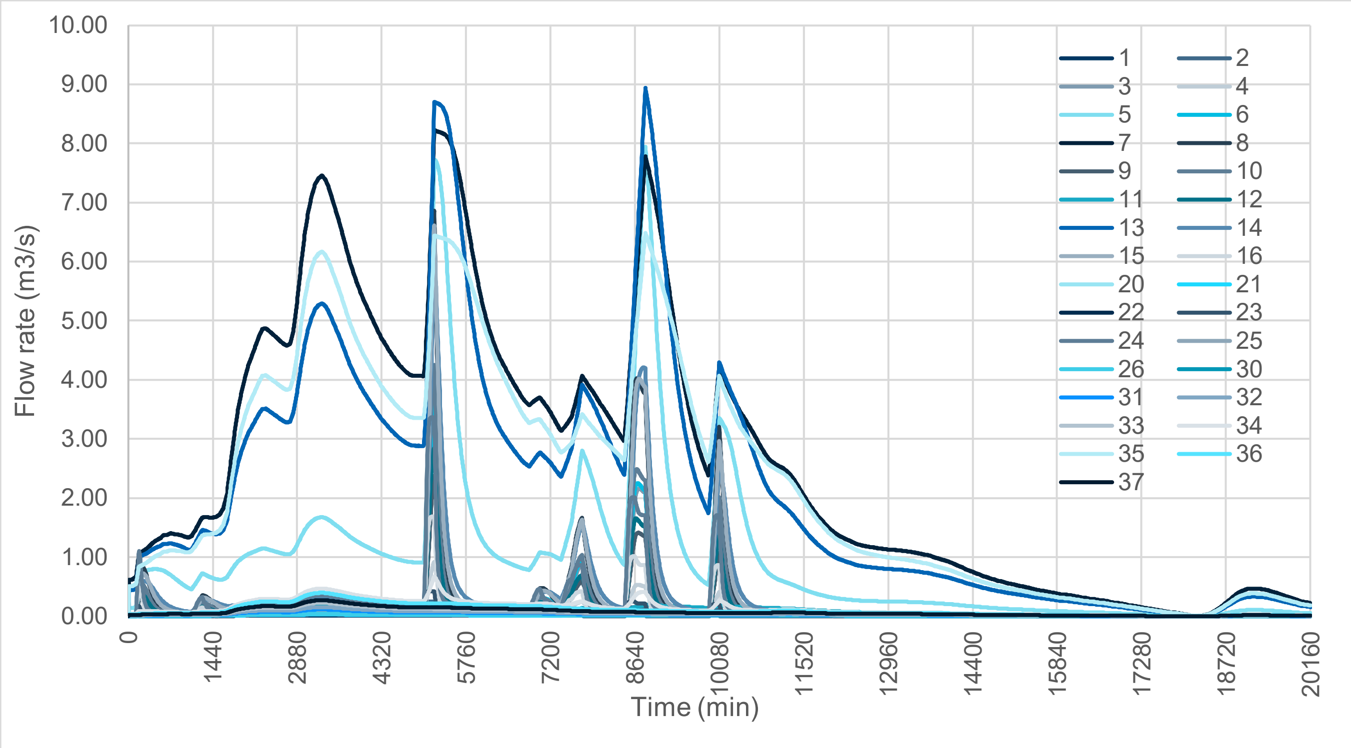

Figure E.12 1% AEP Future scenario combined hydrograph

Appendix F

Hydrodynamic modelling report

Drinking Water Quantitative Assessment

Reservoir Modelling

Alcoa of Australia Limited

09 December 2021

The Power of Commitment

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S3	D	J. Romero	N. Deeks				
S4	1	J. Romero	N. Deeks	NDeeks	M. Brook		9/12/2021

The Power of Commitment

Executive summary

Alcoa of Australia Limited (Alcoa) is proposing to increase production at the Pinjarra Alumina Refinery by 5 percent from 5.0 Mtpa to 5.25 Mtpa and transition the Huntly Bauxite Mine to the proposed Myara North and Holyoake mine regions (the Proposal). The Proposal is located in the Peel Region of Western Australia (WA), approximately 100 km southeast of Perth.

The Proposal will be subject to environmental impact assessment under Part IV of the WA *Environmental Protection Act 1986* (EP Act), and the *Environment Protection Biodiversity Conservation Act 1999* (EPBC Act). The environmental impact assessment will be via a Public Environmental Review (PER).

This report describes numerical modelling to predict reservoir and withdrawal water quality (i.e. inorganic suspended solids (SS), cryptosporidium and hydrocarbons (diesel)) associated with incidents or spills from the proposed transition of Alcoa mining operations in the catchments of three dams (Serpentine Main Dam [SMD], Serpentine Pipehead Dam [SPD], South Dandalup Dam [SDD]) that are part of the Perth's Integrated Water Supply Scheme (IWSS). The purpose of the study is to assess the relative degree to which the transition to the proposed Myara North and Holyoake mine regions will affect the reservoir and withdrawal water quality relative to existing mining activities, and to inform a public drinking water risk assessment of the proposal.

Model Description

A three-dimensional (3D) hydrodynamic model (AEM3D) was used to predict the SS, cryptosporidium and diesel concentrations in the reservoir and withdrawals from catchment inputs of baseline (no mining so only SS considered), and existing and proposed mining scenarios as follows:

– SS was configured to settle according to Stoke's Law through defining conservative (i.e. low settling velocities) characteristic particle densities and diameters for silt and clay. Silt and clay have sufficiently low settling velocities to be potentially transported from stream confluences to the reservoir supply intakes towers in proximity to the dam wall.
– Cryptosporidium oocysts were configured with a process-based model of microbial pollution. Cryptosporidium was selected to evaluate potential microbial risks because chlorination is not an effective treatment process for this pathogen.
– Diesel was configured as a conservative numerical tracer where concentrations within the reservoir are due solely to transport and dispersion, and losses from withdrawals. This is a conservative assumption as volatilisation to the atmosphere, microbial degradation, and settling to adhered particles are not considered.

Supporting Data

Available information and its implementation in the study included:

– Monthly water balance from 2000-2020 of the three dams served to define model inputs of discharge (i.e. external transfers, withdrawals, Alcoa extractions) and to verify simulated water levels.
– Department of Water and Environmental Regulation (DWER) measurements of daily stream flow in three large SMD catchments were used to estimate discharge from ungauged catchments of all three reservoirs to serve as model inputs. DWER stream temperature measurements in one of the large SMD catchments served as model inputs for all simulated stream model inputs.
– Measurements of turbidity (2000-2020) and water temperatures (2000-2008) near the dam walls of the three reservoirs served as model verification data. Simulated SS was compared to measured turbidity assuming a 1:1 relation over the low range of values at the dam wall (i.e. SS and turbidity typically <2 mg/L and <2 NTU, respectively).
– Hourly meteorological model inputs were sourced from the National Centers for Environmental Prediction's (NCEP's) Climate Forecast System, version 2.
– As there were no available digital elevation models of the three reservoirs, the 3D bathymetries were developed from historical topographic data prior to the construction of the dams and the use of GIS

interpolation algorithms. The digital elevation models were then parsed into 100 m by 100 m grids for SMD and SDD, and a 50 m by 50 m grid for SPD.

– Particle size distributions of streambed sediments in natural and existing mining catchments were used to estimate the relative proportion of clay and silt that comprise SS.

The primary data gaps in this study were stream SS (and/or turbidity) measurements in natural and mined catchments. During model verification constant SS concentrations of clay (SS_{clay} of 5 mg/L) and silt (SS_{silt} of 15 mg/L) were used across unmined and/or fully rehabilitated catchments of all three reservoirs, which yielded a reasonable match with the turbidity measurements at the dam walls. Additionally, constant SS_{clay} and SS_{silt} concentrations of external transfers into SDD and SPD were assumed. These SS data gaps represent the highest degree of uncertainty in this investigation. One of the main aims of this study is to determine the 'relative' effect of the proposed mine transition on reservoir and withdrawal SS, which is achieved.

Model Verification

Verification of simulated water levels, water temperatures and SS were through comparisons with available information/measurements of the three reservoirs from July 2017 to October 2019. This model verification period encompassed two moderate-sized winter inflow events (2017 and 2018) following a dry period from 2011-2017 that maintained low reservoir levels, which can be summarised as:

– Simulated SMD and SDD water levels over 2+ years were reproduced well after increases in the discharge of estimated winter inflows during the winters of 2018. SPD water levels and outflow discharge were simulated well with the application of a dynamic outflow boundary condition, where the withdrawal rates were a function of the reservoir's water level.
– Water temperature measurements in the three reservoirs were only available from 2000-2008. A subset of this 2000-2008 measurement period to compare to simulated water temperatures in each reservoir was selected on the basis of the similarity in water balance components. The surface and bottom water temperatures were simulated well in all three reservoirs. Seasonal thermal stratification was simulated in SMD and SDD with a longer duration near the dam wall than at comparative up-reservoir sites. In contrast, the much shallower SPD reservoir does not seasonally stratify, but does undergo intermittent periods of thermal stratification.
– Simulated SS_{clay} comprised most of the SS near the dam walls of the three reservoirs and matched well with turbidity measurements during the 2018 winter in SMD, both the 2017 and 2018 winters in SDD and over the entire simulation in SPD. However, simulated summer SS_{Clay} in both SMD and SDD were underestimated compared to turbidity measurements, which is likely due to a high proportion of organic particles (e.g. phytoplankton) that are not simulated in this study. In response to catchment inflow events, elevated SS_{clay} remains suspended in the water column due to low settling velocities during transport to the dam walls, often as turbid underflows down the bed slope. SPD has substantially lower simulated SS_{Clay} at the dam wall than SMD and SDD because of the relatively small SS loads from the limited catchment area. Further, the high SPD external transfers with low SS, which short-circuit to the nearby intake tower, substantially dilutes the relatively small catchment-derived SS loads. Based on this model verification of SS, there is a good level of confidence in regards to predicted relative changes in the suspended inorganic climate near/at the dam wall in response to inflow events from the proposed additional mining in the catchments.

Scenario Hydrology

The effect of mining activity-related cryptosporidium and diesel spill incidents in the catchments were evaluated over the model verification period (July 2017 to October 2019). To evaluate the relative effects of proposed mining activities on reservoir turbidity due to drainage (primary turbidity control measure) failures relative to the baseline condition (no mining) and existing mining activities, estimates of the 1% and 10% 7-day annual exceedance periods (AEP) from a companion study (GHD 2021b) were spliced into the 2017 winter event and the 2018 summer period as scenario hydrological inputs.

Predicted Effect of Cryptosporidium Incidents

The following simulated cryptosporidium incidents from the catchments are defined in a companion study (GHD 2021a):

– Incident 1: Sewage treatment plant (STP) overflow over 2 days after heavy rainfall.
– Incident 2: Washout of STP effluent irrigation area over 2 days after heavy rainfall.
– Incident 3: Subsurface seepage from STP effluent irrigation area over 3 winter months.
– Incidents 4A-4D: Mobilisation of an infected stool in 3 mining catchments (4A-4C) within each reservoir and a reference catchment closest to each of the dam walls (4D) over 2 days following heavy rainfall (inflow) events.

These cryptosporidium incidents were simulated to occur in 3 catchments in SMD and SDD, and 2 SPD catchments for existing (SMD, SPD) and proposed (SMD, SDD) mining activity scenarios. The predicted effects of these incidents were:

– For SMD, incidents 1, 2 and 3 are predicted to yield relatively low cryptosporidium levels at the dam (~<1×10^{-5} oocysts/L) relative to the mobilisation of infected human stool events (incidents 4A-4C) from existing and proposed mined catchments and the reference unmined catchment closest to the dam wall (reference incident 4D) (~<5×10^{-4} oocysts/L). The typical timescale of elevated cryptosporidium at the dam wall and withdrawals is ~3-4 months. The STP location is proposed to be moved to a catchment with a reservoir confluence closer to the dam wall (and intake tower) than the existing location. This change results in a ~2 fold increase in peak cryptosporidium concentrations, but concentrations remain very low relative to predictions for incidents 4A-4D. Generally, simulated oocyst concentrations in the SMD withdrawals for incidents 4A-4D are similar between the existing and proposed mining catchments.
– As with SMD, SDD incidents 1, 2 and 3 were predicted to yield relatively low cryptosporidium levels at the dam (~<3×10^{-6} oocysts/L) relative to the mobilisation of infected human stool events (incidents 4A-4C) in the proposed mining catchments (~<1×10^{-4} oocysts/L) and with the unmined reference catchment closest to the dam wall (refence incident 4D) (~1<$\times10^{-3}$) oocysts/L). Simulated large scale transport processes in SDD did not distribute pathogens to the same degree throughout the up-reservoir volume as for SMD, in part due to the smaller inflow event to reservoir volume ratio. As with SMD, the typical timescale of elevated cryptosporidium at the dam and withdrawals was ~3-4 months. Due to reduced horizontal transport, cryptosporidium concentrations for incidents 4A-4C were ~2-4 fold lower than for SMD. However, peak SDD concentrations for incident 4D (closest catchment to dam wall) was 2 fold greater than SMD because of reduced horizontal transport and dispersion.
– Simulated SPD cryptosporidium predictions differed substantially from those of SDD and SMD for incidents 4A, 4B and reference incident 4D (incidents 1-3 and 4C not applicable for SPD), which is primarily driven by short-circuiting of external transfers to the intake tower. This short-circuiting leads to low water ages (i.e. duration a water parcel remains in the reservoir) near the dam wall and increasing water age with distance up-reservoir due to the relatively low catchment inputs and low SMD releases. These high short-circuiting volumes induce a hydrodynamic barrier effect in close proximity to the dam wall that inhibits transport and dispersion of up-reservoir waters where the confluences of the two existing (and proposed) mining catchments occur. These factors contribute to the large difference between cryptosporidium concentrations at the dam wall with reference incident 4D (<1-2×10^{-2} oocysts/L for the catchment closest to the dam wall) that are ~1,000- and ~10- fold greater than incidents 4A (<1×10^{-5} oocysts/L for the uppermost mined catchment) and 4B (<1×10^{-3} oocysts/L for the mid-reservoir mined catchment), respectively. In addition, there is a delay of ~1-2 months in the arrival of cryptosporidium to the dam wall and intake for incident 4A relative to incidents 4B and 4D due to this hydrodynamic barrier effect.

Predicted Effect of Diesel Spill Incidents

Simulated diesel spill incidents during moderately low winter inflows assumed the entire 15 m^3 load of fuel transport tanker was directly discharged into a stream at a haul road crossing with no losses due to volatilisation, degradation, adsorption and settling. Hence, the only processes that decrease diesel concentrations upon being spilled into the stream and throughout the reservoir volumes are via dilution in the river and reservoir mixing and dispersion.

These diesel spill incidents were simulated to occur in 3 catchments in SMD and SDD, and 2 SPD catchments for existing (SMD, SPD) and proposed (SMD, SDD) mining scenarios. The predicted effects of these diesel spill incidents include:

– Simulated diesel concentrations at the downstream dam and withdrawals from spills in the existing and proposed SMD mining catchments had peaks of up to 1 μg/L that decreased to <0.2 μg/L within 6-7 months.

– Simulated diesel concentrations at the downstream dam and withdrawals from spills in the proposed SDD mining catchments were similar to SMD predictions with peaks of 1 µg/L that decreased to 0.4 µg/L within 6-7 months.
– Simulated diesel concentrations at the downstream dam and withdrawals from spills in the existing SPD mining catchments had similar spatial and temporal patterns as the cryptosporidium predictions in this reservoir. The diesel concentrations varied from 5 ug/l for a spill in in the mid-reservoir catchment to 1 µg/L for a spill in the up-reservoir catchment. There was also a delay in the arrival of diesel to the dam and withdrawals of ~2 months for a spill in the up-reservoir mining catchment relative to a spill in the mid-reservoir mining catchment. As with variations in cryptosporidium, the hydrodynamic barrier effect induced by short-circuiting of the primary inflow (external transfers) and outflow (withdrawals) in the region of the dam wall effectively decreased the transport and dispersion of diesel from the upper reservoir catchment. Because of SPD's relatively small reservoir volume and relatively high outflow discharge, diesel levels were simulated to decrease to ~0 µg/L within ~10-12 months of the spill.

Predicted Effect on Inorganic Suspended Solids during Large Inflow Events

Scenarios to evaluate the relative differences of large winter and summer inflow events on reservoir and withdrawal SS levels used as model inputs the estimated GHD (2021a) 1% and 10% AEP hydrology for baseline (no mining effects on SS for all three reservoirs), existing (for SMD and SPD, no existing mining activity in SDD) and proposed (for SMD and SDD, no additional SPD catchments for proposed mining activity) mining scenarios. The 1% and 10% AEP inflow events were assumed to have 30% and 75% drainage (i.e. primary turbidity control through retention of mining area water) failure rates. Additionally, two constant SS concentrations in the event of drainage failures (i.e. for water exiting drainage controls and flowing into proximal streams) from mining catchments were simulated that assumed moderate (12.6 and 15.8 mg/L of SS_{Clay} and SS_{Silt}, respectively) and high (25.2 mg/L and 31.5 mg/L of SS_{Clay} and SS_{Silt}, respectively) drainage failure SS levels. Baseline (no mining and fully rehabilitated mining catchments) scenarios had SS_{clay} and SS_{silt} stream concentrations of 5 and 15 mg/L, respectively. The same SS concentrations were adopted for those portions of mining catchments with no mining activity.

The predicted effects of these large inflow events and associated drainage failures on the SS in the reservoirs and withdrawals include:

– Increases to SS_{silt} in all reservoirs and for all scenarios were short duration due to the relatively rapid settling as described beforehand for the verification simulations. Most SS variations were due to SS_{Clay}.
– For SMD with moderate drainage failure SS levels, minimal changes were predicted in the SS at the dam and withdrawals between the baseline, existing and proposed scenarios for either the winter or summer 10% AEP inflow events. SS increases of up to ~0.5 mg/L and ~0.2-0.3 mg/L were simulated with the moderate drainage failure SS levels for the summer and winter 1% AEP inflow events, respectively. With high drainage failure SS levels, minimal variations were again predicted for the 10% AEP winter and summer events. SS increases of up to ~1 mg/L and ~0.3-0.4 mg/L were simulated with the high drainage failure SS levels for the summer and winter 1% AEP events, respectively.
– For SDD, material differences in SS at the dam wall and withdrawals were not predicted for the 1% and 10% AEP summer and winter inflow events between the baseline and proposed scenarios (note no existing mining scenario for SDD) for both moderate and high drainage SS levels. The relatively small proportion of the SDD catchment that is proposed to undergo mining activity does not generate sufficient additional SS loads over the baseline (no mining) scenario to cause a substantive increase.
– As with SDD, material differences in the 1% and 10% AEP summer and winter inflow events between the baseline and proposed SPD scenarios (note no existing mining scenario for SDD) for moderate and high drainage failure SS levels are not predicted. The hydrodynamic barrier effect induced by the SPD primary inflow and outflow in proximity to the dam wall increases the duration of particle settling in the up-reservoir volume prior to transport to the dam wall. Further, the high external transfers with low SS concentrations also dilutes the elevated catchment-derived SS_{clay} levels as they are transported to the dam wall after inflow loading events.

This report is subject to, and must be read in conjunction with, the limitations set out in Section 1.4 and the assumptions and qualifications contained throughout the Report.

Contents

Table index

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Appendices

Acronyms, Abbreviations and Units

Acronym, Abbreviation, Unit	Description
°C	Degrees Centigrade
μm	Micrometre
3D	Three Dimensional
AEP	Annual Exceedance Period
AHD	Australian Height Datum
BoM	Bureau of Meteorology
CFSv2	Climate Forecasting System Version 2
DWER	Department of Water and Environmental Regulation
EP Act	Western Australia Environmental Protection Act 1986
EPA	Environmental Protection Authority
EPBC Act	Environment Protection Biodiversity Conservation Act 1999
ESD	Environmental Scoping Document
E.Y.	Exceedance per Year
FSL	Full Supply Level
GL	Gigalitre
hr	Hour
IWSS	Integrated Water Supply Scheme
km	Kilometre
m	Meter
m^3/s	Cubic Meters per Second
mg/L	Milligrams per Litre
MAFRL	Marine and Freshwater Research Laboratory
mm	Millimetre
ML	Megalitre
Mtpa	Million Tonnes per Annum
NA	Not Applicable
NTU	Nephelometric Turbidity Units
PER	Public Environmental Review
psu	Practical Salinity Units
Q	Discharge
s	Second
SDD	South Dandalup Dam
SMD	Serpentine Main Dam
SPD	Serpentine Pipehead Dam
SS	Inorganic Suspended Solids
SS_{clay}	Clay Component of Inorganic Suspended Solids
SS_{silt}	Silt Component of Inorganic Suspended Solids
T	Temperature
TSS	Total Suspended Solids

Acronym, Abbreviation, Unit	Description
W	Watt
WA	Western Australia
WTP	Water Treatment Plant

1. Introduction

Alcoa of Australia Limited (Alcoa) is proposing to increase production at the Pinjarra Alumina Refinery by 5 percent from 5.0 Mtpa to 5.25Mtpa and transition the Huntly Bauxite Mine to the proposed Myara North and Holyoake mine regions (the Proposal). The Proposal is located in the Peel Region of Western Australia (WA), approximately 100 km southeast of Perth.

The Proposal will be assessed by the Environmental Protection Authority (EPA) under Part IV of the WA *Environmental Protection Act 1986* (EP Act), and the *Environment Protection Biodiversity Conservation Act 1999* (EPBC Act). The Proposal will be assessed via a Public Environmental Review (PER).

This report describes numerical modelling that was undertaken to predict in-reservoir and withdrawal water quality risks from inorganic suspended solids, cryptosporidium and hydrocarbons associated with the transition to the proposed Myara North and Holyoake mine regions in the catchments of three dams (Serpentine Main Dam [SMD], Serpentine Pipehead Dam [SPD], South Dandalup Dam [SDD]) that are part of the Perth's Integrated Water Supply Scheme (IWSS).

1.1 Purpose of this Report

This report provides support for the elements in regards to reservoirs of items 49 and 50 of the Environments Scoping Document (ESD) for the Alcoa Revised Proposal where the following portions of the following Required Work items that are addressed here are underlined:

49. Characterise the hydrology of the Serpentine and South Dandalup Rivers and upper Wungong Brook catchment, and the beneficial use of the Serpentine, Pipehead and South Dandalup reservoirs, including reservoir protection zone. <u>Characterise the current</u> water quality and <u>hydrodynamics of the Serpentine, Pipehead and South Dandalup reservoirs.</u> <u>Describe the impacts from this Proposal on the</u> water yield and <u>water</u> and sediment <u>quality of Serpentine, Pipehead and South Dandalup reservoirs,</u> upstream rivers, tributaries, upper Wungong Brook, and Peel-Yalgorup System Ramsar Site. This is to include a detailed description of the development of river crossings for access/haul roads and conveyors.

50. Undertake a public drinking water risk assessment for the Serpentine, Pipehead and South Dandalup Dam reservoirs and upper Wungong Brook catchment, including source vulnerability assessment, in accordance with the Australian Drinking Water Quality Standards and relevant contemporary guidance. The risk assessment should consider potential contaminants arising from mining activities and infrastructure, as well as mobilisation of existing contaminants from past catchment activities. <u>For identified high risks to public drinking water beneficial uses, undertake a detailed assessment of potential impacts to human health in accordance with contemporary guidance</u>.

1.2 Scope

The scope of this reservoir numerical modelling study is to address ESD items 49 and 50 through:

– Developing a three-dimensional (3D) hydrodynamic model of SMD, SPD and SDD to simulate the fate and transport of contaminants of potential concern (i.e. inorganic suspended solids [SS], microbial pathogens, hydrocarbons from fuel spills) that may arise from existing and proposed mining activities in the catchments.
– Carrying out model verification through comparisons with available in-reservoir measurements of water levels, temperature, and turbidity.
– Predicting water quality variations within the reservoir and the withdrawals for existing and proposed mining activities, specifically:
  - Increases to SS during sizeable rainfall (and reservoir inflow) events due to the failure of water retention mining infrastructure.
  - Cryptosporidium loads into the reservoirs during high reservoir inflow events due to accidental overflow from sewage treatment plants, washout of treated sewage from irrigated woodlots and mobilisation of infected human stools. Additionally, subsurface drainage of treated sewage from irrigated woodlots into

nearby streams was also considered as a potential pathogen hazard to the water quality of the reservoirs and withdrawals.
- Accidental diesel spills from fuel tankers into streams.

The findings from this study served to inform a public drinking water risk assessment of the proposed mining activity transition (GHD 2021a).

1.3 Overview of Approach

The study's approach to predict the effects of the mining transition proposal was to:

– Define the reservoir inputs (e.g. inflows) and outputs (e.g. withdrawals) of the three dams (Section 2.2).

– Refine a monthly water balance of the past 20 years (2000-2020) to serve as model inputs for catchment inflows, withdrawals and external transfers (Section 3.1), and as water level model verification data (Section 4.2.1).

– Collate measurements of stream discharge and temperature (Section 3.2), in-reservoir temperature and turbidity (Section 3.3), and meteorology (Section 3.4) to serve as model inputs (Section 4.1) and model verification data (Sections 3.3).

– Carry out reservoir model verification simulations (Section 4.1.7) and describe key patterns of thermal stratification and SS within the reservoir and the withdrawals (Section 4.3).

– Evaluate the effects between baseline (no mining activity), and existing and proposed mining activity scenarios (Section 5), which includes:
  - Establishment of catchment hydrological inputs for 'representative' (Sections 3.1 and 3.2) and 'high' rainfall/catchment inflow (Section 5.1.3) scenarios.
  - Characterisation of SS (Sections 4.1.7 and 5.1.3), pathogen (cryptosporidium) (Section 5.1.2) and hydrocarbons (Section 5.1.2) catchment loads to evaluate water quality effects from existing and proposed mining activity in the catchments of the three dams.
  - Reservoir simulations of a suite of scenarios to predict the relative difference between the baseline, and existing and proposed mining activity for SMD (Section 5.2), SDD (Section 5.3) and SPD (Section 5.4).

– Discuss the predicted relative differences in the water quality risks between the baseline, and existing and proposed mining activity.

1.4 Limitations

This report: has been prepared by GHD for Alcoa of Australia Limited and may only be used and relied on by Alcoa of Australia Limited for the purpose agreed between GHD and Alcoa of Australia Limited as set out throughout this report.

GHD otherwise disclaims responsibility to any person other than Alcoa of Australia Limited arising in connection with this report. GHD also excludes implied warranties and conditions, to the extent legally permissible.

The services undertaken by GHD in connection with preparing this report were limited to those specifically detailed in the report and are subject to the scope limitations set out in the report.

The opinions, conclusions and any recommendations in this report are based on conditions encountered and information reviewed at the date of preparation of the report. GHD has no responsibility or obligation to update this report to account for events or changes occurring subsequent to the date that the report was prepared.

The opinions, conclusions and any recommendations in this report are based on assumptions made by GHD described in this report. GHD disclaims liability arising from any of the assumptions being incorrect.

GHD has prepared this report on the basis of information provided by Alcoa of Australia Limited and others (including Government authorities), which GHD has not independently verified or checked beyond the agreed scope of work. GHD does not accept liability in connection with such unverified information, including errors and omissions in the report which were caused by errors or omissions in that information.

1.5 Assumptions

Modelling assumptions in this assessment include:

– Temperature is the primary driver of water density variations in the three reservoirs in this study. The modelling does not evaluate the very small effect of variations in conductivity between the reservoirs and the various catchments. All reservoir and catchment stream salinity values are set to a value of 0.1 psu in this assessment. Further, the effect of inorganic suspend solids (SS) on water density is not considered, as the levels required to generate density variations do not likely occur.

– Total suspended solids (TSS) is a combination of inorganic and organic particles. There are only measurements of turbidity available for the three reservoirs. It is assumed that the primary contribution to SS during and for several months after inflow events are inorganic particles, of which those transported to the dam wall are primarily small particle sizes (e.g. clay and fine silt) that remain in suspension.

– A 1:1 relation between SS and turbidity is adopted for model verification (simulated SS versus measured turbidity) and to inform the GHD (2021a) drinking water risk assessment (to translate simulated SS to drinking water guideline turbidity values). A 1:1 relation between SS and turbidity is typically a reasonable approximation in many relatively clear water bodies. In this study, all three dams can be categorised as clear water bodies with typical turbidity measurements of <2 NTU.

– Algal and other organic matter particles are not considered in the model due to the lack of data for model verification. True colour measurements are available (i.e. indicative of dissolved organic matter), but there is insufficient data to simulate organic matter dynamics.

– From a land use change perspective and the associated risks of increased SS at the dam wall due to failures of sediment retention control infrastructure around existing and proposed mining areas, it is primarily inorganic SS that is likely to cause deleterious water quality impacts at the intake towers of the reservoirs during and the aftermath of inflow events. Catchment discharge and SS loads are as described in GHD (2021b).

– Cryptosporidium is the simulated pathogen here because of the ineffectiveness of chlorination, which is the primary WTP treatment process of the SPD draws. Estimates of cryptosporidium loads during inflow events due to STP infrastructure failure (i.e. STP overflow, washout of treated wastewater irrigated woodlot, transport of infected human stool near a water course) and over the winter wet season (i.e. subsurface drainage of treated wastewater irrigated woodlot) are as described in GHD (2021a). Further, once the pathogens are routed to a stream, no further deactivation of cryptosporidium is considered until the confluence with the reservoir. Only dilution with catchment waters is used to determine the model input concentration into the reservoir.

– Worst case fuel spill scenarios are defined as an accidental release of the entire diesel tank volume into a stream. The diesel spill is simulated as a conservative tracer (e.g. no reduction due to fate processes such as volatilisation) with only dilution of catchment inflows to estimate hydrocarbon concentrations that enter the reservoir.

2. Reservoir Model

2.1 Numerical Model

AEM3D is a 3D numerical model that includes hydrodynamic, thermodynamic and biogeochemical modules to simulate the temporal behaviour of stratified water bodies from environmental forcing (Hodges and Dallimore 2018). AEM3D simulates the velocity, temperature and salinity of surface waters that are subjected to environmental and anthropogenic forcing such as wind, tides, surface heating and cooling, inflows, withdrawals, bubblers and mixers. Additionally, AEM3D can be configured to optionally simulate nutrients, biogeochemistry, particle and aquatic biology dynamics based on a water quality module adapted from the Computational Aquatic Ecosystem Dynamics Model (Romero et al 2004).

In this study, AEM3D was configured to simulate the relative effect of various mining-related scenarios in the catchments on the spatial and temporal variations of SS, cryptosporidium and diesel where:

– Inorganic suspended solids (SS) were configured to settle according to Stoke's Law through defining the characteristic particle density and diameter of silt and clay. Silt and clay are the catchment soil types with sufficiently low settling velocities to be potentially transported from stream confluences with the reservoirs to the intake towers in proximity to the dam wall.
– Cryptosporidium oocysts were configured on the basis of Hipsey et al's (2008) process-based model of microbial pollution. Cryptosporidium was selected as the most conservative pathogen to evaluate potential microbial risks associated with mining activity because chlorination is not an effective treatment process.
– Diesel was configured as a conservative numerical tracer and therefore concentrations within the reservoir from catchment inputs are due solely to transport and dispersion, and losses from withdrawals. This is a conservative assumption as volatilisation to the atmosphere, microbial degradation, and settling to adhered particles are not considered.

2.2 Primary Inputs and Outputs of Water

Figure 1 provides a schematic of the primary inputs and outputs of water for the three dams, which can be summarised as:

– Serpentine Main Dam (SMD) (reservoir model #1) has inputs of potential contaminants via the catchments and releases (draw) directly into the Serpentine Pipehead Dam (SPD).
– South Dandalup Dam (SDD) (reservoir model #2) has catchment inputs and releases (draw) as SMD. In addition, there are also extractions for existing (and proposed) Alcoa mining operations and transfers from outside the catchment.
– Serpentine Pipehead Dam (SPD) (reservoir model #3) has catchment inputs, releases (draw to IWSS after chlorination at the WTP), transfers from outside the catchment (a large proportion from the Southern Seawater Desalination Plant), and releases from SMD.

Environmental releases from SPD for downstream water users, and ecological and social values are managed as per DWER (2017). Environmental releases from SPD were not simulated as they comprise a small proportion of this reservoir's water balance.

Rainfall is a model input, and evaporation is simulated by the model on the basis of simulated surface water temperatures, and model inputs of air temperature, relative humidity and wind speed. No groundwater inputs or losses were considered.

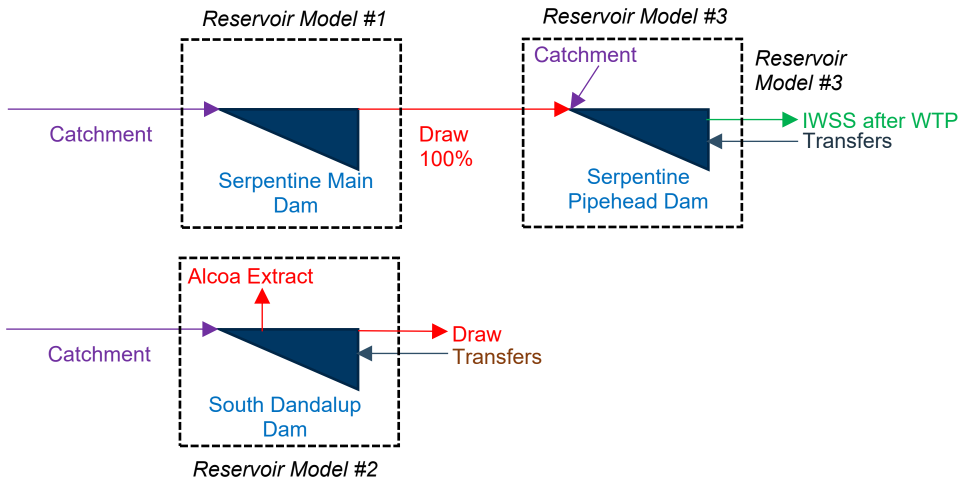

Figure 1 ***Primary inputs and outputs of water of the three dams in the study.***

3. Data

3.1 Monthly Water Balance

Table 1 summarises the relevant monthly water balance data that was provided on April 19th, 2021, by Water Corporation for the three reservoirs.

Table 1 Monthly water balance data availability from Water Corporation of the three reservoirs.

Data	SMD	SDD	SPD
Bathymetry	NA	NA	NA
Water Level	Monthly 2000-2020	Monthly 2000-2020	Monthly 2000-2020
Inflows[1]	Monthly 2000-2020	Monthly 2000-2020	Monthly 2000-2020
Draw (Supply)	NA Not calculated by Water Corporation	Monthly 2000-2020 as IWSS+Dwellingup Draw & Alcoa Extraction	Monthly 2000-2020
Withdrawals Levels (depth of water draw or extraction)	NA	NA	NA
Transfers (Sources)	None	Monthly from Lower South Dandalup	NA

[1] Not available

Where data was not available in the monthly water balance data in Table 1 for each of the three dams, the following estimates were made:

– Annual monthly averages of rainfall and pan evaporation from the Bureau of Meteorology (BoM) station at Karnet (Station Number: 00911) were incorporated into the monthly water balance.
– Relations of volume and surface area versus water level for SMD and SDD were derived from hypsographic information. A relation between volume versus water level for SPD was developed from Water Corporation's 2000-2020 monthly water balance. SPD surface area was assumed to be at Full Supply Level (FSL) (0.62 km^2) to estimate evaporation and rainfall, which are both relatively small components of the water balance of this reservoir (i.e. dominated by external transfers and draws).
– The water balance residual was used to estimate additional monthly inputs or outputs to the reservoirs in the following manner:
  - Excess water was estimated as additional draws (supply).
  - Shortfalls of water were estimated as additional transfers (SPD) or inflows (SMD, SDD)

Figure 2 summarises the monthly water balance from 2000-2020 where key patterns include:

– Catchment inflows and draws from both SMD and SDD have decreased over the past 20 years. In particular, the SMD draws have decreased substantially over the past decade with very low extractions to supply SPD from July 2017-October 2019.
– The primary water source of SPD has transitioned from SMD draws prior to 2006 to external transfers from other sources.
– The selected modelling period (Section 4.1.1) from 1 July 2017 to 1 October 2019 corresponds to low reservoir water levels in SMD and SDD with two relatively wet winters in 2017 and 2018 and then a dry 2019 winter. In contrast, SPD maintains a relatively constant level approximately 1 m below the FSL of 165.5 m AHD due to this water body's highly managed balance between external transfers and draws (supply).

[1] Estimates of the basis of monthly water balances for SMD, SDD and SPD.

– Temperature measurements in the dams were available from 2000-2008, but not thereafter (see Section 3.3). The selection of a year for each reservoir over this 2000-2008 period to compare with 2017-2019 simulated temperatures was based on the similarity of monthly water balance components in Figure 3, which were:

- For SMD the 2002-3 measurements are compared to the 2017-18 simulation period.
- For SDD the 2003-4 measurements are compared to the 2017-18 simulation period.
- For SPD the 2006-7 measurements are compared to the 2017-18 simulation period.

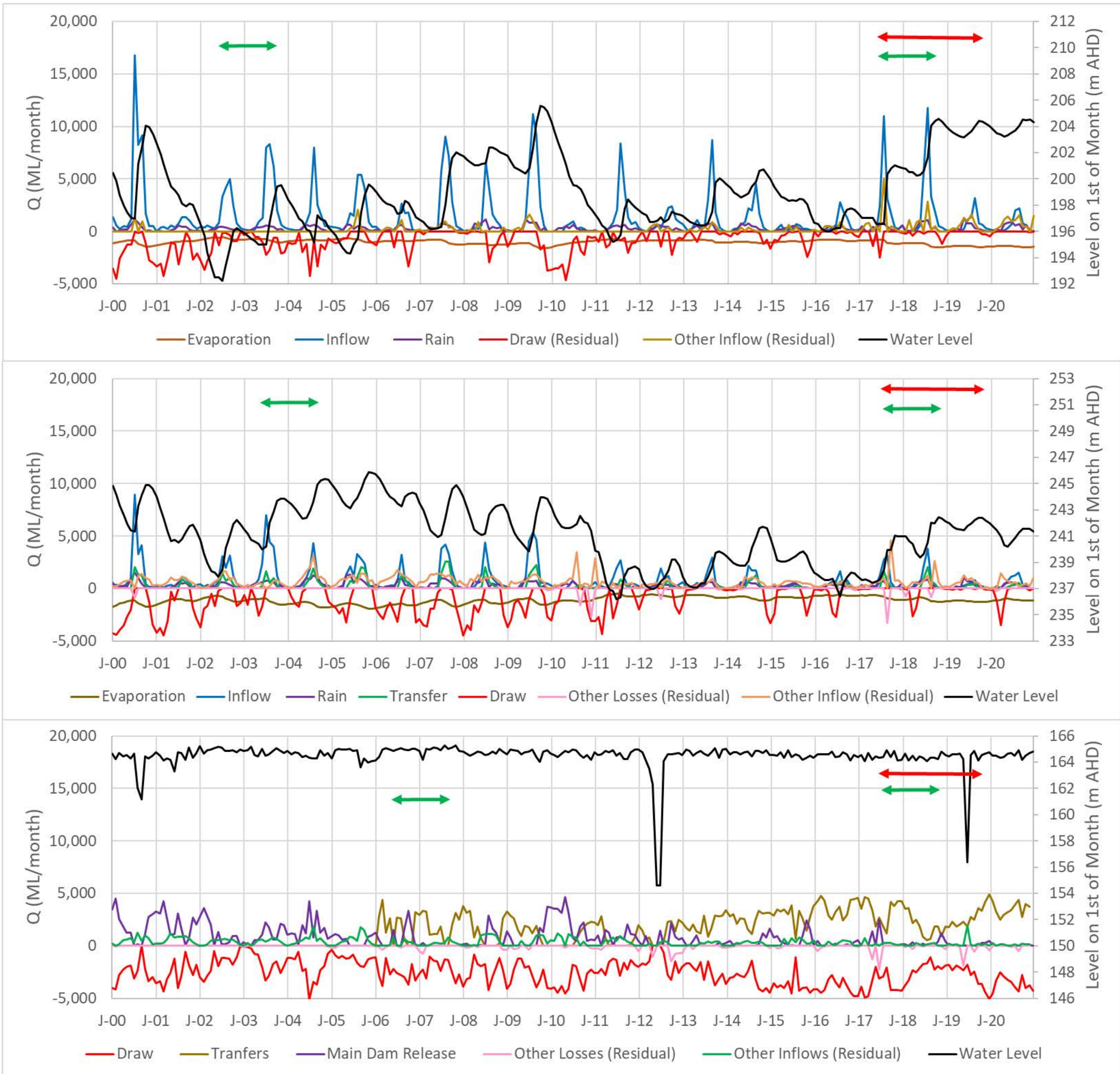

Figure 2 ***Monthly water balance from 2000-2020 for Serpentine Main Dam (SMD) (top), South Dandalup Dam (SDD) (middle) and Serpentine Pipehead Dam (SPD) (bottom).[2] Red arrow shows model period from 1 July 2017-1 October 2019. Green arrows show periods in which thermal stratification is compared between measurements (2000-2008) and simulations (2017-2019).***

[2] Maximum value of level on plots approximately correspond to each reservoir's full supply level (FSL).

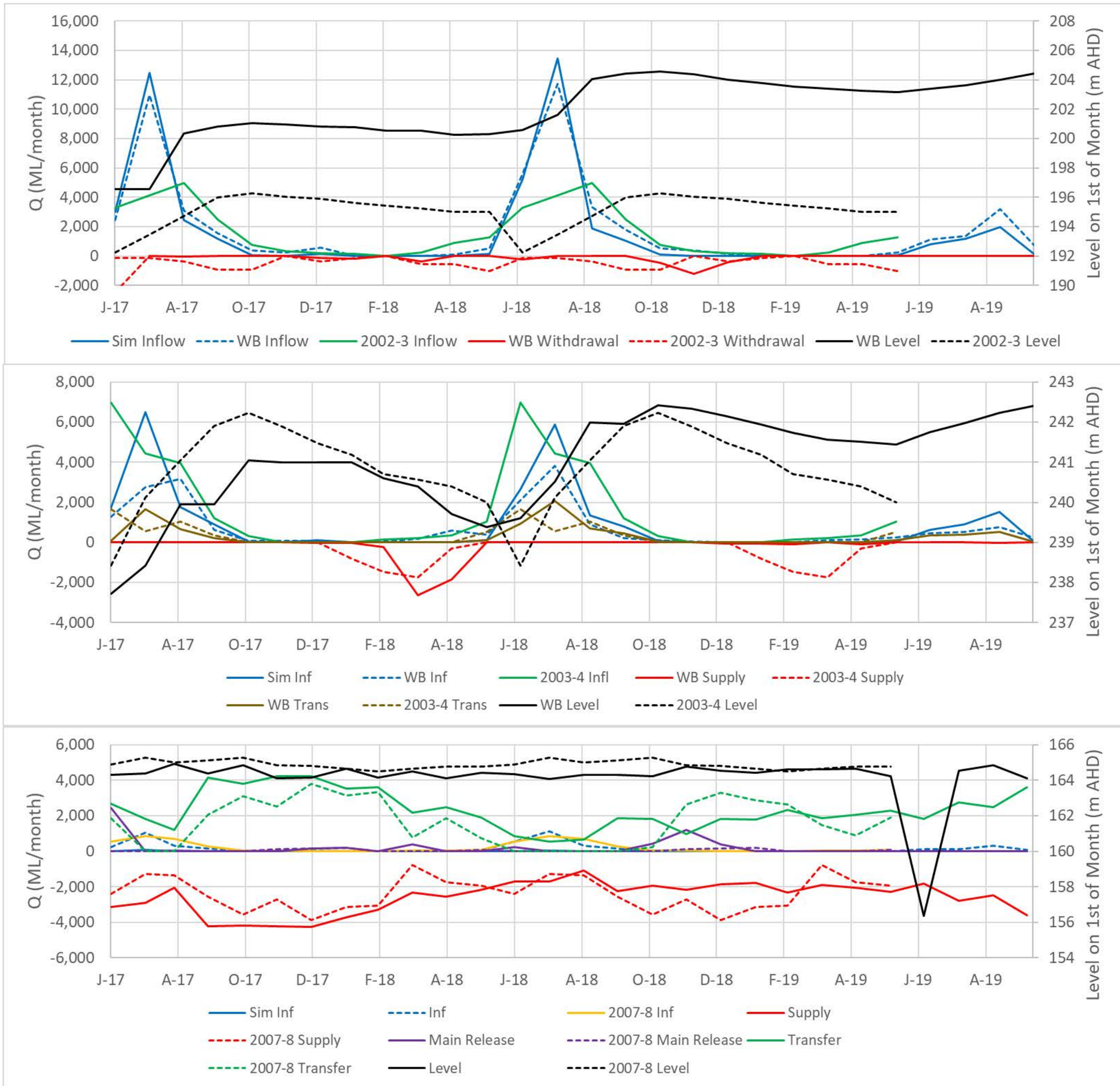

Figure 3 ***Monthly water balance comparison of simulation period (1 July 2017-1 November 2019) and measurement periods for thermal stratification of Serpentine Main Dam (SMD) (top, 2002-3), South Dandalup Dam (SDD) (middle, 2003-4) and Serpentine Pipehead Dam (SPD) (bottom, 2006-7).***

3.2 Stream Data

3.2.1 Gauged Daily Stream Inflows into Serpentine Main Dam

Average measured daily discharge by the DWER over the period of 2000-2020 of the three major SMD streams (Serpentine River, Big Brook, 39 Mile Brook) are shown in Figure 4. No major streams in the SDD catchment have been gauged over the past 20 years, only two small tributaries (Del Park and Gordon Catchment with maximum average daily discharges of 0.06 and 0.04 m^3/s, respectively). Over the longest stream measurement record, namely Big Brook, peak winter discharge during the verification period (1 July 2017 to 1 October 2019) during 2017 and 2018 were near/at the maximum over the past 20 years. In contrast, the peak winter discharge of 2019 was near/at the minimum over the 20 years.

Figure 4 ***Daily average Department of Water and Environmental Regulation (DWER) discharge measurements from 2000-2020 of the Serpentine River, Big Brook and 39 Mile Brook in the SMD catchment. Red arrow shows selected model verification period.***

Monthly (Figure 5) and daily (Figure 6) Big Brook and 39 Mile Brook discharge are highly correlated with the Serpentine River.

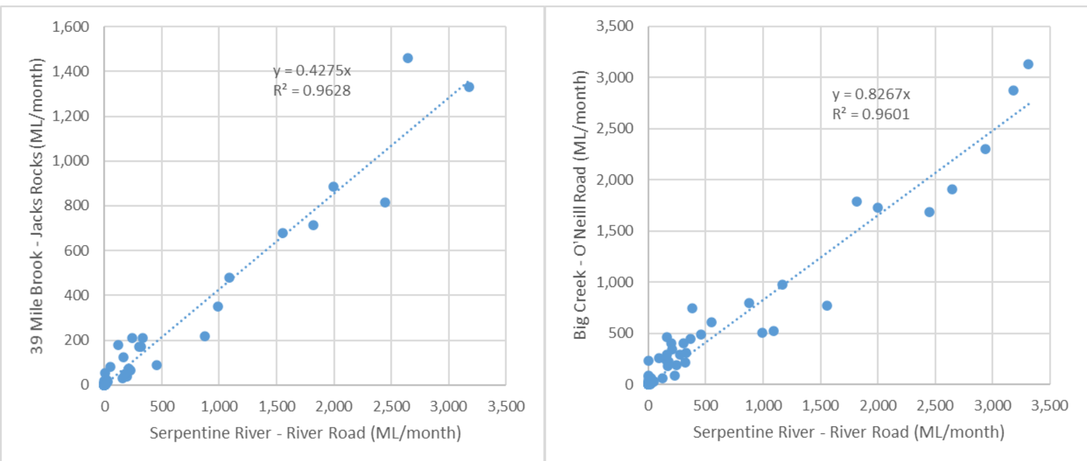

Figure 5 ***Linear regressions between monthly Department of Water and Environmental Regulation (DWER) Serpentine River discharge measurements and those of Big Brook and 39 Mile Brook.***

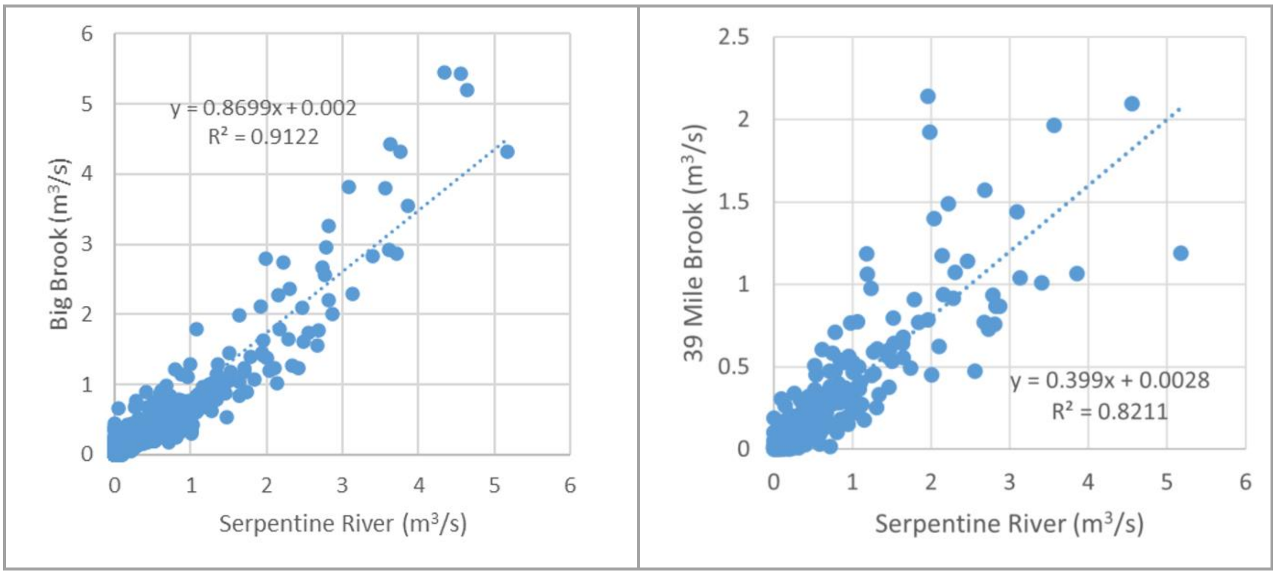

Figure 6 *Linear regressions between daily Department of Water and Environmental Regulation (DWER) Serpentine River discharge measurement and those of Big Brook and 39 Mile Brook.*

3.2.2 Total Discharge Estimates into Reservoirs

Table 2 summarises the methodology to estimate the total inflows into SMD based on the three gauged streams. The gauged catchment area of these three streams accounts for nearly two-thirds of the SMD's total catchment area where the remaining 1.6% and 31.1% are attributable to the reservoir surface area at FSL and the ungauged catchment area, respectively. Linear regression coefficients of monthly discharge from Big Brook and 39 Mile Brook relative to Serpentine River are 82.7% and 42.8% (Figure 5), respectively. These linear coefficients expressed on a per km^2 basis (see Table 2) are 0.0041, 0.0056 and 0.0079 1/km^2 for the Serpentine River, Big Brook and 39 Mile Brook, respectively. These linear areal coefficients were used to estimate discharge from ungauged portions of the catchments.

Table 2 *Derivation of areal linear coefficients to estimate total stream discharge into Serpentine Main Dam (SMD).*

Stream	Location	Area (km^2)	% of Catchment Area	Linear Regression Coefficient relative to Gauged Serpentine River	R^2	Linear Coefficient per km^2	Coarse Estimate of Ungauged Catchment Area (km^2)	Total Catchment Area (km^2)	Linear Coefficient for Total Stream Catchment relative to Gauged Serpentine River
Serpentine River	River Road 614035	243	36.6%	1	1	0.00412	112.1	355.1	1.462
Big Brook	O'Neill Road 614037	149	22.4%	0.827	0.96	0.00555	68.8	217.8	1.209
39 Mile Brook	Jack Rocks 614031	55	8.3%	0.428	0.96	0.00778	25.4	80.4	0.626
	Reservoir @ FSL	10.7	1.6%					10.7	
	Ungauged Catchment	206.3	31.1%	1.375		0.00582			
	Total	664	100.0%				206.3	664.0	

A comparison of the monthly inflow estimates into SMD between Water Corporation's monthly water balance relative to the areal coefficient estimates in Figure 7 are in reasonable agreement.

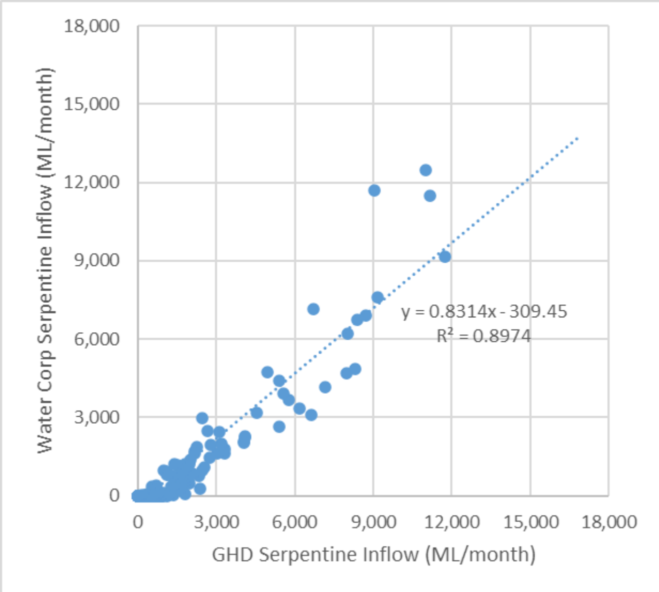

Figure 7 ***Comparison of total Serpentine Main Dam (SMD) catchment inflows via areal coefficient estimates and Water Corporation's monthly water balance.***

For SDD there are no discharge measurements of the major stream (South Dandalup River) over the past 20 years. The average coefficient per square kilometre of the three gauged streams from the proximal SMD catchment of 0.00582/km^2 (Table 2) was used to estimate total SDD catchment inflow as summarised in Table 3.

Table 3 ***Catchment coefficient estimate for South Dandalup Dam (SDD) inflows.***

Stream	Location	Area (km^2)	% of Catchment Area	Linear Coefficient per km^2	Linear Coefficient for Total Stream Catchment relative to Gauged Serpentine River
South Dandalup River		295.2	94.9%	0.00582	1.717
	Reservoir @ FSL	15.8	5.1%		
	Total	311	100.0%		

3.2.3 Stream Temperatures

Figure 8 summarises the stream temperatures of Big Brook from 1 July 2001 through 2000, where during winter, when most high flow events occur, they are in the range of ~5-15°C.

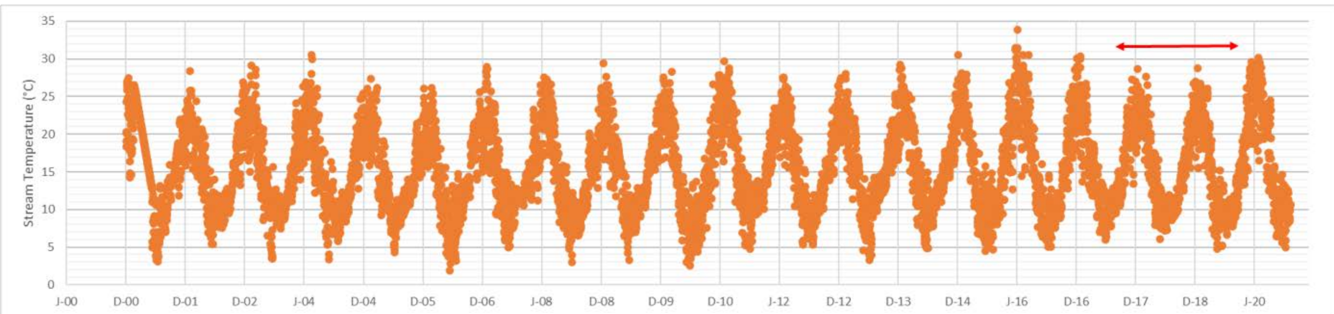

Figure 8 ***Daily Department of Water and Environmental Regulation (DWER) average stream temperature measurements from 2000-2020 of Big Brook (red arrow denotes model verification period).***

3.3 Measurements of Reservoir Water Temperatures and Turbidity near the Dam Walls

Water Corporation provided measurements of turbidity from 2000-2020 near the dam walls of SMD, SDD and SPD at least on a quarterly basis, but at times as frequently as weekly. However, available water temperature measurements only span from 2000-2008.

3.3.1 Serpentine Main Dam

Temperature and turbidity measurements in SMD at the dam wall are illustrated in Figure 9 where:

– Temperatures range from 12-13°C in winter to 25-26°C in summer, noting that measurements cease in 2008.

– Except for elevated turbidity in 2002, levels were generally below 1 NTU. Over the model verification period turbidity was generally below 1 NTU and generally ~0.5 NTU.

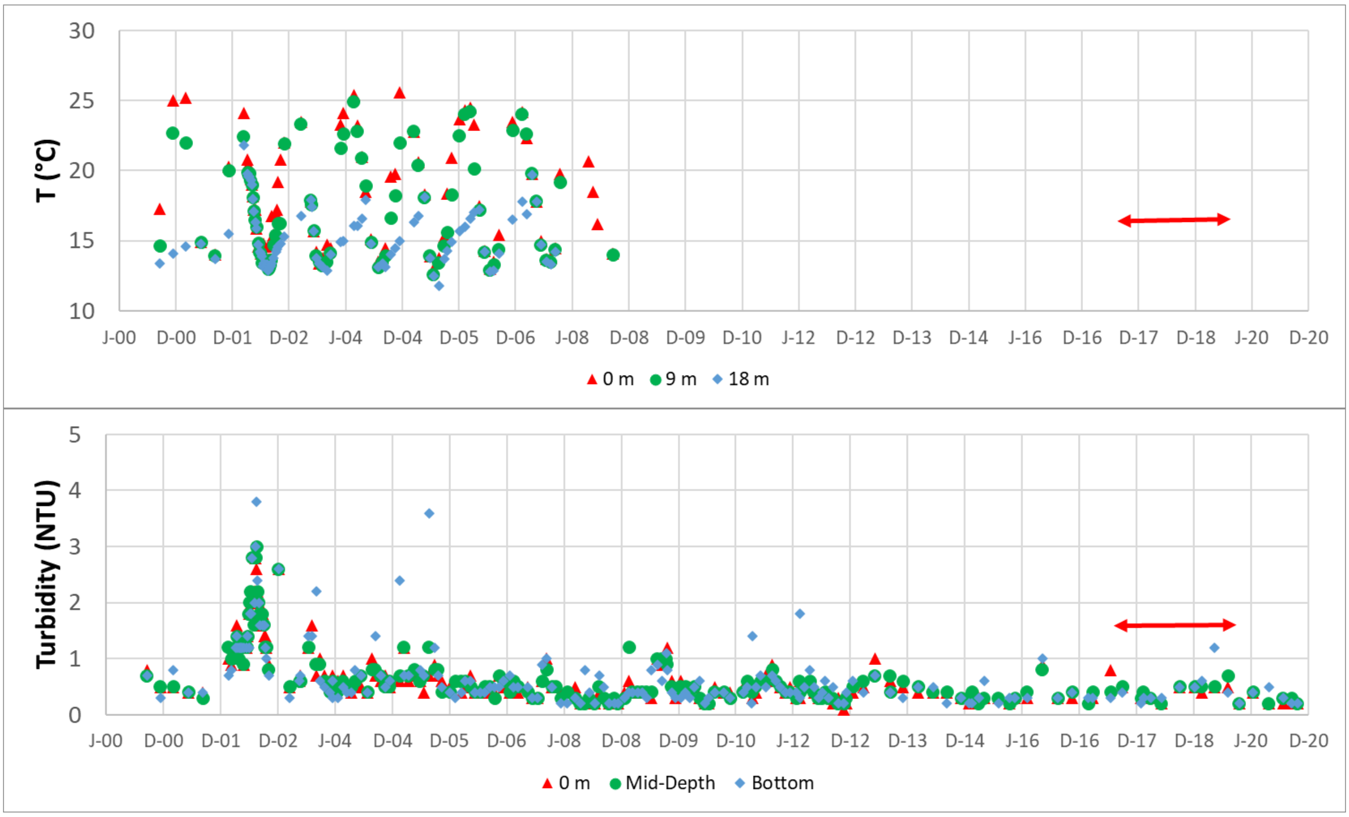

Figure 9 *Surface (0 m), mid-depth and near-bottom Water Corporation measurements of temperature (T, upper) and turbidity (lower) of the water column at the dam wall from 2000-2020 in Serpentine Main dam (SMD) (red arrow model verification period).*

3.3.2 South Dandalup Dam

Temperature and turbidity measurements in SDD at the dam wall are illustrated in Figure 10 where:

– Temperatures range from 12-13°C in winter to 25-26°C in summer, noting that measurements cease in 2008.

– Except for high levels in the 2011 and 2016 winters, turbidity was generally at or below 1 NTU throughout the 20 years. The 2016 winter was relatively dry with the lowest water level over the past 20 years (Figure 2), Hence it is unlikely that elevated turbidity during these periods was due to catchment inflow, but rather another source such as transfers into SDD.

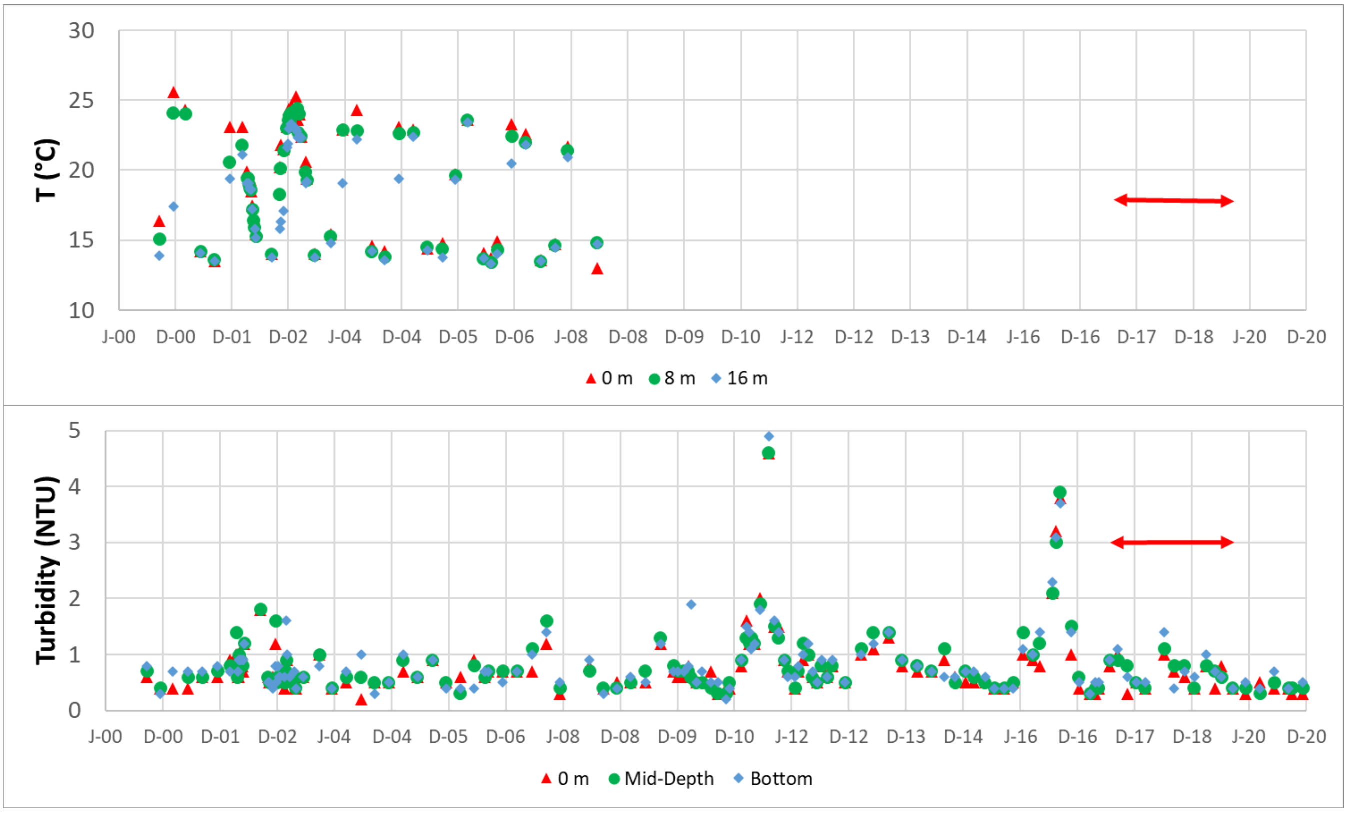

Figure 10 ***Surface (0 m), mid-depth and near-bottom Water Corporation measurements of temperature (T, upper) and turbidity (lower) of the water column at the dam wall from 2000-2020 in South Dandalup Dam (SDD) (red arrow model verification period).***

3.3.3 Serpentine Pipehead Dam

Temperature and turbidity measurements in SPD at the dam wall are illustrated in Figure 10 where:

- Temperatures range from 12-13°C in winter to 25-26°C in summer, noting that measurements cease in 2008.
- Except for elevated turbidity in the winter of 2012, levels were generally at or below 1 NTU throughout the most of the 20 year record. Over the model verification period turbidity was generally below 1 NTU and generally ~0.3-0.5 NTU.

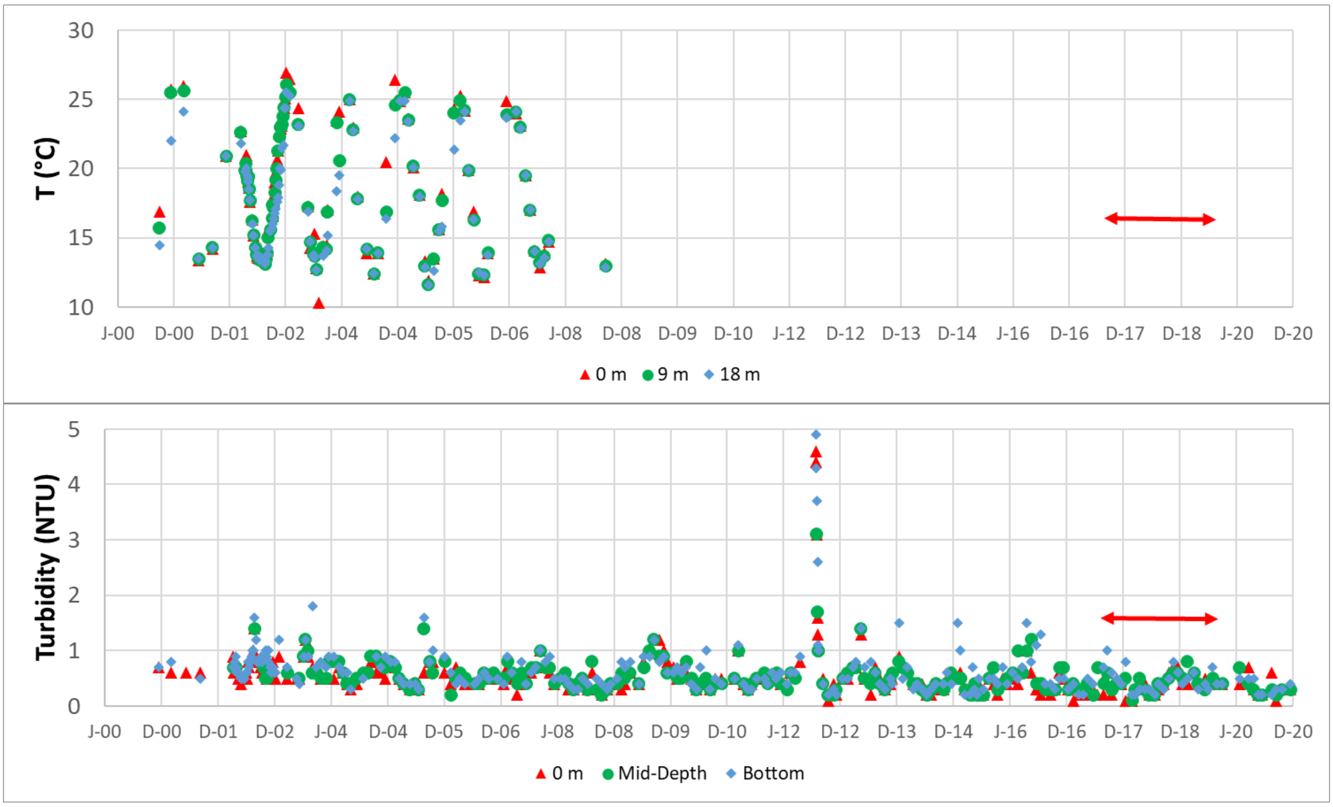

Figure 11 ***Surface (0 m), mid-depth and near-bottom Water Corporation measurements of temperature (T, upper) and turbidity (lower) of the water column at the dam wall from 2000-2020 in Serpentine Pipehead Dam (SPD) (red arrow model verification period).***

3.4 Meteorology

Hourly meteorological inputs were sourced from the National Centers for Environmental Prediction's (NCEP's) Climate Forecast System, version 2 (CFSv2) (Suranjana *et al.* 2014) grid cell nearest to the reservoirs. Figure 12 illustrates the hourly CFSv2 meteorology data that served as inputs to the model.

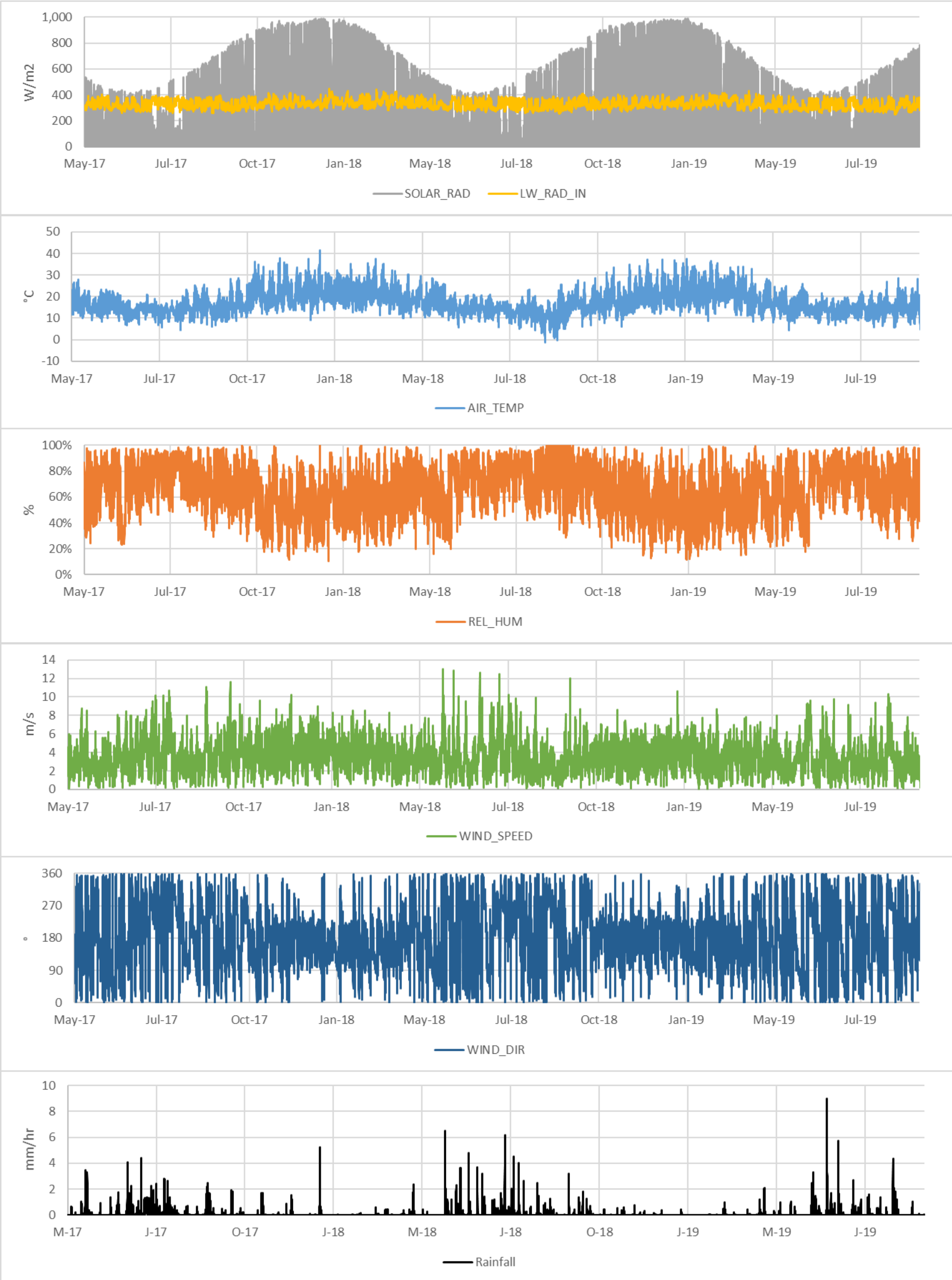

Figure 12 ***Hourly CFSv2 meteorology from 1 May 2017 to 1 October 2019 of shortwave and incoming longwave radiation (top), air temperature (upper middle), relative humidity (middle), wind speed and direction (lower middle) and rainfall (lower).***

4. Model Establishment and Verification

4.1 Model Inputs

4.1.1 Model Verification Period

A continuous multi-year simulation period for model verification was selected on the following basis:

– Turbidity data was available from Water Corporation from 2000-2020.
– CFSv2 meteorology available from 2015-2020.
– Reliable stream hydrology measurements were available for SMD from 2000-2020. SDD and SPD catchment inflows (no discharge measurements of any large streams from 2000-2020) were estimated from relations of the proximal SMD catchment (see Section 3.2.2).
– Occurrence of at least one substantive inflow event.
– A low reservoir level with reduced volumetric dilution capacity.

On the basis of these criteria the period from 1 July 2017 to 1 October 2019 was selected as the verification modelling period.

4.1.2 Bathymetry of Reservoirs

Spatial data suitable to construct a 3D bathymetry file of each of the three reservoirs was not available. Therefore, the bathymetry of the reservoirs was developed from historical topographic data prior to the construction of the dams and the use of GIS interpolation algorithms to develop digital elevation models. The digital elevation models were then parsed into 100 m by 100 m grids for SMD and SDD, and 50 m by 50 m grids for SPD to serve as bathymetric inputs for the reservoir modelling, which are illustrated in Figure 13, Figure 14 and Figure 15, respectively. The simulated locations of the reservoir confluences of the major streams and smaller catchments are also shown in these figures along with the intake towers (for water supply extraction) and estimates of external transfer locations.

The accuracy of the reservoir volumes at Full Supply Level (FSL) as summarised in Table 4 are considered sufficient for the objectives of this investigation. Though the volume discrepancy is relatively sizeable for SPD (~10%), given the relatively low water age of this reservoir (see Figure 65), this is considered acceptable.

Table 4 Comparison of volumes and surface areas at Full Supply Level (FSL) of Serpentine Man Dam (SMD), Serpentine Pipehead Dam (SPD) and South Dandalup Dam (SDD) between modelling inputs and Water Corporation website.

Reservoir	FSL Level (m AHD)	Water Corp Volume (GL)	Model Volume (GL)	Volume Discrepancy
Serpentine Main	212.4	137.7	143.0	3.9%
Serpentine Pipehead	165.5	3.14	2.83	-11.8%
South Dandalup	252.8	138.0	144.8	4.9%

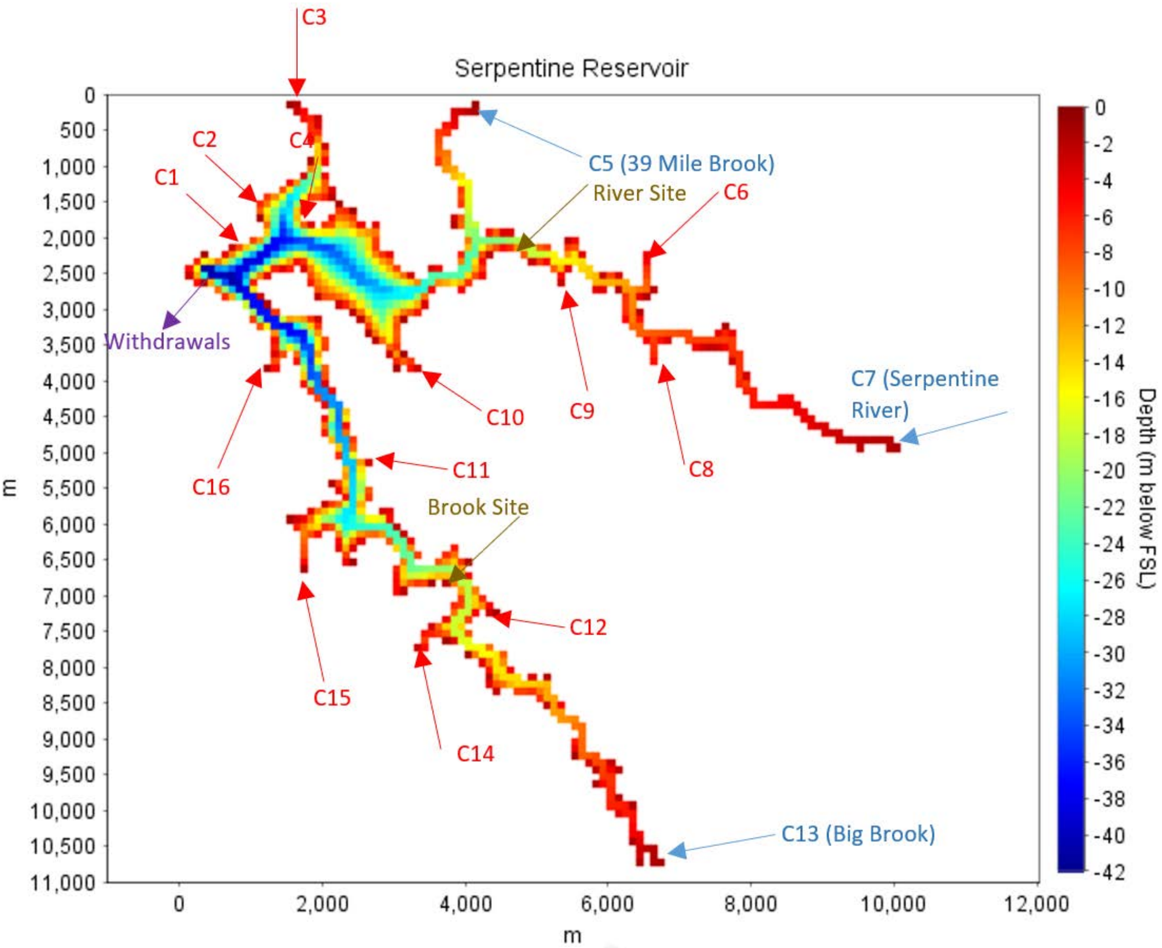

Figure 13 *Serpentine Main Dam (SMD) bathymetry along with three Department of Water and Environmental Regulation (DWER) gauged major streams (blue), intake tower (purple), 13 other catchments (red) and assessment sites (gold).*

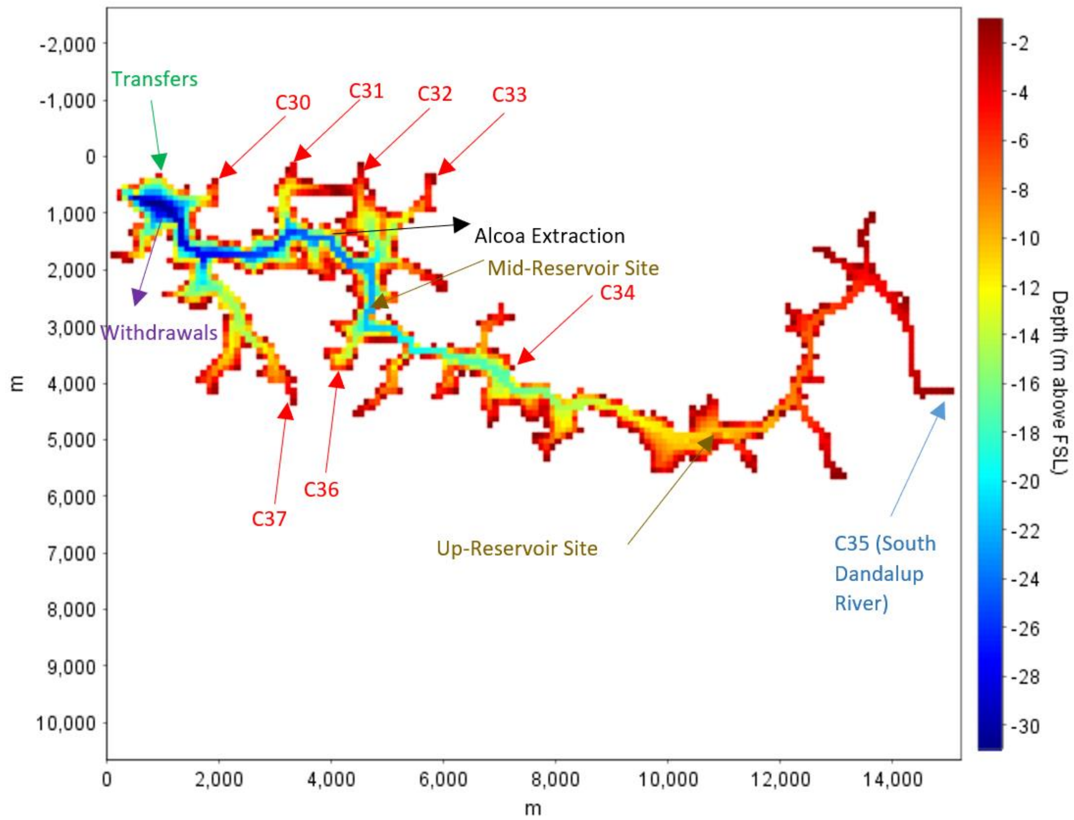

Figure 14 **_South Dandalup Dam (SDD) bathymetry along with the major stream, 7 other catchments, external transfers from Lower South Dandalup (green), Alcoa extractions (black) and assessment sites (gold)._**

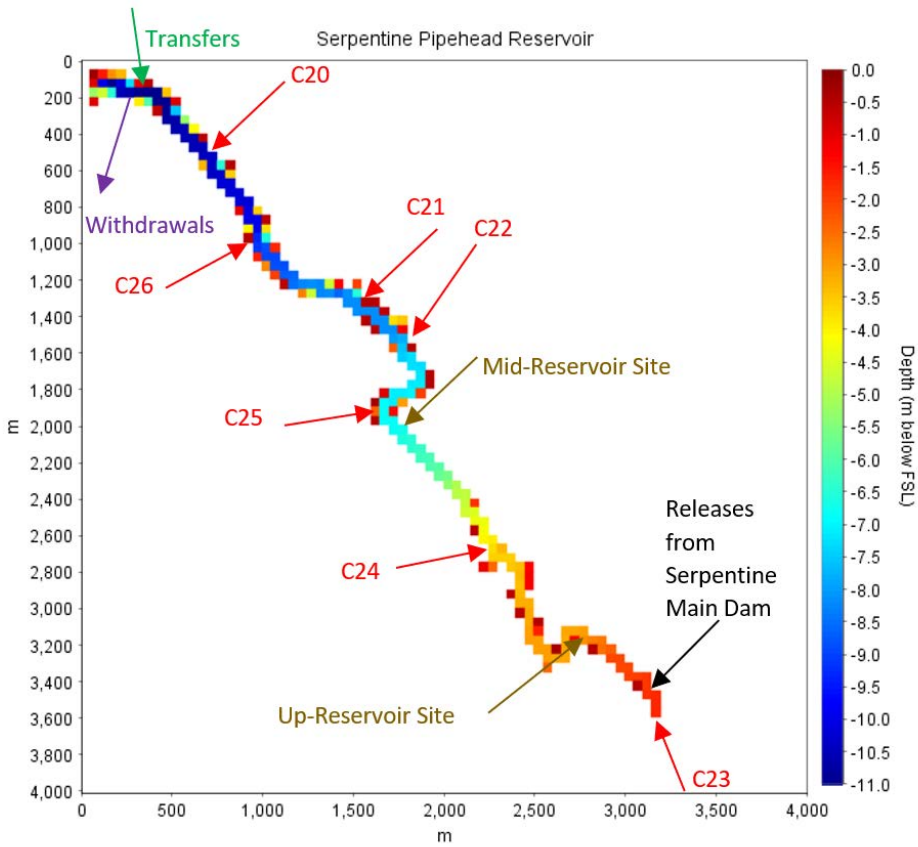

Figure 15 **_Serpentine Pipehead Dam (SPD) bathymetry along with 7 catchments, external transfer (green), Serpentine Main Dam (SMD) releases (black) and assessment sites (gold)._**

4.1.3 Meteorology

Refer to Section 3.4 for a description of the meteorological inputs that were applied to the reservoir model.

4.1.4 Catchment Inflows

Total daily catchment discharge estimates into the three reservoirs from the regression relations in Section 3.2.2 served as inputs to the 2017-2019 verification simulations, which are illustrated in Figure 16. The amount of the total daily discharge that was allocated to each of the simulated streams was the percentage of each of the catchment areas to the total reservoir catchment area. Big Brook stream temperatures that served as model inputs for all stream temperatures (Figure 8).

4.1.5 External Transfers

SDD and SPD external transfers were assumed to occur in proximity to the dam wall (Figure 14 and Figure 15) via inspection of Google Earth images. The external transfers were based on the monthly water balance information from the Water Corporation (Section 3.1).

4.1.6 Withdrawal Discharge from and Locations in Reservoirs

No explicit draw (withdrawal) data (i.e. draw volume per day and depth of draw from reservoir through intake tower) was available for SMD.[3] For the purposes of the 2017-2019 SMD verification simulation were as estimated from the revised monthly water balance (Section 3.1). Model inputs for the SDD draws were as provided in the monthly water balance by Water Corporation (Section 3.1).

The SPD water balance is dominated by external transfers and draws. Model inputs for external transfers into SPD were as provided in the monthly water balance by Water Corporation (Section 3.1). However, the draws were configured as a dynamic outflow boundary condition dependent on surface water level height on the basis of the following piece-wise linear relations:

- -2 m below FSL or lower than draw is 0 m^3/s.
- -1.5 m below FSL than draw is 0.25 m^3/s.
- -1 m below FSL than draw is 1 m^3/s.
- -0.5 m below FSL than draw is 1.75 m^3/s.
- 0 m below FSL than draw is 3 m^3/s.

[3] For their monthly water balance Water Corporation does not calculate the draw from SMD.

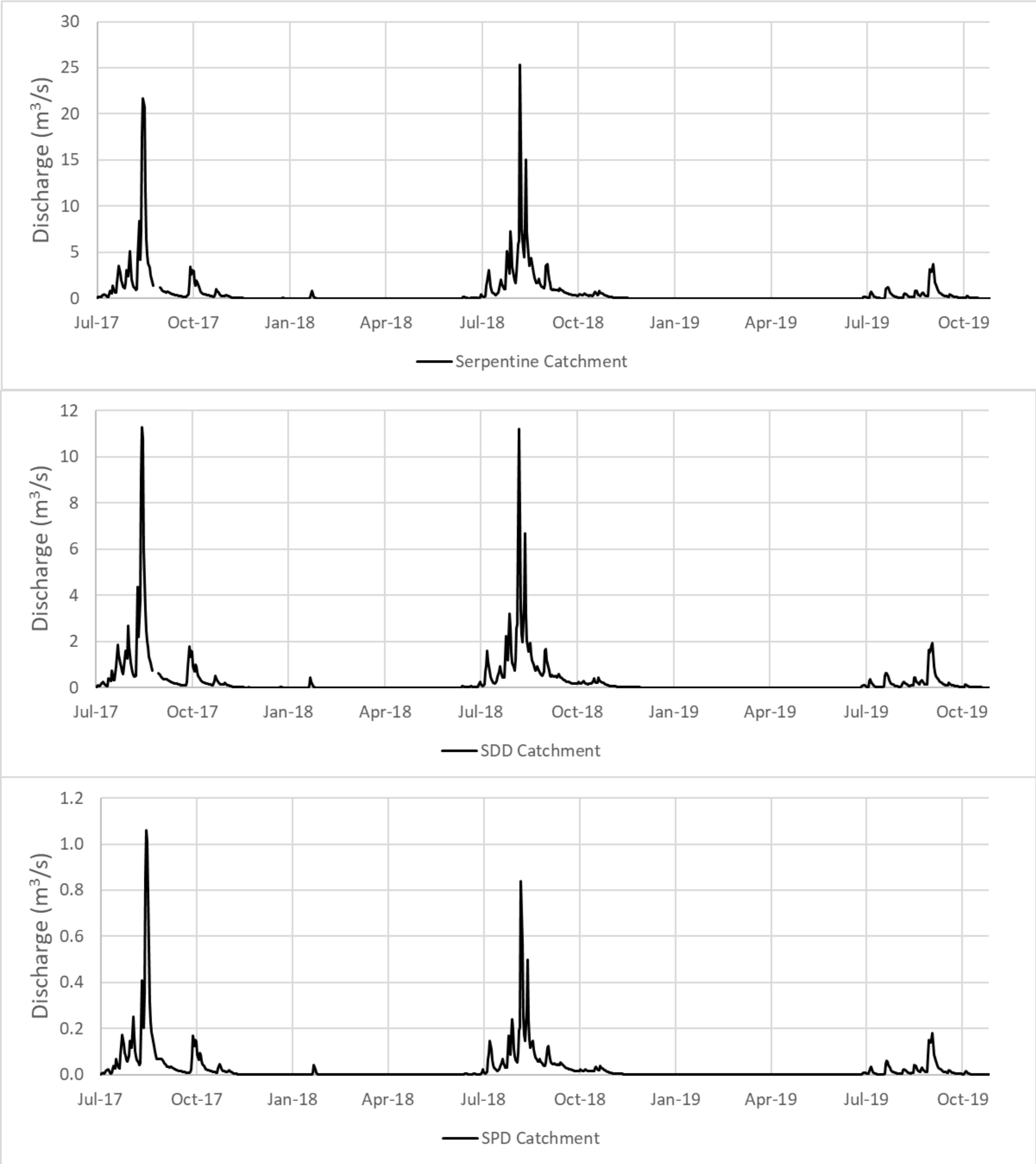

Figure 16 *Daily modelled stream discharge into Serpentine Main Dam (SMD) (top), South Dandalup Dam (SDD) (middle) and Serpentine Pipehead Dam (SPD) (bottom).*

4.1.7 Suspended Solids

Two particle types were configured to simulate the inorganic suspended solids (SS) concentrations from inputs into the reservoirs, namely clay (SS_{clay}) and silt (SS_{silt}). The model was configured with the following SS parameters:

- Particle density of 2,650 kg/m^3.
- Particle diameters of 1 and 5 µm for SS_{clay} and SS_{silt}, respectively. Clay is defined as particle diameters of 1-4 µm. Silt is defined as particle diameters of 4-63 µm. Very fine silt is defined as particle diameters of 4-8 µm.

Hence, the characteristic diameters configured here are conservative in that they both represent the smallest particle diameters for SS_{clay} and SS_{silt}.

– Application of stokes settling, which yields characteristic settling velocities of 1×10^{-6} m/s and 1×10^{-5} m/s for SS_{clay} and SS_{silt}, respectively.

There were no available reliable measurements of stream turbidity or suspended solids, so estimates were determined. The clay and silt components of SS were set to constant concentrations of:

– SS_{clay} as 5 mg/L.
– SS_{silt} as 15 mg/L.

SS_{clay} of 5 mg/L was based on a sensitivity analysis over a range of concentrations that yielded reasonable simulated SS levels when compared to turbidity measurements at the dam wall over the 2017-2019 verification period for all three reservoirs (see Section 4.2.3). The silt concentration of 15 mg/L was based on particle size distribution measurements of natural streambed sediments (see Table 10), which indicates 20% and 60% of the material is clay and silt, respectively. On this basis SS_{silt} was estimated as a three-fold increase of SS_{clay}. Though these constant clay and silt concentrations are overestimates during low flow periods, volumetrically most of the catchment loads into the reservoirs occur during winter inflow events when these SS levels are reasonable. The following inorganic SS concentrations for the SDD and SPD external transfers (note there are no external transfers into SMD) were fixed based on a sensitivity analysis over a range of concentrations, which yielded reasonable simulated SS when compared to turbidity measurements over the 2017-2019 verification period:

– SDD external transfers had SS_{clay} and SS_{silt} concentrations of 3.0 mg/L and 0.5 mg/L, respectively.
– SPD external transfers had SS_{clay} and SS_{silt} concentrations of 0.45 mg/L and 0.05 mg/L, respectively.
– SMD releases to SPD had SS_{clay} and SS_{silt} concentrations of 0.95 and 0.05 mg/L, respectively. Because of the small volume of SMD releases to SPD over the 2017-2019 verification period, these silt and clay concentrations do not have any meaningful effect on the simulations.

These data gaps in stream turbidity and/or SS measurements yield the highest degree of uncertainty in this investigation.

4.2 Model Verification

4.2.1 Reservoir Surface Levels

Model verification of reservoir surface levels of the three reservoirs was on the basis of comparisons between simulations and those of the monthly water balance.

Initially the simulated SMD water levels matched well with those of the monthly water balance for the 2017 winter, but the 2018 winter levels were underestimated. A ~50% increase to the estimated inflows over the 2018 winter high discharge period (i.e. 14 July-2 September 2018) reproduced the Water Corporation's monthly water levels (Figure 17).

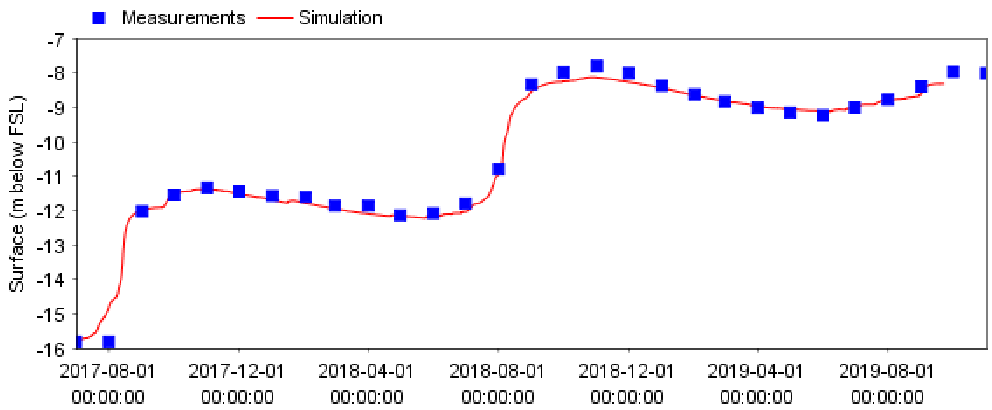

Figure 17 ***Comparison of measured and simulated Serpentine Main Dam (SMD) surface levels on the 1st of the month from July 2017 to June 2019.***

The simulated SDD water levels matched well with those of the Water Corporation's monthly water balance model for the 2017 winter, but the 2018 winter levels were underestimated. A ~25% increase to the estimated inflows over the high winter 2018 discharge period (i.e. 14 July-2 September 2018) reproduced the Water Corporation's monthly water levels (Figure 18).

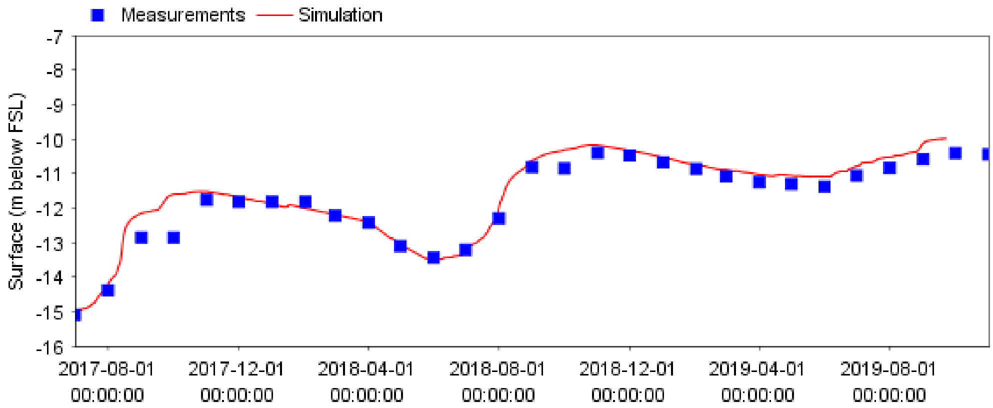

Figure 18 ***Comparison of measured and simulated South Dandalup Dam (SDD) surface levels on the 1st of the month from July 2017 to June 2019.***

The simulated SPD water levels were within the range of the Water Corporation's monthly water balance model over the simulation period (Figure 19) with application of the outflow (withdrawal) dynamic boundary condition as described in Section 4.1.6. Further, the simulated withdrawals with the dynamic outflow boundary condition matched well with the monthly water balance model (Figure 20).

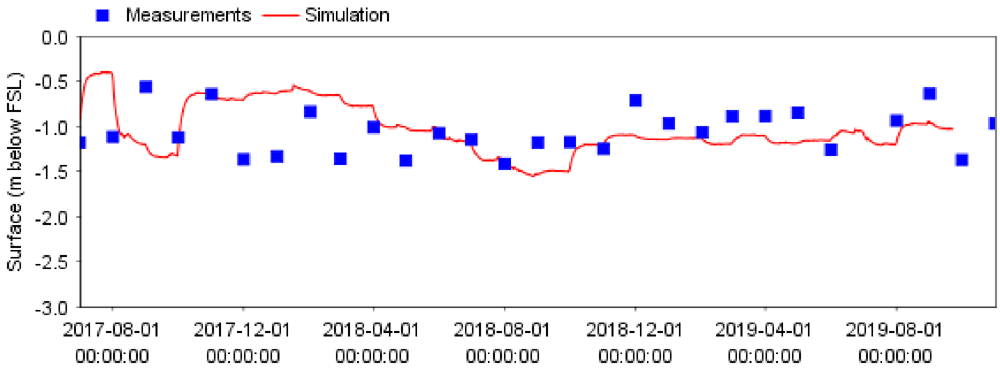

Figure 19 ***Comparison of measured and simulated Serpentine Pipehead Dam (SPD) surface levels on the 1st of the month from July 2017 to June 2019.***

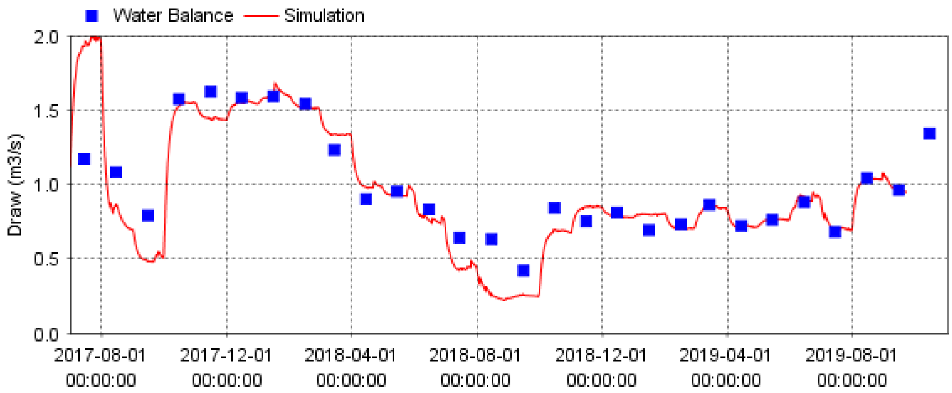

Figure 20 ***Comparison between average monthly water balance and simulated sub-daily Serpentine Pipehead Dam (SPD) draws.***

4.2.2 Temperature

As described in Section 3.3, water temperature measurements of the three reservoirs were only available until 2008. Selection of appropriate periods from the available 2000-2008 temperature measurements to compare to the 2017-2019 verification simulation was based primarily on similarities in the water balance components (i.e. water levels, catchment inflows, draws and transfers) (see Figure 3 of Section 3.1).

Comparison of simulated (2017-18) and measured (SMD 2002-3, SDD 2003-4, SPD 2006-7) water temperatures show a reasonable degree of similarity given the coarse similarity in monthly water balance terms for SMD (Figure 21), SDD (Figure 22) and SPD (Figure 23), respectively. These comparisons demonstrate the following:

– The surface heat balance was modelled well as the simulated surface water temperatures are in reasonable agreement with measurements from the selected comparative year of each reservoir. Hence, the CFSv2 meteorological inputs are acceptable. Note that there was not calibration of meteorological inputs.
– The bottom water temperatures are simulated reasonably well in terms of the rate of hypolimnetic heating and the duration of seasonal stratification for SMD and SDD.

On the basis of these comparisons, the model adequately simulates water temperatures and patterns of thermal stratification in all three reservoirs. Further discussion on the thermal stratification dynamics of the reservoirs is provided in Section 4.3.1.

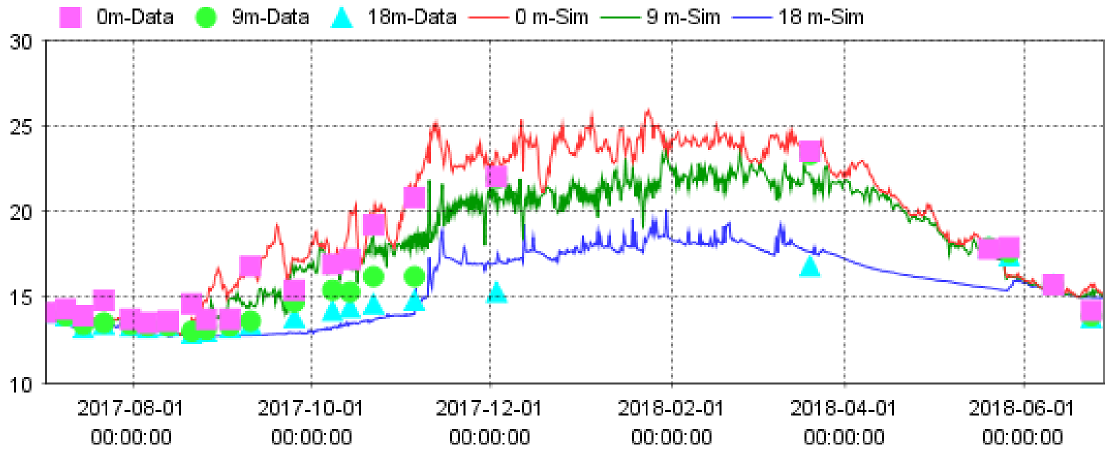

Figure 21 ***Comparison of the Serpentine Main Dam (SMD) 2017-2018 simulated (lines) and 2002-2003 measured (symbols) temperatures at the surface, mid-depth and deep water column near the dam wall from July to June.***

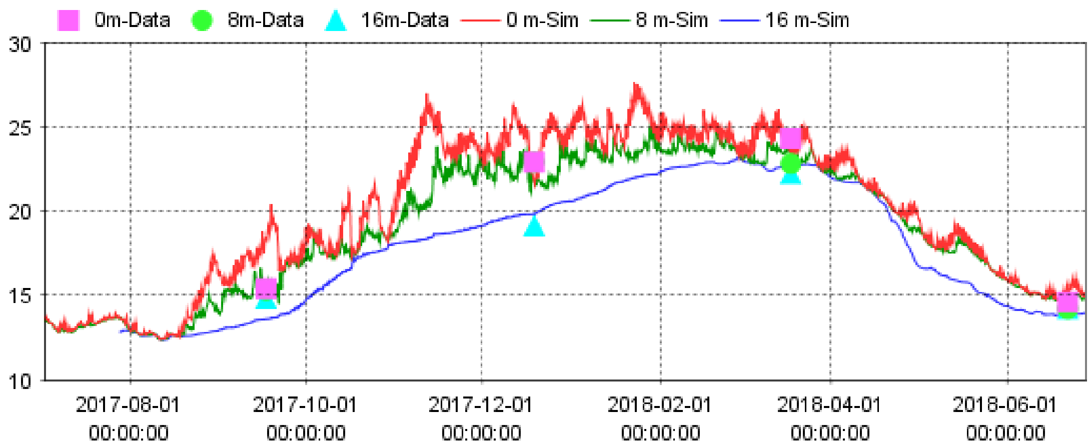

Figure 22 ***Comparison of the South Dandalup Dam (SDD) 2017-2018 simulated (lines) and 2003-2004 measured (symbols) temperatures at the surface, mid-depth and deep water column near the dam wall from July to June.***

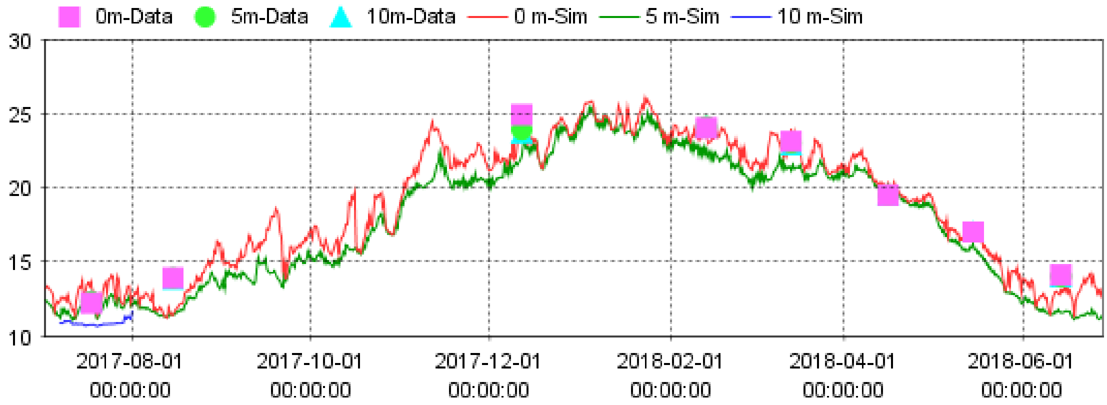

Figure 23 ***Comparison of the Serpentine Pipehead Dam (SPD) 2017-2018 simulated (lines) and 2006-2007 measured (symbols) temperatures at the surface, mid-depth and deep water column near the dam wall from July to June.***

4.2.3 Simulated Inorganic Suspended Solids (SS) and Turbidity Measurements

A comparison of the simulated SS_{clay} in the surface, mid-depth and deeper water column with the available turbidity measurements at the dam wall of the three reservoirs from 2017-2019 is shown in Figure 24. SS_{clay} comprises most of the suspended inorganic particles present in water near the dam wall (refer to Section 4.3.2). The simulated clay component of SS is in reasonable agreement with measurements assuming a SS:turbidity ratio of 1:1, which is applicable at these low concentrations (Section 1.5). The following is noted:

- The simulated SMD SS_{clay} is overestimated during the 2017 winter and underestimated during both the 2017 and 2018 summers. The simulated overestimate in winter 2017 SS_{clay} is ~2-fold greater than measurements, however the simulated 2018 winter levels are similar to turbidity observations. The simulated summer underestimates may be due to a larger proportion of organic SS (e.g. phytoplankton), which is not simulated here.
- The simulated SDD SS_{clay} matches reasonably well during both the 2017 and 2018 winters, but is underestimated during both 2017 and 2018 summers. As with SMD, the summer underestimates may be due to a larger proportion of organic SS (e.g. phytoplankton), which is not simulated here.
- SPD SS_{clay} is simulated well throughout the model verification period.

Given the uncertainty in SS from catchment inputs and external transfers, along with the inability to apply the AEM3D model's biogeochemical modules to simulate organic particle dynamics (e.g. phytoplankton, nutrient and organic carbon) due to a lack of data, the simulated SS_{clay} reproduces reasonably well the measured winter turbidity at the dam walls of the three reservoirs in response to sizeable inflow events. One of the key risks from the proposed mining transition is increased reservoir turbidity due to high inorganic particle loads from mined catchments. The model verification of SS here with available turbidity measurements at the dam wall indicates that the model can adequately quantify the relative effect on inorganic SS of withdrawal near the dam wall across a range of winter inorganic particle loading scenario.

Further discussion on the seasonal and interannual SS patterns in the reservoirs is provided in Section 4.3.2.

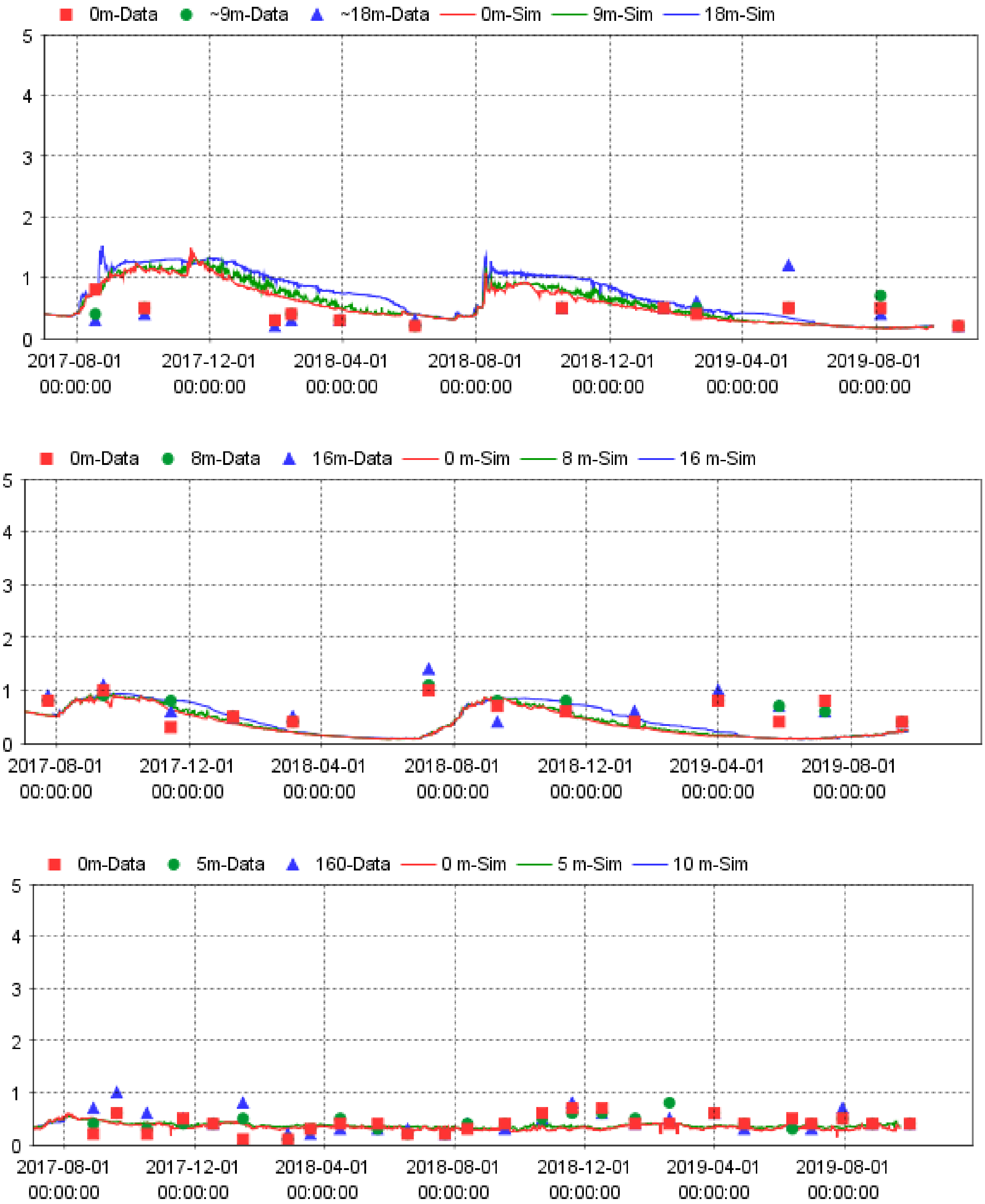

Figure 24 ***Comparison of the simulated clay component of inorganic suspended solids (SS_{clay} in mg/L) and measured turbidity (NTU) at the surface, mid-depth and deeper water column from July 2017 to October 2019 for Serpentine Main Dam (SMD) (top), South Dandalup Dam (SDD) (middle) and Serpentine Pipehead Dam (SPD) (bottom).***

4.3 Key Reservoir Processes during Model Verification Period

4.3.1 Seasonal Patterns of Thermal Stratification

Figure 13, Figure 14 and Figure 15 show the three assessment sites in each reservoir (i.e. near dam wall near the intake towers and two up-reservoir sites) that are used to illustrate seasonal patterns of thermal stratification in SMD, SDD and SPD, respectively. The simulated water levels, patterns of thermal stratification (as isotherms through the water column with time at each assessment site), and withdrawal temperatures at the three assessment sites for each reservoir are shown in Figure 25, Figure 26 and Figure 27 for SMD, SDD and SPD, respectively,. In SMD and SDD the simulated thermal stratification patterns include:

- Seasonal thermal stratification is maintained at the up-reservoir sites, but more so with the substantially cooler hypolimnetic temperatures at the dam site.
- The several meter increase in water levels during the 2018 winter resulted in seasonal thermal stratification that was more pronounced in the up-reservoir sites than the previous season at lower water levels.
- Short-term (~1 day) fluctuations in hypolimnetic temperatures are simulated at the dam sites over the thermally stratified period. These fluctuations are caused by sustained high wind events that induce internal waves via tilting of the thermocline at the dam wall. During such events higher rates of vertical mixing occur.

In SPD seasonal thermal stratification was not maintained, but brief periods (days to weeks) of intermittent thermal stratification were simulated.

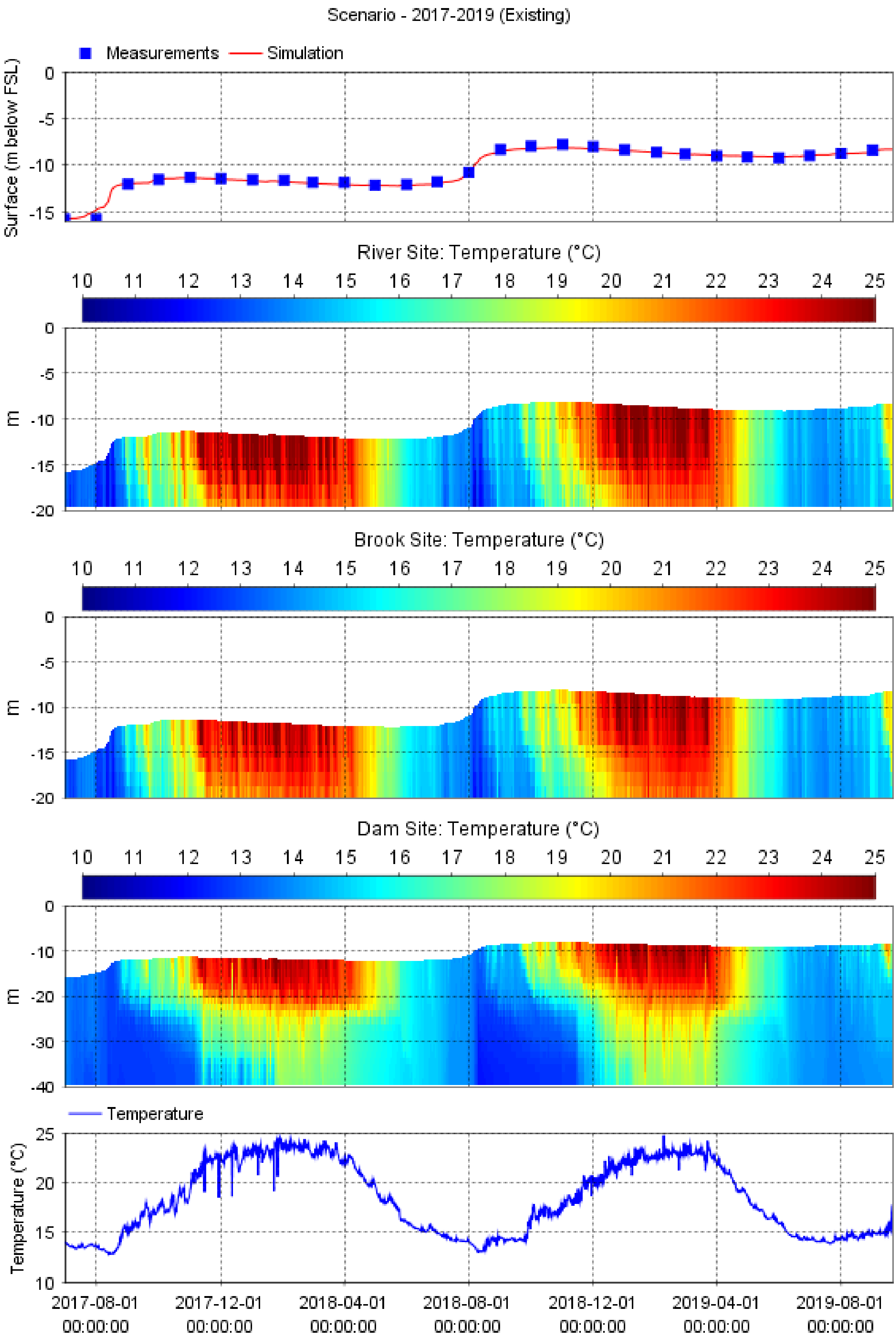

Figure 25 ***Simulated and measured Serpentine Main Dam (SMD) water levels (top), and simulated isotherms at the dam (upper middle), river (middle) and brook (lower middle) assessment sites, and simulated withdrawal temperatures (bottom).***

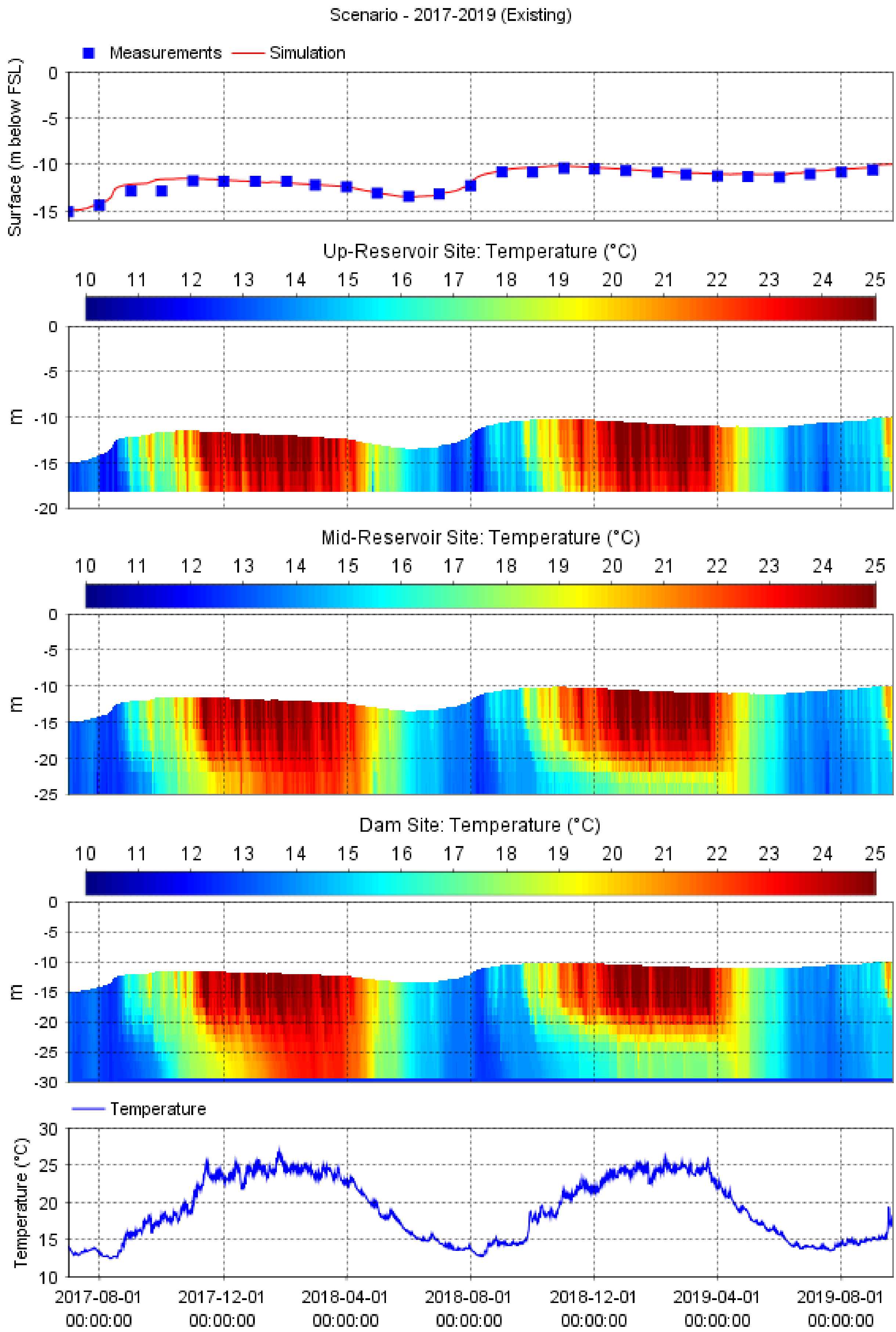

Figure 26 *Simulated and measured South Dandalup Dam (SDD) water levels (top), and simulated isotherms at the dam (upper middle), river (middle) and brook (lower middle) assessment sites, and simulated withdrawal temperatures (bottom).*

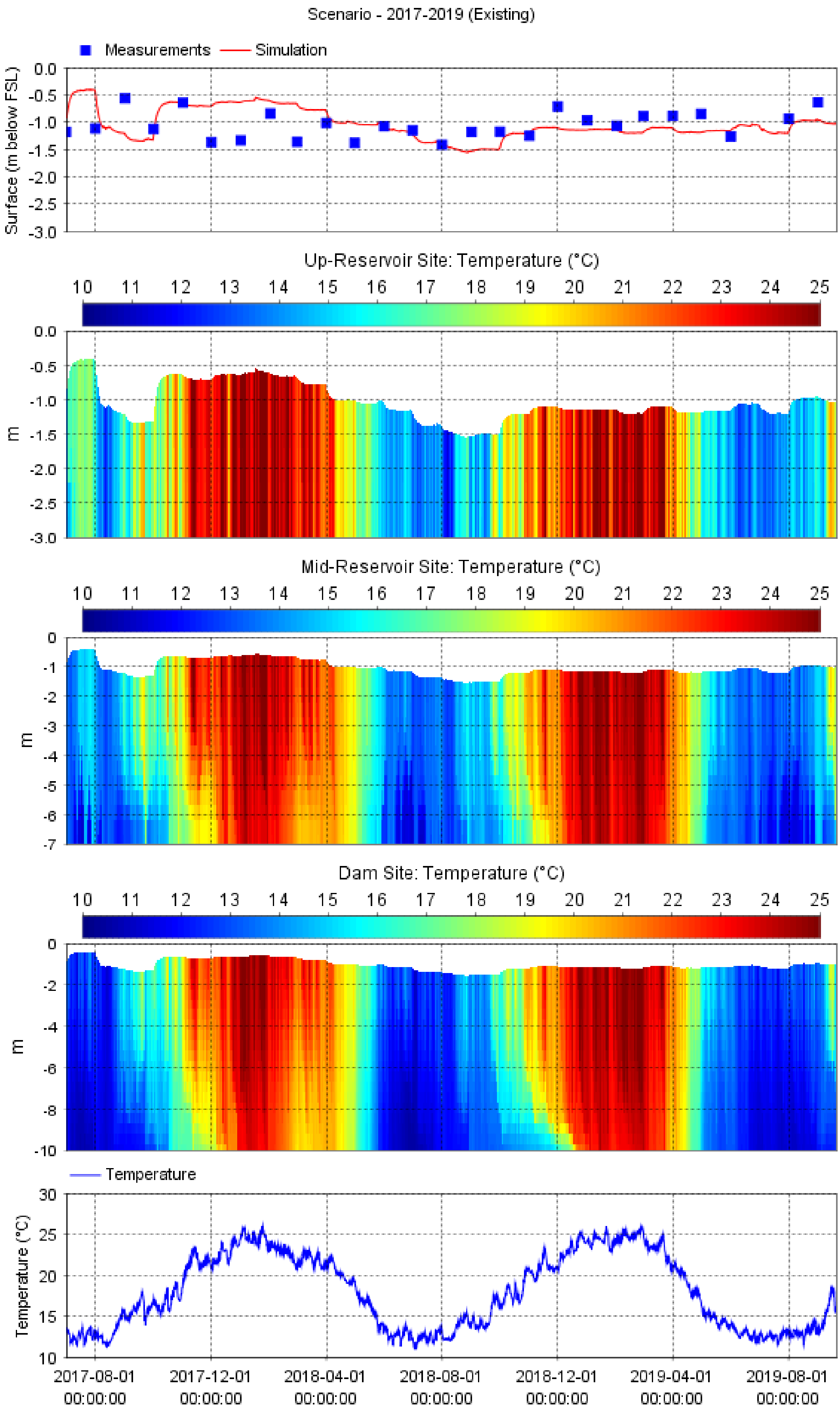

Figure 27 ***Simulated and measured Serpentine Pipehead Dam (SPD) water levels (top), and simulated isotherms at the dam (upper middle), river (middle) and brook (lower middle) assessment sites, and simulated withdrawal temperatures (bottom).***

4.3.2 Spatial Patterns of Inorganic Suspended Solids (SS) during the 2017 and 2018 Inflow Events

Spatial snapshots of the simulated SS_{Clay} every 2 weeks during the 2017 and 2018 inflow events along the thalwegs of SMD (Serpentine River arm), SDD and SPD are provided in Figure 28, Figure 29 and Figure 30, respectively.

Elevated SS_{clay} levels typically are simulated in the upstream portions of SMD and SDD because these particles tend to remain in suspension due to their very low settling velocities. These elevated levels in SMD and SDD typically are transported down the reservoir bed slope towards the dam as turbid underflows. Hence, substantially lower SS_{clay} occurs in the upper half of the water column in proximity to the dam walls.

In contrast, SS_{clay} is much lower in SPD relative to the other two reservoirs for several reasons:

– Relatively low SS catchment loads occur into SPD because of the small catchment area.

– External transfers into SPD have high discharge and low SS, which dilutes SS from catchment inflow events.

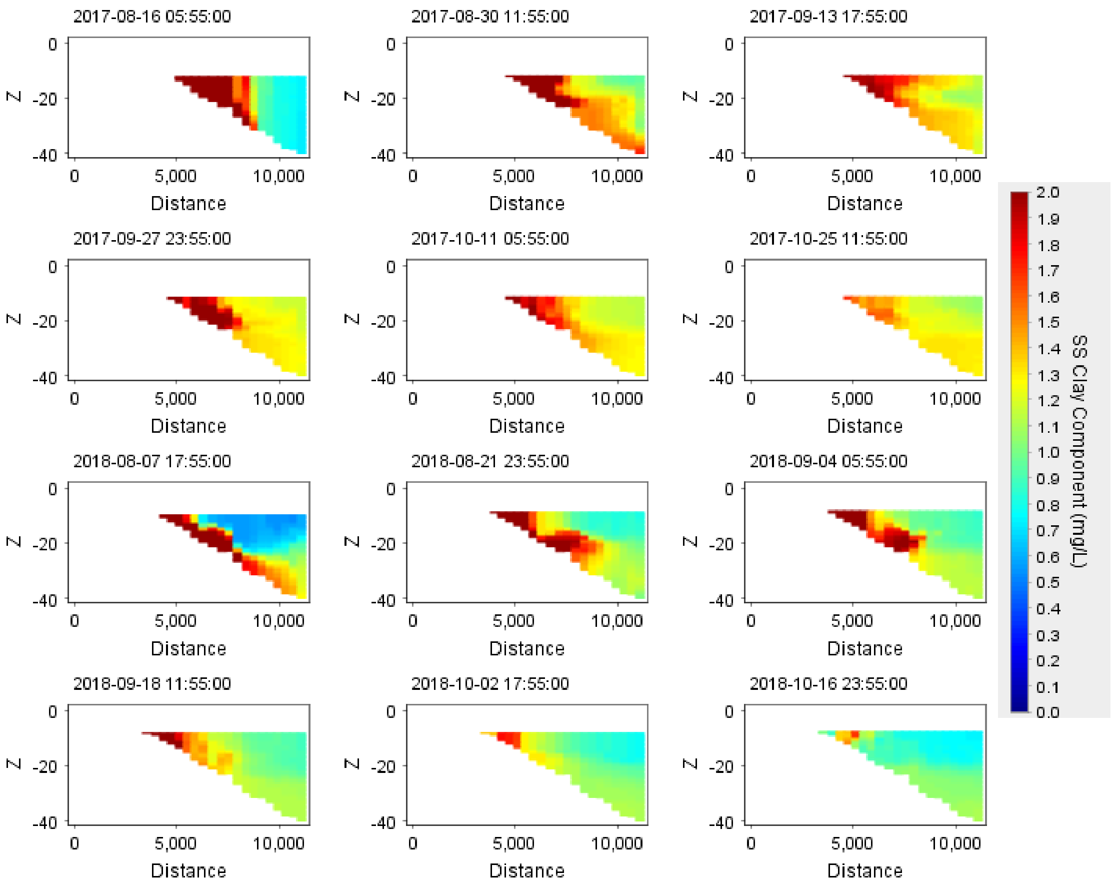

Figure 28 Spatial snapshots of the simulated Serpentine Main Dam (SMD) clay component of inorganic suspened solids (SS_{clay}) every 2 weeks during the 2017 (upper half) and 2018 (lower half) winter inflow events along the Serpentine River thalweg.

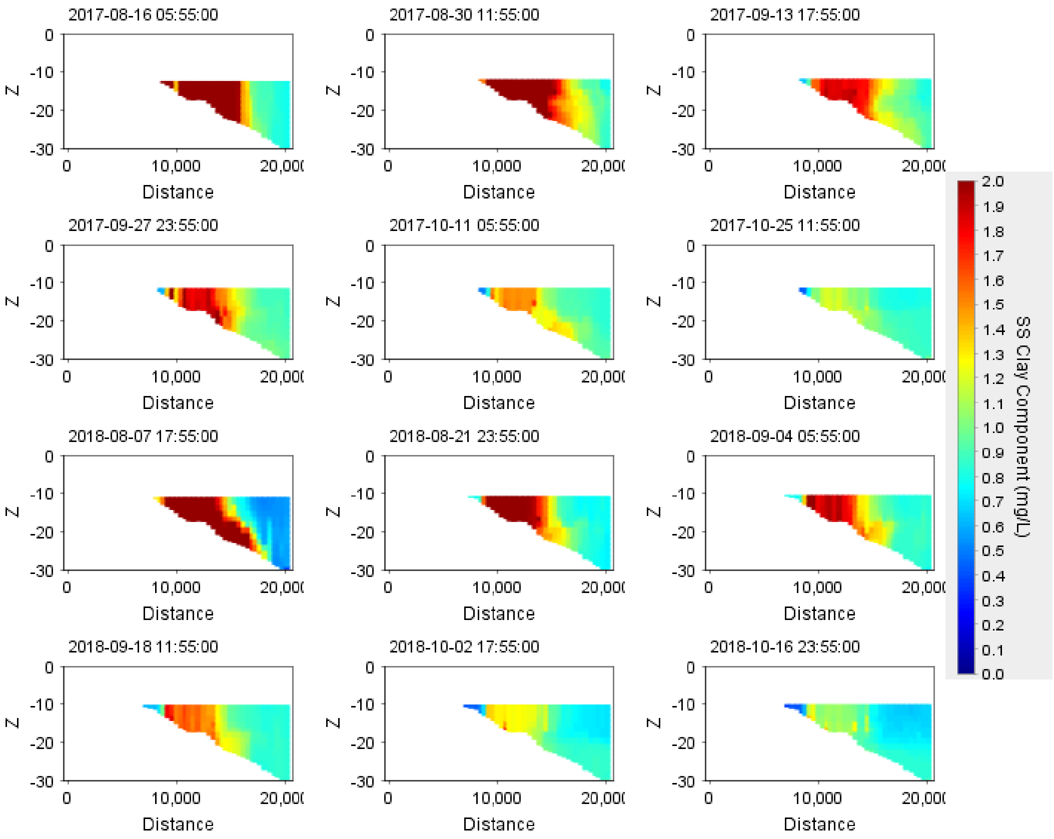

Figure 29 ***Spatial snapshots of the simulated South Dandalup Dam (SDD) clay component of inorganic suspened solids (SS_{clay}) every 2 weeks during the 2017 (upper half) and 2018 (lower half) winter inflow events along the South Dandalup River thalweg.***

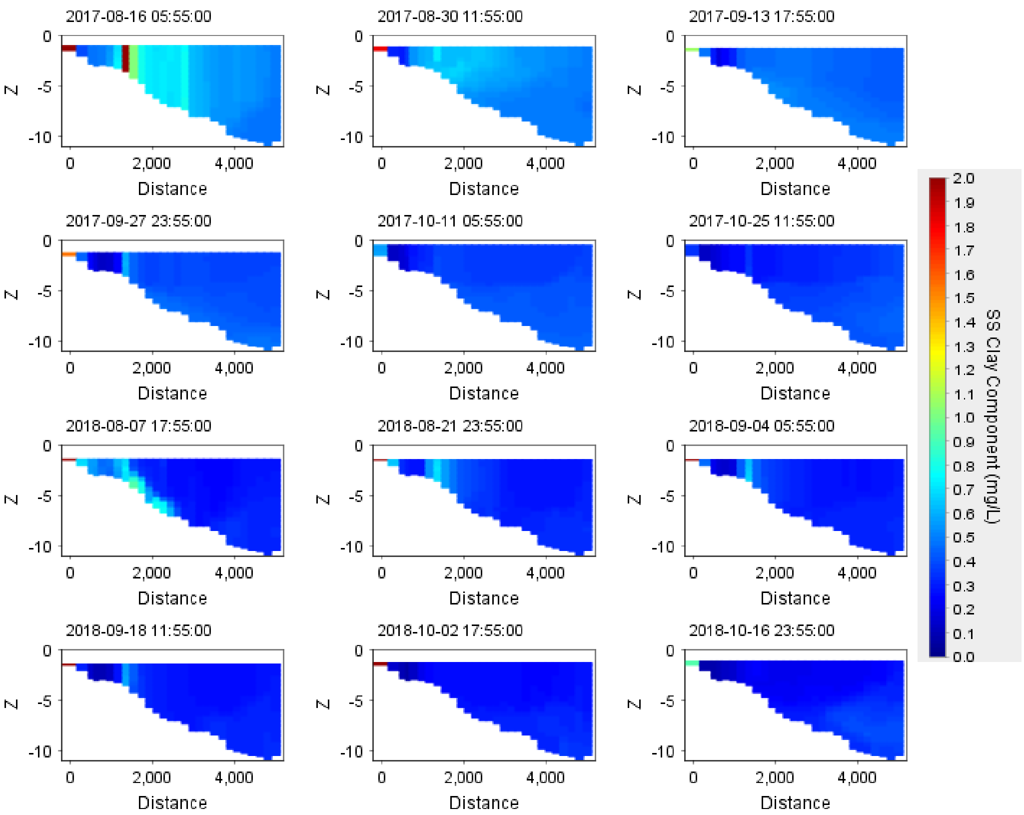

Figure 30 ***Spatial snapshots of the simulated Serpentine Pipehead Dam (SPD) clay component of inorganic suspened solids (SS_{clay}) every 2 weeks during the 2017 (upper half) and 2018 (lower half) winter inflow events along the Serpentine River thalweg.***

Spatial snapshots of SS_{silt} every 2 weeks during the 2017 and 2018 inflow events along the thalwegs of SMD, SDD and SPD are provided in Figure 31, Figure 32 and Figure 33, respectively. This shows that elevated SS_{silt} levels are short-lived relative to SS_{clay} because of their higher settling velocities. During the period that silt remains in suspension, as with clay it tends to be transported down the reservoir bed slope within turbid underflows. Because of the relatively small catchment inputs, silt levels in SPD are simulated to be very low.

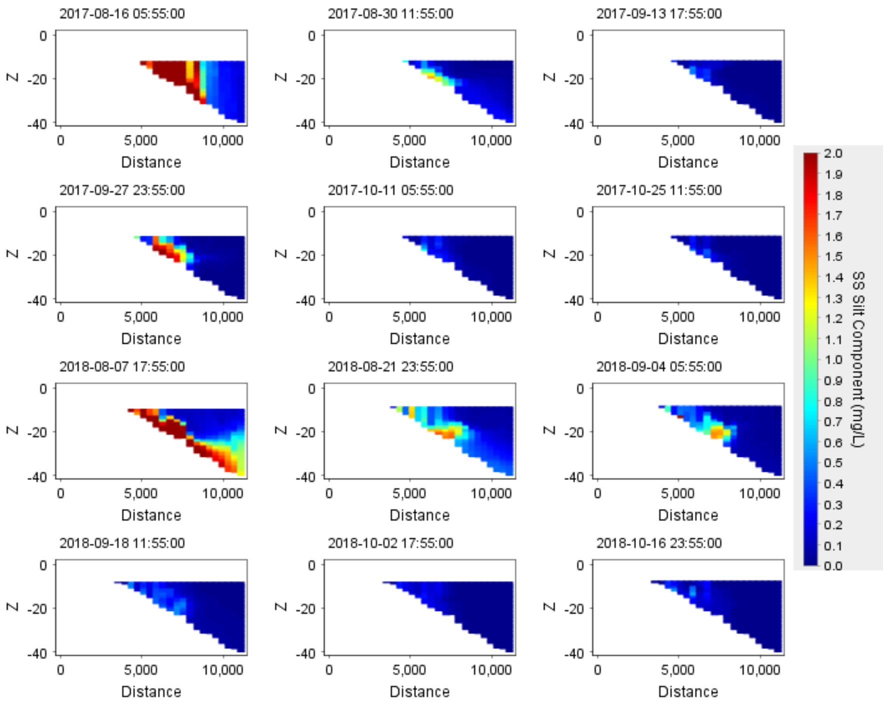

Figure 31 ***Spatial snapshots of simulated Serpentine Main Dam (SMD) silt component of inorganic suspened solids (SS_{silt}) every 2 weeks during the 2017 (upper half) and 2018 (lower half) winter inflow events along the Serpentine River thalweg.***

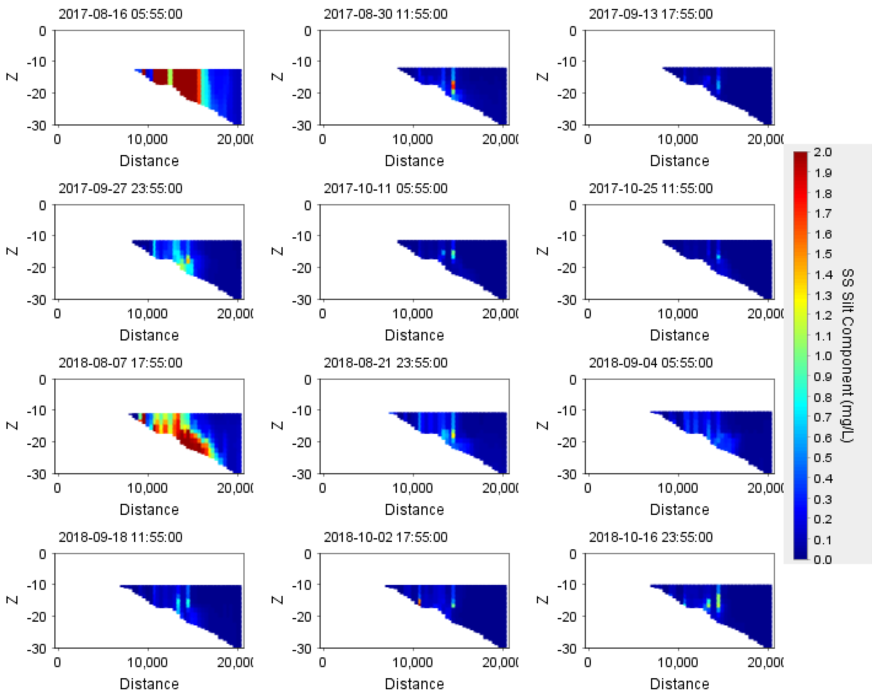

Figure 32 ***Spatial snapshots of simulated South Dandalup Dam (SDD) silt component of inorganic suspened solids (SS_{silt}) every 2 weeks during the 2017 (upper half) and 2018 (lower half) winter inflow events along the South Dandalup River thalweg.***

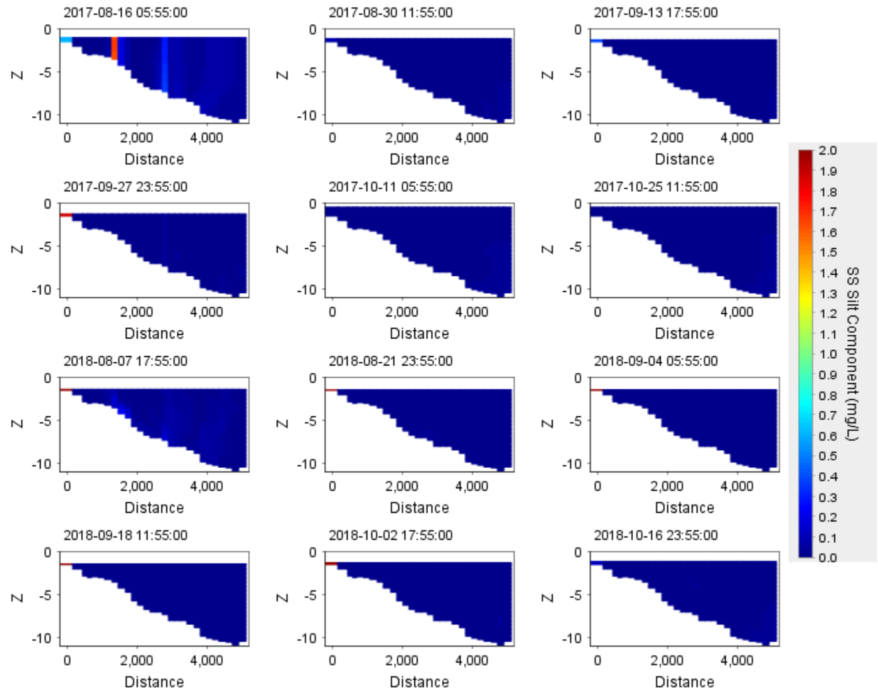

Figure 33 ***Spatial snapshots of simulated Serpentine Pipehead Dam (SPD) silt component of inorganic suspened solids (SS_{silt}) every 2 weeks during the 2017 (upper half) and 2018 (lower half) winter inflow events along the Serpentine River thalweg.***

Figure 13, Figure 14 and Figure 15 show the three assessment sites in each reservoir (i.e. near dam wall near the intake towers and two up-reservoir sites) that are used to illustrate seasonal patterns of SS in SMD, SDD and SPD, respectively. The simulated water levels, spatial and temporal patterns of SS_{clay} and SS_{silt} (as isopleths through the water column with time at each assessment site), and withdrawal SS_{clay} and SS_{silt} are shown in Figure 34 to Figure 39 for the three reservoirs. Simulated spatial patterns of SS include:

– There is a considerable decrease due to dispersion and settling of SS from the upstream portion of the reservoirs to the dams.

– Simulated elevated levels of SS_{Clay} are relatively short-lived. For SMD and SDD as clay particles are transported as turbid underflows and are not readily vertically transported back into the mixed layer. This is primarily due to the establishment of a winter thermocline due to the inputs of cool winter inflows that act as a barrier to upwards vertical transport of these particles.

– For SMD and SDD the winter 2017 inflow event caused higher SS_{clay} in the mixed layer for a longer period than the winter 2018 event. Inspection of the spatial pattern of SS_{clay} on 13 September 2017 shows that a simulated mechanism led to the rapid transport of high clay content waters to the dam wall in the near surface waters.

– For SMD and SDD, much lower levels of elevated SS_{silt} were simulated near the intake tower (typically <0.5 mg/L) for a very short duration. As described previously, the higher settling velocity of silt relative to clay yields considerably lower concentrations and substantially shorter durations of suspension in the water column for the 2017 and 2018 winter inflow events.

– Generally, simulated SPD SS levels were very low in response to the 2017 and 2018 winter inflow events relative to those of SMD and SDD.

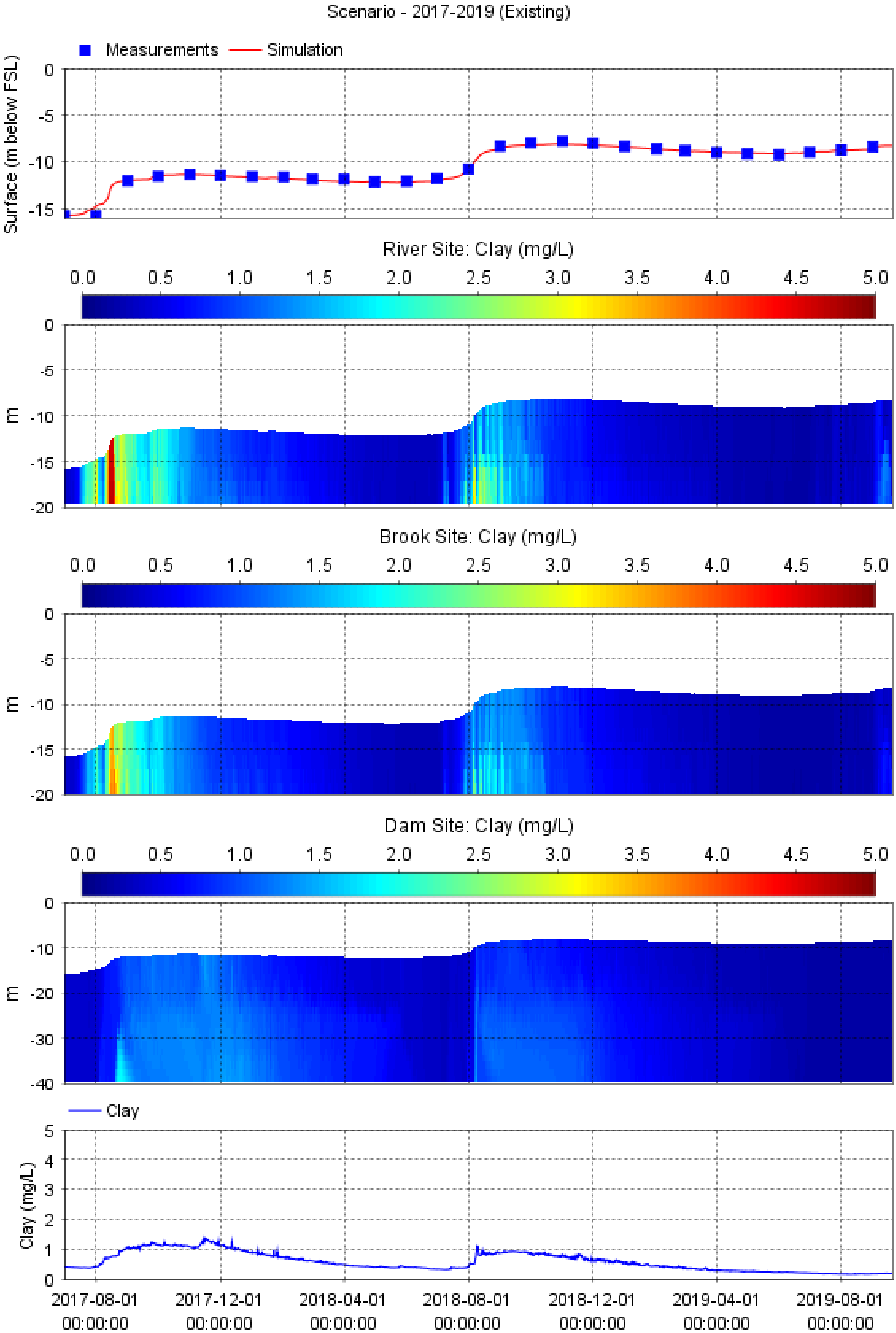

Figure 34 ***Simulated and measured Serpentine Main Dam (SMD) water levels (top), simulated isopleths of the clay component of inorganic suspened solids (SS_{clay}) at the dam (upper middle), river (middle) and brook (lower middle) assessment sites, and simulated SS_{clay} of the withdrawals (bottom).***

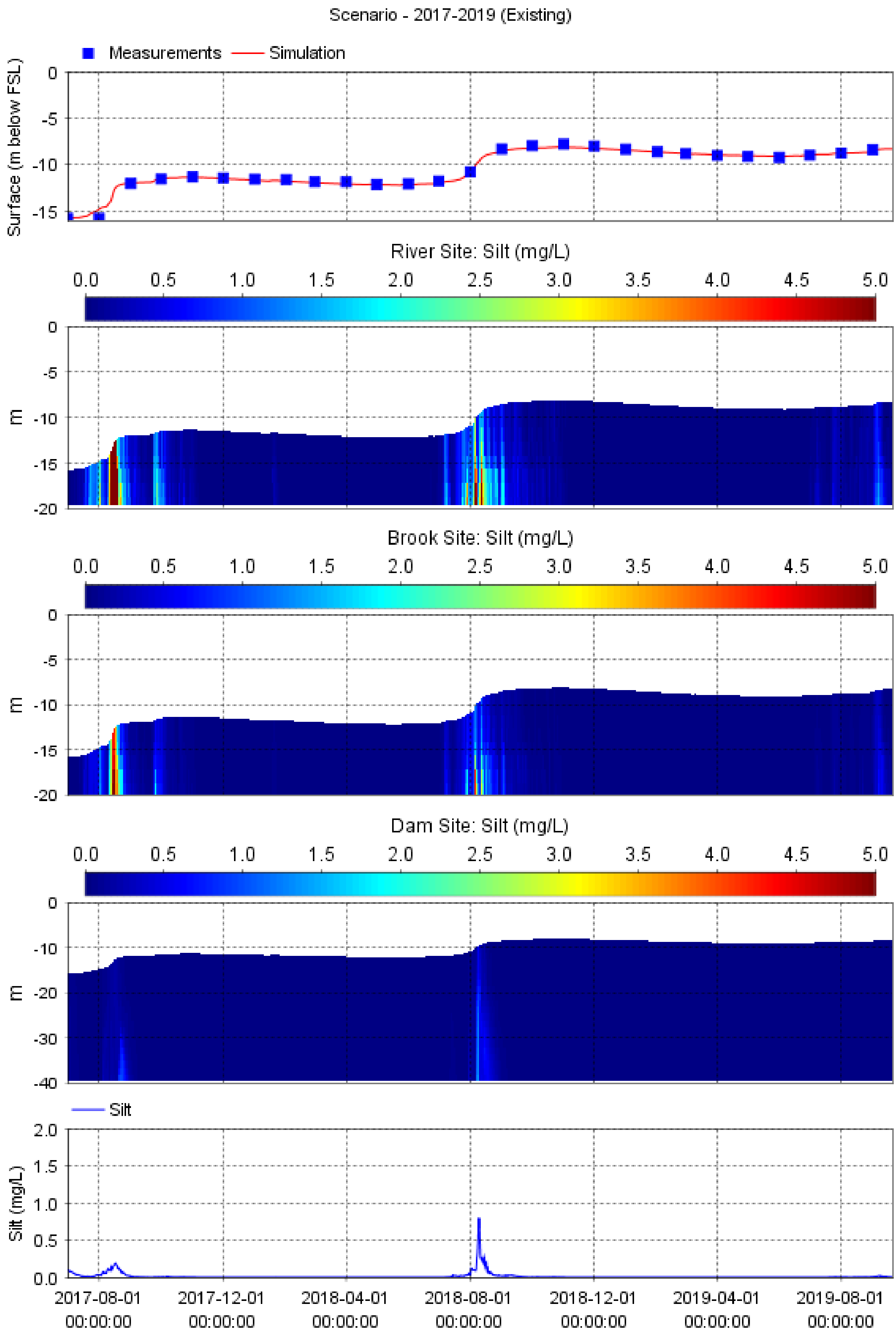

Figure 35 ***Simulated and measured Serpentine Main Dam (SMD) water levels (top), simulated isopleths of silt component of inorganic suspened solids (SS_{silt}) at the dam (upper middle), river (middle) and brook (lower middle) assessment sites, and simulated SS_{silt} of the withdrawals (bottom)***

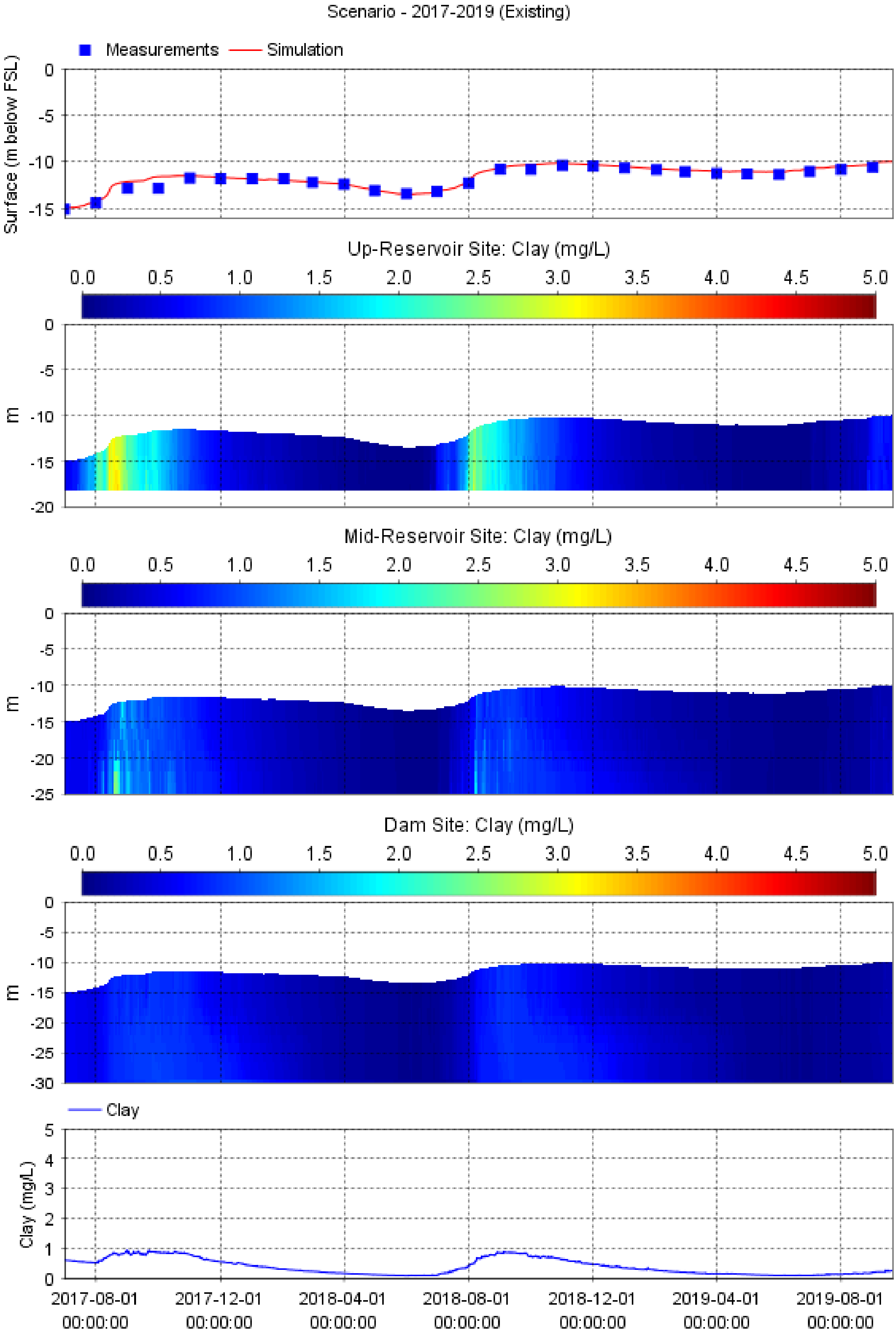

Figure 36 ***Simulated and measured South Dandalup Dam (SDD) water levels (top), simulated isopleths of clay component of inorganic suspened solids (SS_{clay}) at the dam (upper middle), river (middle) and brook (lower middle) assessment sites, and simulated SS_{clay} of the withdrawals (bottom).***

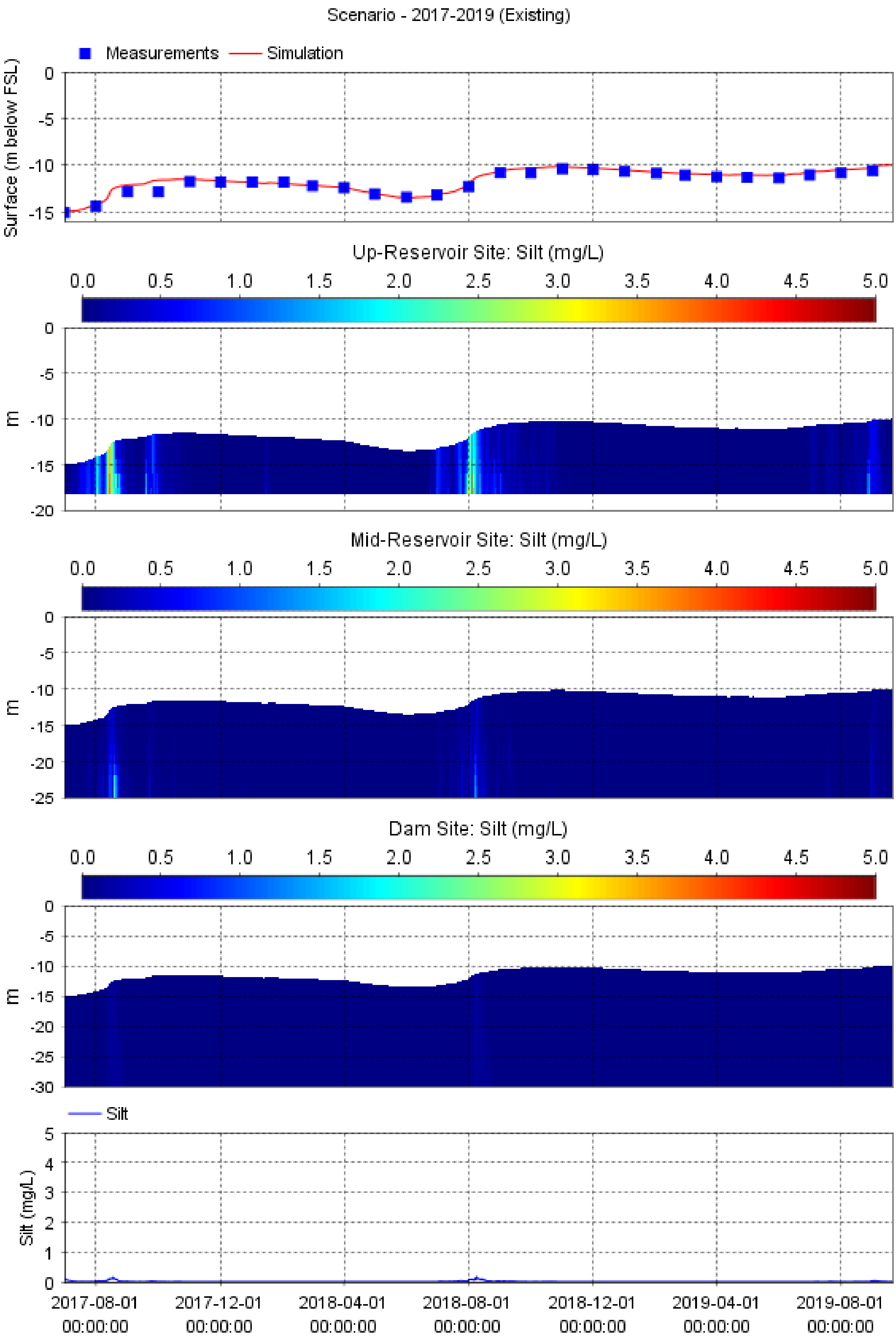

Figure 37 ***Simulated and measured South Dandalup Dam (SDD) water levels (top), simulated isopleths of silt component of inorganic suspened solids (SS_{silt}) at the dam (upper middle), river (middle) and brook (lower middle) assessment sites, and simulated SS_{silt} of the withdrawals (bottom).***

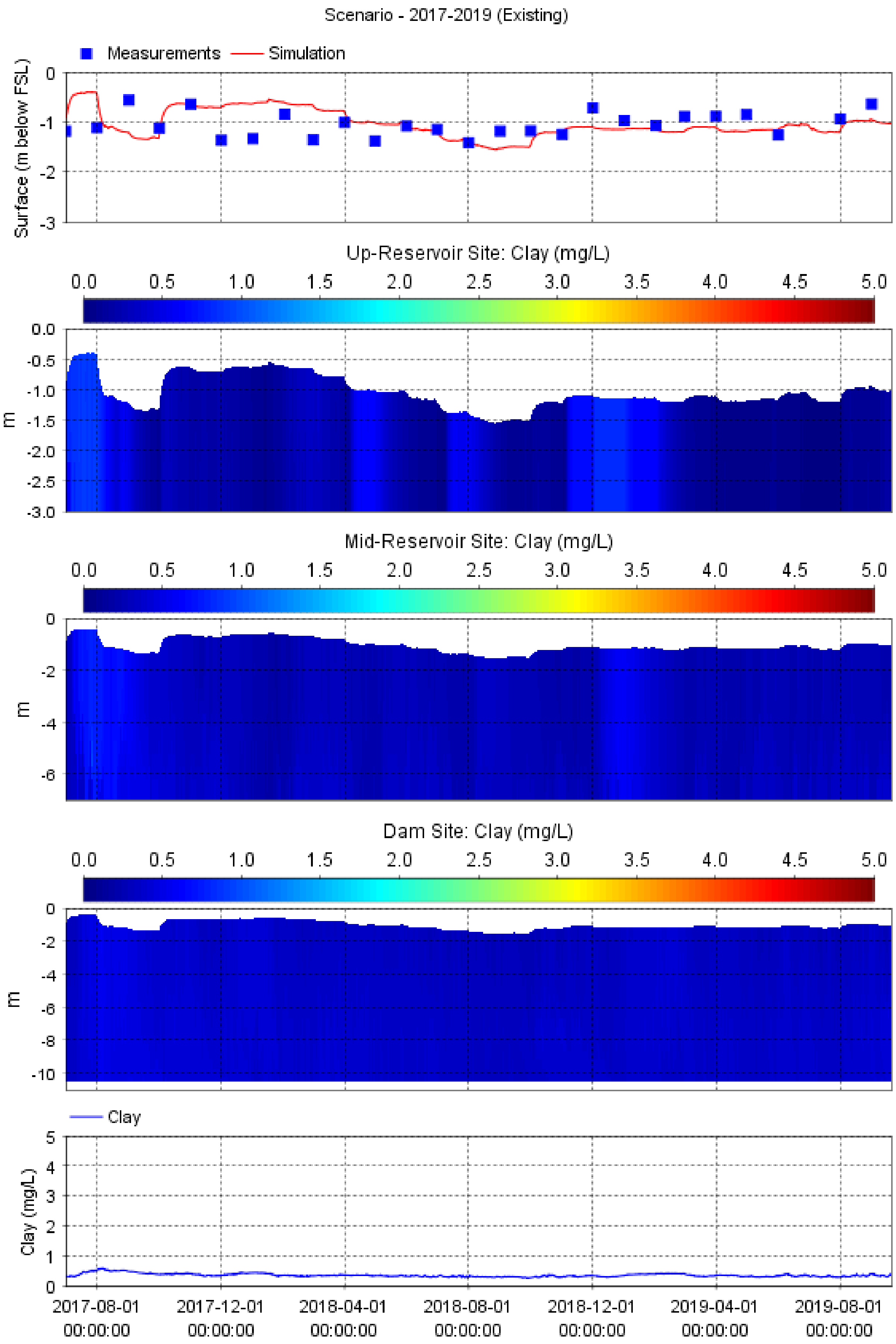

Figure 38 ***Simulated and measured Serpentine Pipehead Dam (SPD) water levels (top), simulated isopleths of clay component of inorganic suspened solids (SS_{clay}) at the dam (upper middle), river (middle) and brook (lower middle) assessment sites, and simulated SS_{clay} of the withdrawals (bottom).***

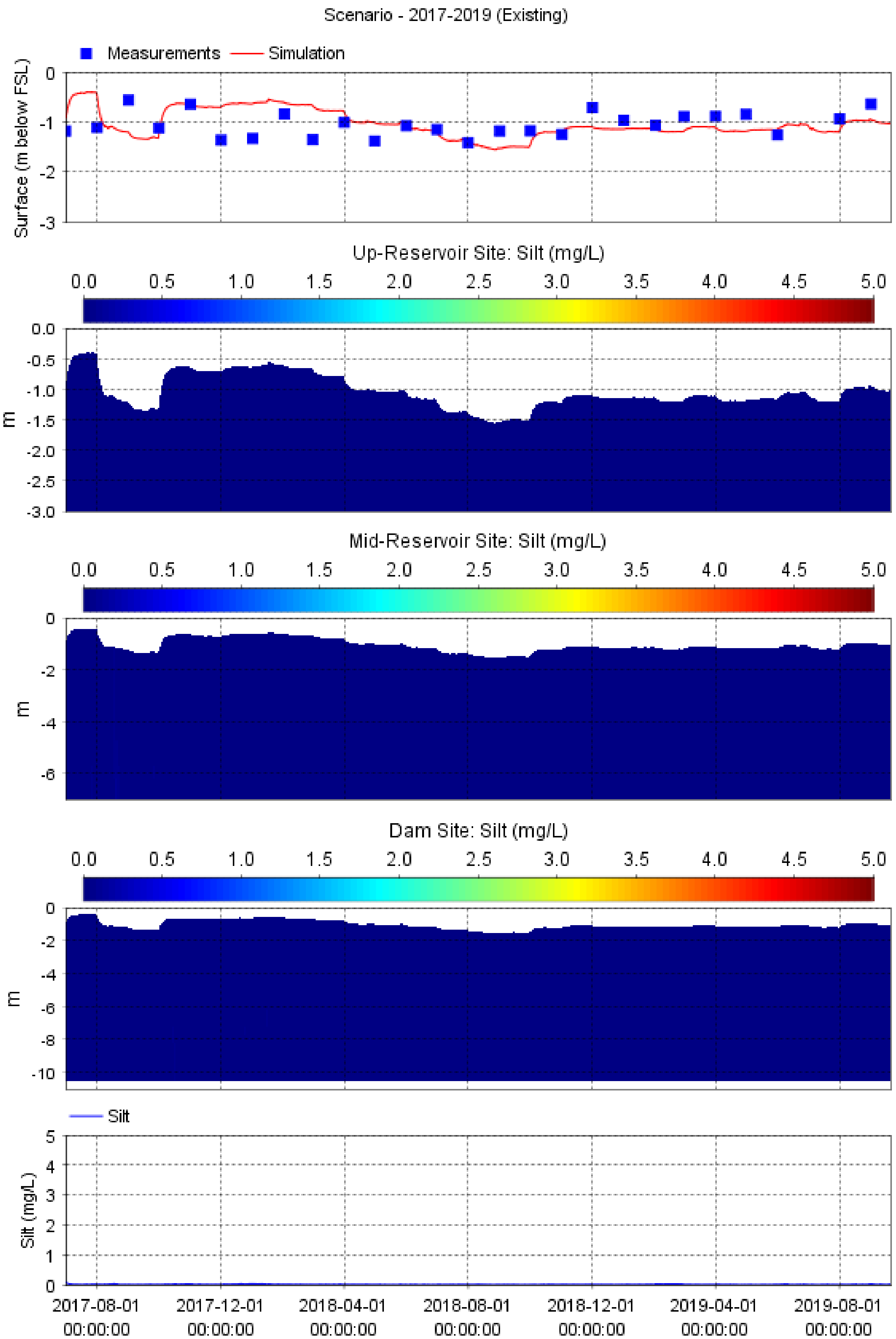

Figure 39 ***Simulated and measured Serpentine Pipehead Dam (SPD) water levels (top), simulated isopleths of silt component of inorganic suspened solids (SS_{silt}) at the dam (upper middle), river (middle) and brook (lower middle) assessment sites, and simulated SS_{silt} of the withdrawals (bottom).***

5. Scenarios

5.1 Inputs

5.1.1 Initial Dam Water Level

The initial dam water level for all scenarios was -15.8 m FSL (196.6 m AHD). This is 0.5 m lower than the 20th percentile over the 1985-2020 period of 197.1 m AHD.

5.1.2 Cryptosporidium and Diesel Spill Incidents

The 1 July 2017 to 1 October 2019 verification simulation period was used to characterise the effects of cryptosporidium and diesel spill incidents for the primary beneficial use of water supply (i.e. drinking water quality). The hydrological model inputs are described in sections 4.1.4 to 4.1.6. Cryptosporidium is evaluated in this assessment because it is a chlorine-treatment resistant pathogen, and the reliance of the downstream treatment system on chlorination for disinfection. The pathogen component of the modelling assessment considered four hazard types as described in GHD (2021a) and summarised in Table 5.

Table 5 Cryptosporidium hazards and scenario definitions.

Hazard	Source	Pathway	Receptor	Duration
1: STP raw sewage overflow	Raw sewage overflow at some point in STP 18 m3/day sewage @ 2,000 oocysts/L = 36 million oocysts/day	Overflow occurs during wet catchment conditions and heavy rainfall Transport via overland flow and shallow channel flow ~ several hundred metres of Jarrah forest @ 5-10% slope Attenuation ~2 log10	360,000 oocysts/day discharge into creek Creek flowing into reservoir	Two days overflow[4]
2: STP effluent irrigation area washout	Treated effluent accumulates at surface of irrigation area during wet catchment conditions 18 m3/day treated sewage @ 200 oocysts/L[5] = 3.6 million oocysts/day Sustained heavy rainfall causes wash out of accumulated oocysts ~ ten times daily deposition = 36 million oocysts/day	Washout occurs during wet catchment conditions and heavy rainfall Transport via overland flow and shallow channel flow ~ several hundred metres of Jarrah forest @ 5-10% slope Attenuation ~2 log10	360,000 oocysts/day discharge into creek Creek flowing into reservoir	Two days heavy rainfall
3. STP effluent irrigation area subsurface flow	Treated effluent leaches into subsurface during winter/spring when rainfall exceeds evapotranspiration 18 m3/day treated sewage @ 200 oocysts/L = 3.6 million oocysts/day	Oocysts in leachate transported by shallow perched aquifer ~ several hundred metres to creek or downslope seepage face Attenuation ~ 4 log10	360 oocysts/day discharge into creek Creek flowing into reservoir	Three months shallow seepage per year
4. Defecation in the field	Asymptomatic infected staff member defecates in the field, in bushland adjacent to mine pit or rehabilitation area 150 g stool @ 1 million oocysts/g = 150 million oocysts	Stool present/remaining in wet catchment conditions during heavy rainfall event Approximately 10% is washed out and transported via overland flow and shallow channel flow ~ several tens of metres of Jarrah forest @ 5-10% slope	15,000,000 oocysts discharge into creek Creek flowing into reservoir	Following two days of heavy rainfall

[4] Two days is a reasonable period for a 24 hour/day manned site to notice and to manage such an incident.
[5] 1 $\log_{10}$ reduction from raw sewage due to treatment.

Locations of each of these simulated pathogen incidents for the existing and proposed mining cases are summarised in Table 6, which can be cross-referenced spatially with Figure 13.

Table 6 ***Catchments where cryptosporidium hazards simulated in the three reservoirs for the existing and proposed mining scenarios.***

Hazard	SMD		SDD		SPD	
	Existing	Proposed	Existing	Proposed	Existing	Proposed
1: STP raw sewage overflow	Catchment 13	Catchment 5	No existing mining	Catchment 35	No STP in catchment	No STP in catchment
2: STP effluent irrigation area washout	Catchment 13	Catchment 5		Catchment 35		
3. STP effluent irrigation area subsurface flow	Catchment 13	Catchment 5		Catchment 35		
4. Defecation in the field	Catchments 16 (4A), 10 (4B), 9 (4C) Reference: Catchment 1 (4D, Dam recreation area)	Catchments 3 (4A), 5 (4B), 7 (4C) Reference: Catchment 1 (4D, Dam recreation area)	Catchments 35 (4A), 34 (4B), 33(4C) Reference: Catchment 30 (4D, Dam recreation area)	Catchments 35 (4A), 34 (4B), 33(4C) Reference: Catchment 30 (4D, Dam recreation area)	Catchments 23 (4A), 24 (4B), only two mining catchments so no 4C Reference: Catchment 20 (4D, Dam recreation area)	As existing case

A diesel spill incident is assumed to occur under typical winter conditions, where there is sufficient baseflow in streams to convey the fuel to the reservoir. It has been assumed that Alcoa transports diesel in tanks with capacities up to 15,000 litres. The model inputs for a diesel spill incident were defined conservatively as:

– The diesel spill occurs on a haul road stream crossing within an existing or proposed mining catchment.
– At the time of the incident the fuel truck is full and spills its entire load of diesel.
– The spill occurs directly into a stream with sufficient discharge to transport all of the diesel to the reservoir.

The spill duration into the reservoir is assumed to be 4 hours with a linear increase/decrease to/from a peak concentration at 2 hours. As a conservative measure the entire 15 m^3 of spilled diesel is assumed to be transported and discharged into the reservoir with no losses due to volatilisation, degradation, and adsorption and settling in the stream or in the reservoir. Hence, the only processes that decrease spilled diesel concentrations are river dilution, reservoir mixing and dispersion, and withdrawals from the dams.

Diesel spill incidents were simulated in the existing and proposed mining catchments (i.e. those with haul road stream crossings) as summarised in Table 7, which can be cross-referenced spatially with Figure 13 to Figure 15.

Table 7 ***Catchments with diesel spill incidents for existing and proposed mining activity scenarios.***

Incident	SMD		SDD		SPD	
	Existing	Proposed	Existing	Proposed	Existing	Proposed
Diesel Spill (15 m3)	Catchments 8, 13, 16	Catchments 3, 5, 6	Non, no existing mining	Catchments 35, 36	Catchments 23, 24	Catchments 23, 24

It is highly unlikely that Alcoa will transport any fuel during a large storm event. Hence, it was assumed that the spill incident occurs after peak stream discharge during the winter 2017 inflow event during moderately low stream flow. Further, it was assumed that diesel entered the reservoirs over a period of 4 hours from 1000 to 1400 on 24 August 2017.

5.1.3 Inorganic Suspended Solids (SS) Assessment

A summary of the catchments in SMD, SDD and SPD (refer to Figure 13 to Figure 15) that are defined as those with existing and proposed (existing[6] and proposed mining areas) mining activity is provided in Table 8. All remaining catchments were considered to be un-mined or fully rehabilitated historical mining areas with baseline SS loads.

Table 8 Existing and proposed mining catchments.

Reservoir	Existing Mining Catchments	Proposed Mining Catchments
SMD	4, 7-16	1-16
SDD	No existing mining, all historical mining assumed to be fully rehabilitated	23, 24
SPD	23, 24	23, 24 (same as existing)

Scenario inputs to evaluate the effect of winter and summer inflow events on reservoir and withdrawal SS levels used the GHD (2021a) hydrology estimates over 2 weeks and hourly intervals of the 1% and 10% annual exceedance periods [AEP] for baseline (no mining), and existing and proposed mining scenarios as summarised in Table 9. GHD (2021a) also estimated the 1 exceedance per year (E.Y.) for the baseline, existing and proposed mining activities, but these flows were too small to have any material effect on the SS climate of the reservoirs, and thereby were not evaluated. Though there are a total of 18 potential scenarios per reservoir (i.e. 3 flow events [1% and 10% AEP, 1 E.Y.] x 2 seasons [winter, summer] x 3 mining cases [baseline, existing, proposed]), only a subset were evaluated for each of the reservoirs, namely:

- No 1 E.Y. flow events were simulated for any of the three reservoirs.
- For SMD, 12 scenarios were evaluated assuming effective SS management of mining areas (see Appendix A for inputs). An additional 8 scenarios were also evaluated assuming ineffective SS management of mining areas with substantial increases in drainage failure SS concentrations (see Appendix C for inputs).
- For SDD, there has not been recent mining activity in the catchment (historical mining activity is assumed to be fully rehabilitated), so 8 scenarios were evaluated assuming effective SS management of mining areas (see Appendix E for inputs). An additional 4 scenarios were also evaluated assuming ineffective SS management of mining areas (see Appendix G for inputs).
- For SPD, the catchments with proposed mining activity are the same as the existing mining catchments, so 8 scenarios were evaluated assuming effective SS management of mining areas (see Appendix I for inputs). An additional 4 scenarios were also evaluated assuming ineffective SS management of mining areas (see Appendix K for inputs).

[6] In this assessment, the proposed catchments include both the existing and proposed mining catchments. It is conservatively assumed that rehabilitation of existing catchments will not be completed over the timescale of implementation of the proposal.

Table 9 Overview of inorganic suspended solids (SS) scenarios.

Scenario ID	Catchment clearing	Starting level	Synthetic flow event season	Synthetic Storm event and drainage failure rate[7]	SMD Simulated	SDD Simulated	SPD Simulated
E	Existing	1 July 2017	Not applicable, actual 2017-2019 hydrology	Not applicable, no drainage failures	Diesel and cryptosporidium incidents in **existing** and **proposed** mining catchments	No **existing** mining in catchments	Diesel and crypto incidents in **existing** mining catchments
P	Proposed					Diesel and cryptosporidium incidents in **proposed** mining catchments	Same catchments for **proposed** mining catchments as **existing** mining catchments
01	Baseline (No mining effects on SS)		2017 Summer	1% AEP with no drainage failures	Yes, baseline for increased SS assessments of **existing** and **proposed** mining activities	Yes, baseline for increased SS assessments of **proposed** mining activities	Yes, baseline for increased SS assessments of **existing** mining activities
02				10% AEP with no drainage failures			
03				1 E.Y. with no drainage failures	No, negligible SS increase from small inflow events with no drainage failures		
04			2018 Winter	1% AEP with no drainage failures	Yes, baseline for increased SS assessments of **existing** and **proposed** mining activities	Yes, baseline for increased SS assessments of proposed mining activities	Yes, baseline for increased SS assessments of **existing** mining activities
05				10% AEP with no drainage failures			
06				1 E.Y. with no drainage failures	No, negligible SS increase from small inflow events with no drainage failures		
07	Existing		2017 Summer	1% AEP with 75% drainage failures	Yes, to assess increased SS of **existing** mining activities	No existing mining in catchments	Yes, to assess increased SS of **existing** mining activities
08				10% AEP with 30% drainage failures			
09				1 E.Y. with 5% drainage failures	No, negligible SS increase from small inflow events with no drainage failures		
10			2018 Winter	1% AEP with 75% drainage failures	Yes, to assess increased SS of **existing** mining activities	No existing mining in catchments	Yes, to assess increased SS of **existing** mining activities
11				10% AEP with 30% drainage failures			
12				1 E.Y. with 5% drainage failures	No, negligible SS increase from small inflow events with no drainage failures		
13	Proposed		2017 Summer	1% AEP with 75% drainage failures	Yes, to assess increased SS of **proposed** mining activities		No, same catchments for **proposed** mining catchments

[7] Zero drainage failure for areas with existing mining activity in all baseline scenarios.

14				10% AEP with 30% drainage failures		as **existing** mining catchments
15				1 E.Y. with 5% drainage failures	No, negligible turbidity increase from small inflow events with no drainage failures	
16			2018 Winter	1% AEP with 75% drainage failures	Yes, to assess increased SS of **proposed** mining activities	No, same catchments for **proposed** mining catchments as existing mining catchments
17				10% AEP with 30% drainage failures		
18				1 E.Y. with 5% drainage failures	No, negligible turbidity increase from small inflow events with no drainage failures	

GHD (2021a) assumed these 7-day 1% and 10% AEP inflow events resulted in the following drainage failures in mining areas, which are adopted here:

– A 30% drainage failure rate for the 10% AEP inflow event for the existing and proposed scenarios. For the proposed scenarios, both the existing and proposed mining areas are assumed to have a 30% drainage failure rate, as it is conservatively assumed that existing mining areas will not be rehabilitated over the timescale of the proposed mining activity.
– A 75% drainage failure rate for the 1% AEP inflow event for the existing and proposed mining scenarios.

Variations in catchment discharge due to drainage failures generally did not have a major effect in terms of the overall water budgets of the reservoirs. However, drainage failures have a more substantive increase on stream SS_{clay} and SS_{silt}, which is described next.

The model configuration of SS_{clay} and SS_{silt} for baseline (non-mined or fully rehabilitated) mining areas is described in section 4.1.7. In this section the configuration of SS associated with drainage failures is outlined.

Turbidity is an optical measure of total suspended solids (TSS). In the absence of reliable continuous turbidity (and/or TSS) monitoring for mined and un-mined catchments, soil sampling of three natural streams and three mining sumps were collected and relations between TSS and turbidity for these samples in suspension were determined by Murdoch University's Marine and Freshwater Research Laboratory (MAFRL). The results of this investigation are illustrated in Figure 40, which indicates the SS of natural catchments and sumps are approximately a factor of 1.42 and 0.63 of the turbidity, respectively. However, over the range of interest (up to 60-70 NTU) a 1:1 relation is a good approximation, and is utilised here.

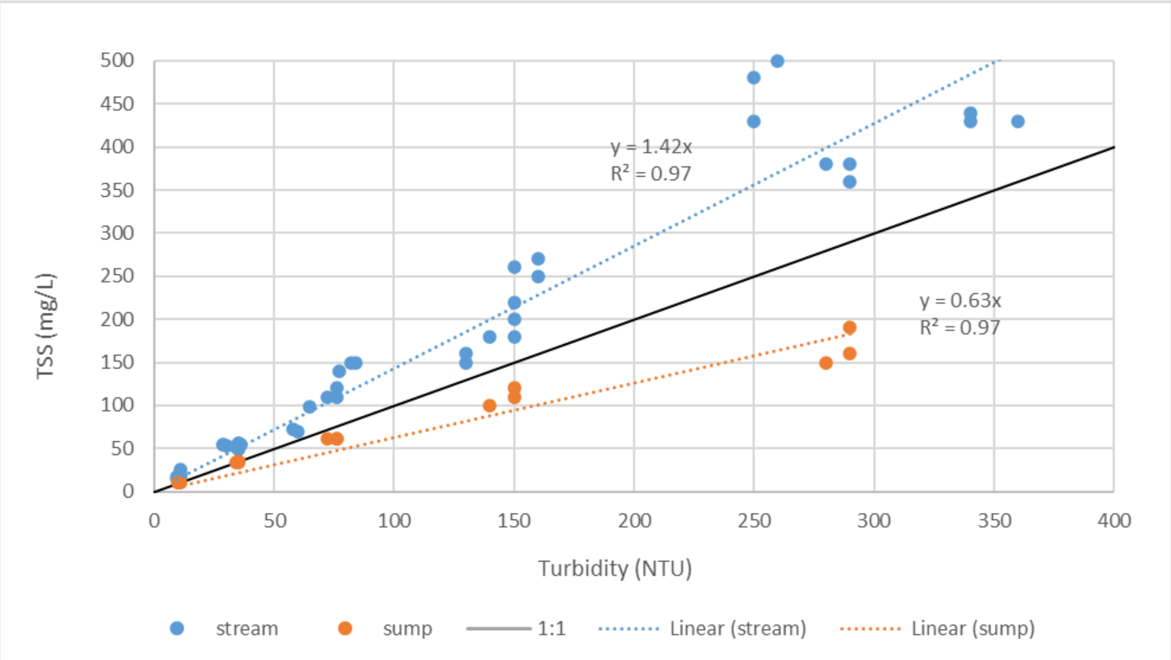

Figure 40 ***Relation between turbidity and TSS.***

TSS is made up of a range or particle diameters. Particle size distribution (PSD) analyses were carried out by MAFRL on the soil samples from the natural streambeds and mining sumps and the proportion of clay, silt and sand is summarised in Table 10 for both soil types. These findings were used to determine the proportion of SS that was allocated to SS_{clay} and SS_{silt} from drainage failures. Note the natural streambed clay:silt ratio of 1:3 is used for both the model verification simulations and the baseline scenarios (section 4.1.7).

Table 10 ***PSD of un-mined and mined streambed soil samples.***

Streambed Type	Clay	Silt	Sand
Mined	40%	50%	10%
Unmined	20%	60%	20%

SS_{clay} of 5 mg/L was established as a reasonable constant value for non-mined and mined catchments with no drainage failures (i.e. as used during verification of the hydrodynamic model in section 4.2.3). A SS_{silt} of 15 mg/L was adopted on the basis of the PSD ratio between clay and silt PSD measurements for these catchment conditions in Table 10. These baseline SS_{clay} and SS_{silt} concentrations are assumed to be constant throughout the catchments regardless of the magnitude of stream discharge except for occurrences of mining drainage failures. In fact, these levels are representative of concentrations during elevated flow events, but not low or moderate flows. However, as the SS load during low inflow periods do not have a material effect on most of the reservoir volume, this simplification is apt for the purposes of this investigation.

The reliability of available turbidity measurements of drainage failure events is suspect. Hence, a constant drainage failure turbidity of 31.5 NTU or 31.5 mg SS/L (assuming a 1:1 SS:turbidity ratio) was assumed in the case of effective drainage turbidity management, which equates to 12.6 mg/L and 15.8 mg/L for SS_{clay} and SS_{silt}, respectively. This is conservative in terms of the current operational stream limit in mined catchments of 25 NTU for no more than 1 hour. For the case of ineffective drainage turbidity management, the continuous SS (or turbidity) concentration during drainage failures was doubled to 63 NTU or 63 mg SS/L, which equates to 25.2 mg/L and 31.5 mg/L of SS_{clay} and SS_{silt}, respectively.

Each catchment into the reservoirs incorporated these SS concentrations in combination with discharge from the mined and un-mined (and rehabilitated) areas as follows:

- Zero surface runoff (and thereby no SS loads) for mining areas within catchments.
- Baseline SS_{clay} and SS_{silt} of 5 and 15 mg/L, respectively, for un-mined and fully rehabilitated areas within catchments.
- Drainage failure SS_{clay} and SS_{silt} of 12.6 mg/L and 15.8 mg/L, respectively, for mined areas of catchments with drainage failures and an effective drainage turbidity management.
- Drainage failure SS_{clay} and SS_{silt} of 25.2 mg/L and 31.5 mg/L, respectively, for mined areas of catchments with drainage failures and an ineffective drainage turbidity management.

Large particles (i.e. sand) that enter the reservoirs will not be transported a material distance down-reservoir due to rapid settling.

5.2 Serpentine Main Dam (SMD)

5.2.1 Existing and Proposed 2017-2019 Scenarios (Cryptosporidium and Hydrocarbon Spill Assessment)

Suspended Solids

Patterns of suspended inorganic solids (SS) in SMD are described in Section 4.3.2 for these scenarios.

Cryptosporidium

Simulated cryptosporidium concentrations along a transect of the Serpentine River arm at 4 day intervals over the first 3 weeks of reference hazard 4D (i.e. mobilisation of infected human stool from catchment 1 closest to the dam wall) is illustrative of the potential risk from this pathogen (Figure 41). Spatial patterns of simulated cryptosporidium levels of this hazard varied between the 2017 and 2018 winter inflow events where:

- Elevated levels during the 2017 winter event tended to remain in the upper water column.
- Cryptosporidium concentrations during the 2018 winter had greater vertical mixing and dispersion throughout the water column.

Isopleths of cryptosporidium concentration near the dam for hazards 1, 2, 3, 4A and 4D for the existing and proposed mining scenarios over the 2017-2019 simulation period are summarised in Figure 42 and Figure 43, respectively. These figures illustrate the relative magnitude and duration of cryptosporidium risks from infected human stool and STP-related incidents. For example, hazards 1 (STP overflow), 2 (STP irrigation area washout) and 3 (STP irrigation area subsurface drainage) are predicted to yield relatively low cryptosporidium levels at the dam (~<1×10^{-5} oocysts/L) in comparison to concentrations from loading of an infected human stool (~<5×10^{-4}

oocysts/L) from existing and proposed mining catchments (hazard 4A) and the reference un-mined catchment closest to the dam wall (hazard 4D). Characteristics of simulated cryptosporidium incidents include:

– The typical timescale of elevated cryptosporidium levels is ~3-4 months.
– Over these ~3-4 months the oocysts occur throughout the water column.

Simulated cryptosporidium levels in the withdrawals for release to SPD over the 2+ year simulations of the existing and proposed mining scenarios are presented in Figure 44. The only material difference in the pathogen risk is that the proposed STP location will be moved to a catchment with a reservoir confluence closer to the dam wall (and intake tower) than the existing STP location. Further, the proposed STP catchment has a lower discharge than the existing STP catchment with concomitant lower stream dilution of cryptosporidium prior to entry into the reservoir for hazards 1-3. Both of these factors result in a ~2 fold increase in peak cryptosporidium concentrations, which are still very low relative to simulated levels for hazards 4A -4D. The higher concentrations for hazards 4A-4D are similar for the existing and proposed mining scenarios over the 2017-2019 simulation period used to characterise pathogen risks in this study.

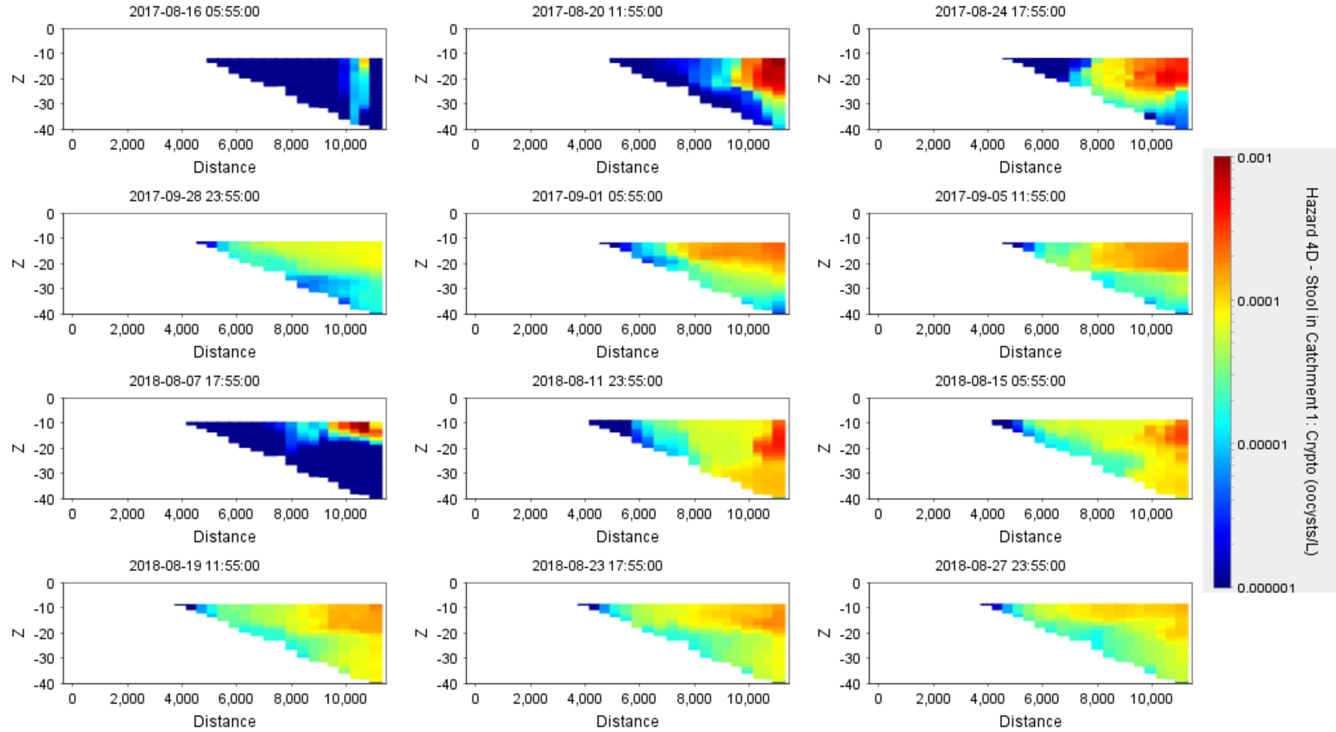

Figure 41 ***Cryptosporidium along the Serpentine River arm of Serpentine Main Dam (SMD) over 4 day intervals at the onset of hazard 4D during the 2017 (top 2 panels) and 2018 (bottom 2 panels) winter inflow events for hazard 4D.***

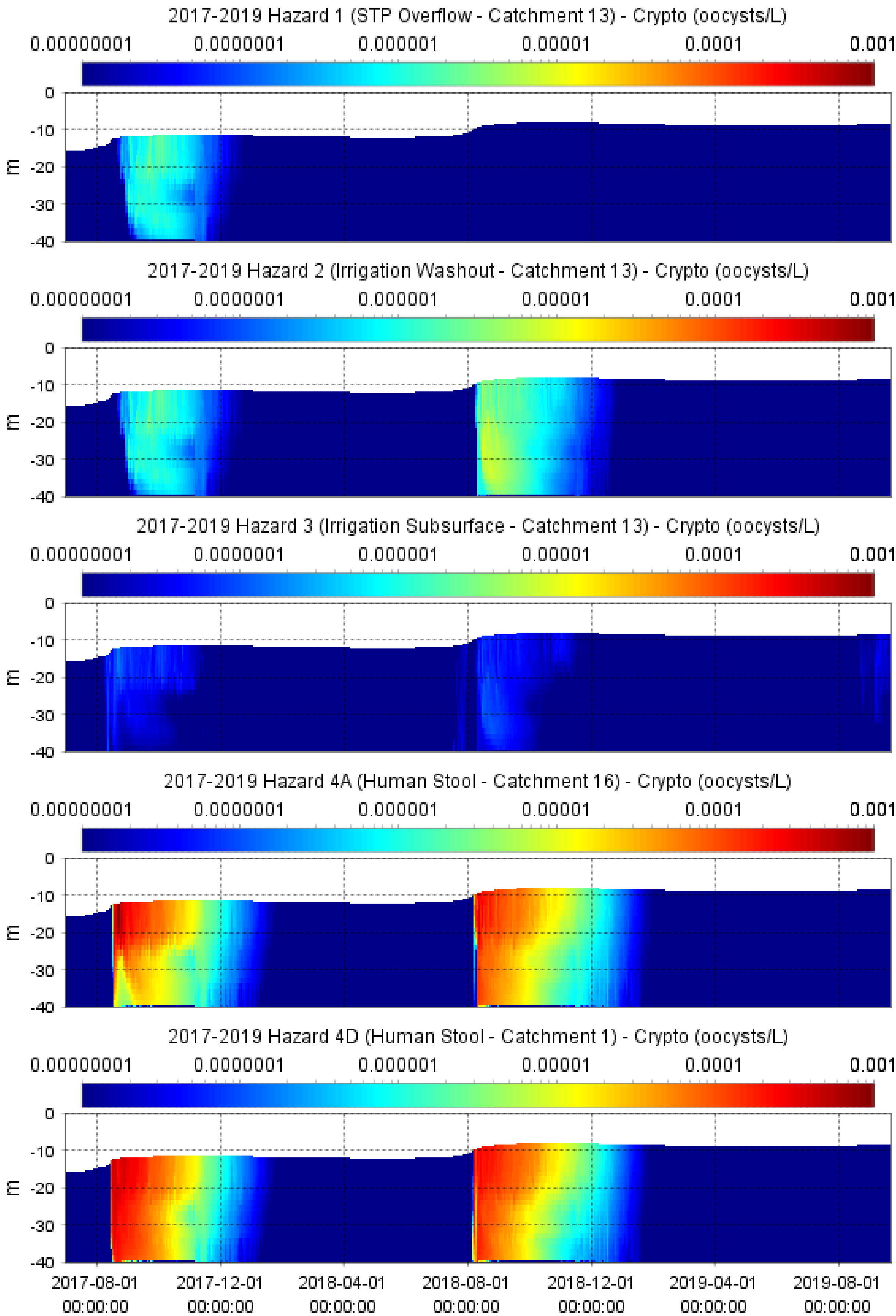

Figure 42 ***Isopleths of cryptosporidium concentration near the Serpentine Main Dam (SMD) dam wall for selected hazards for the existing mining scenario over the 2017-2019 simulation period.***

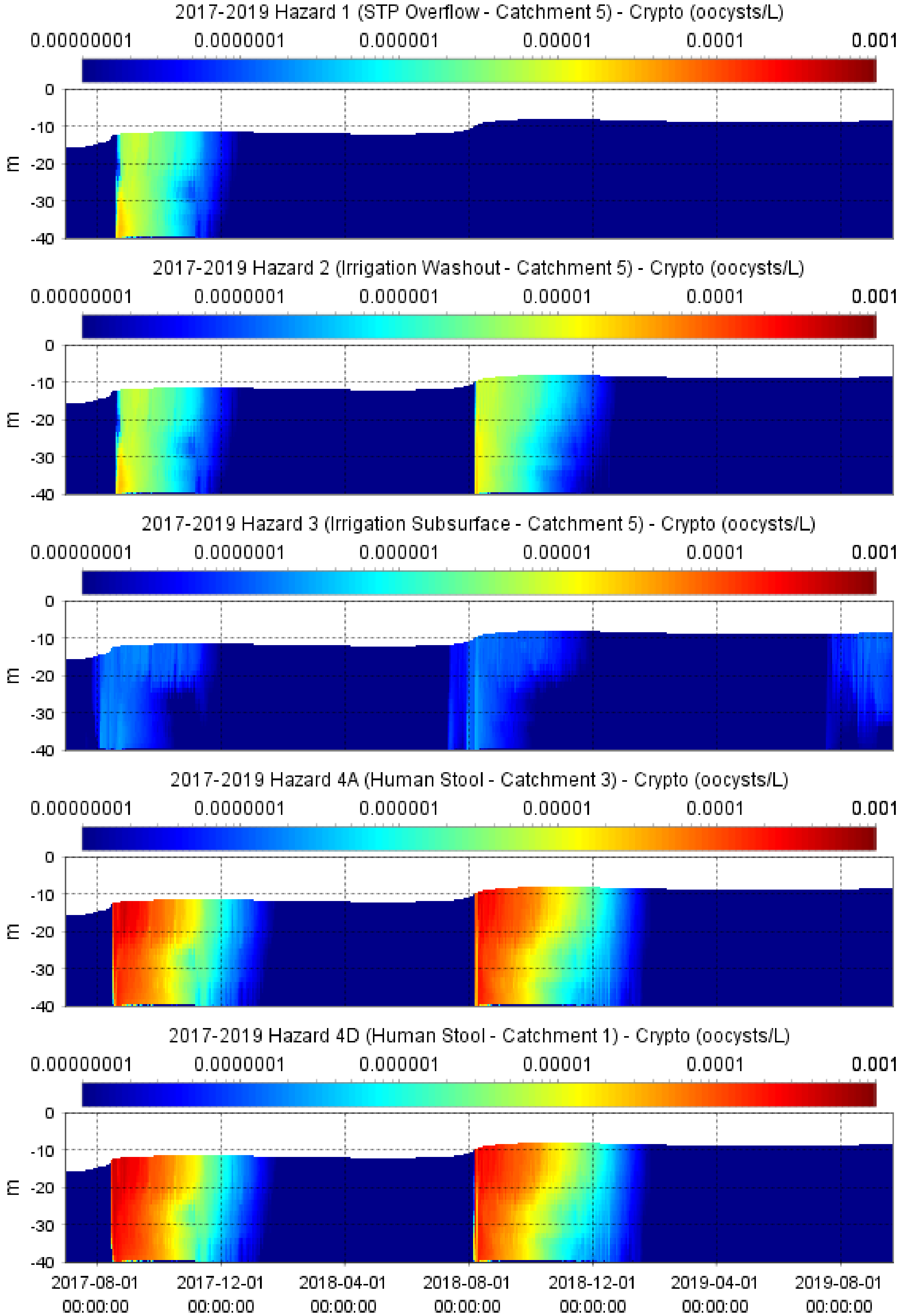

Figure 43 ***Isopleths of cryptosporidium concentration near the Serpentine Main Dam (SMD) dam wall for selected hazards for the proposed mining scenario over the 2017-2019 simulation period.***

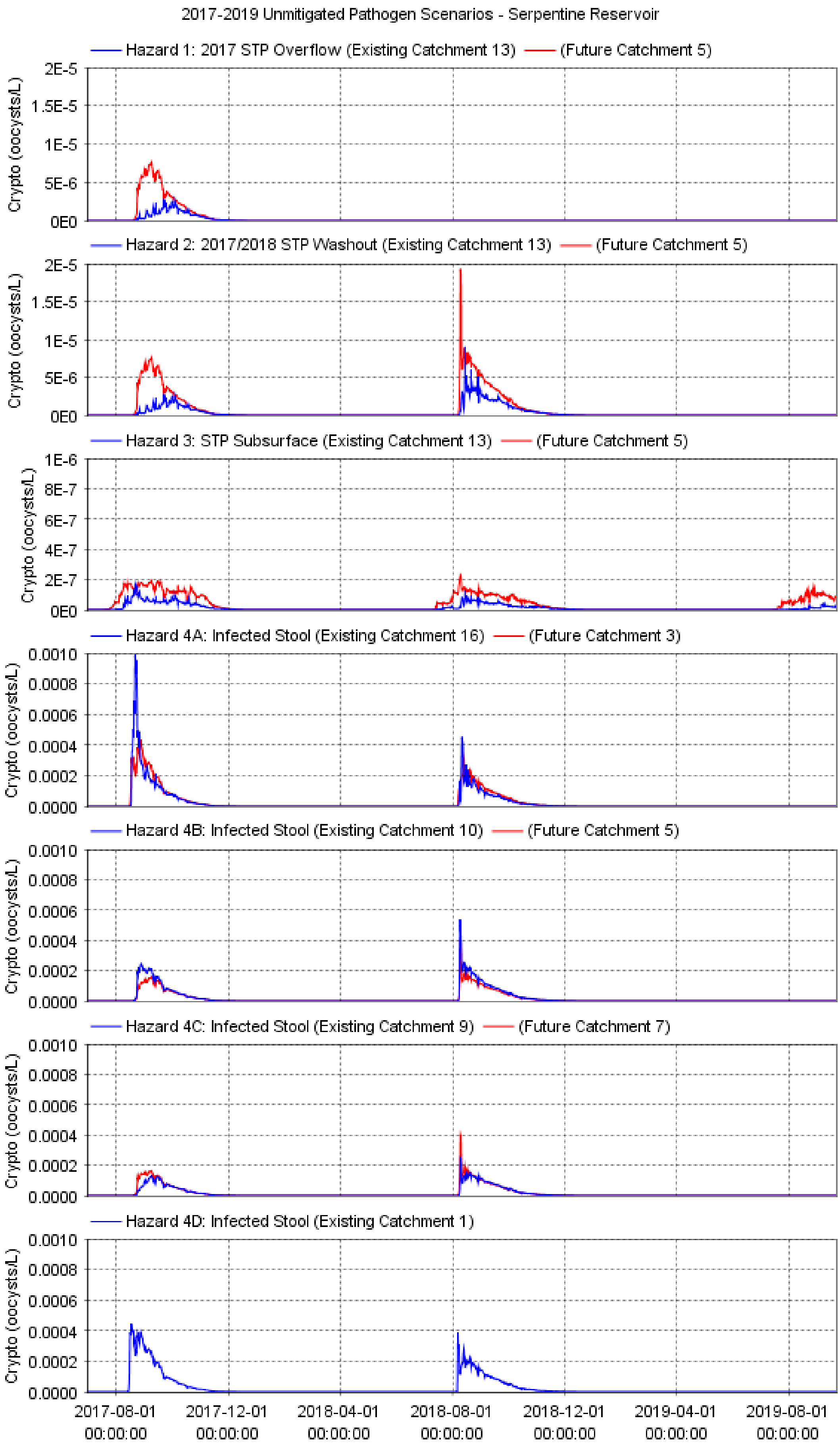

Figure 44 ***Comparison of simulated cyrptosporidium concentration of Serpentine Main Dam (SMD) withdrawals of the seven hazards for existing and proposed mining scenarios over the 2017-2019 simulation period.***

Diesel Spill

Diesel concentrations at the dam wall and in the withdrawals from spills in the selected existing and proposed SMD mining catchments (i.e. haul roads with stream crossings) had similar patterns (Figure 45 to Figure 48). Peak diesel concentrations of up to 1 μg/L were predicted with all levels below 0.2 μg/L within 6-7 months of the spill. As noted in section 5.1.2, simulated diesel concentrations do not account for any fate losses due to volatilisation, degradation or settling to adhered particles (i.e. diesel modelled as a conservative tracer in the reservoir).

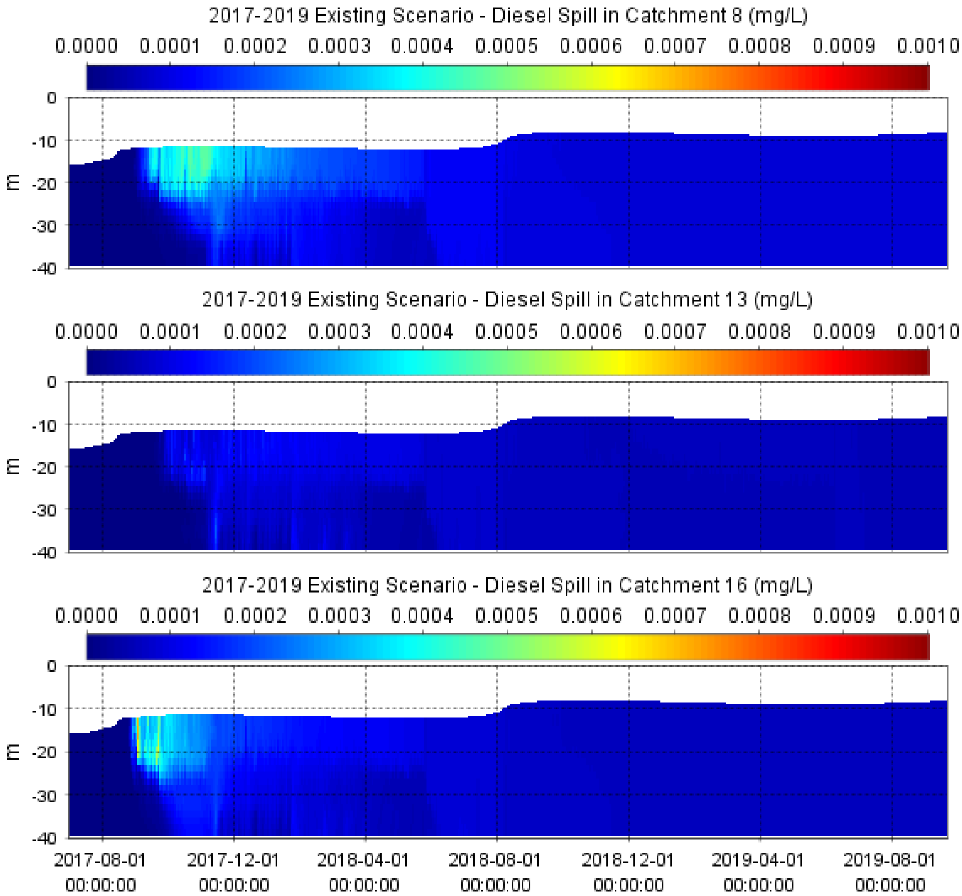

Figure 45 ***Isopleths of diesel concentrations near the Serpentine Main Dam (SMD) dam wall from spills for the existing mining scenario over the 2017-2019 simulation period.***

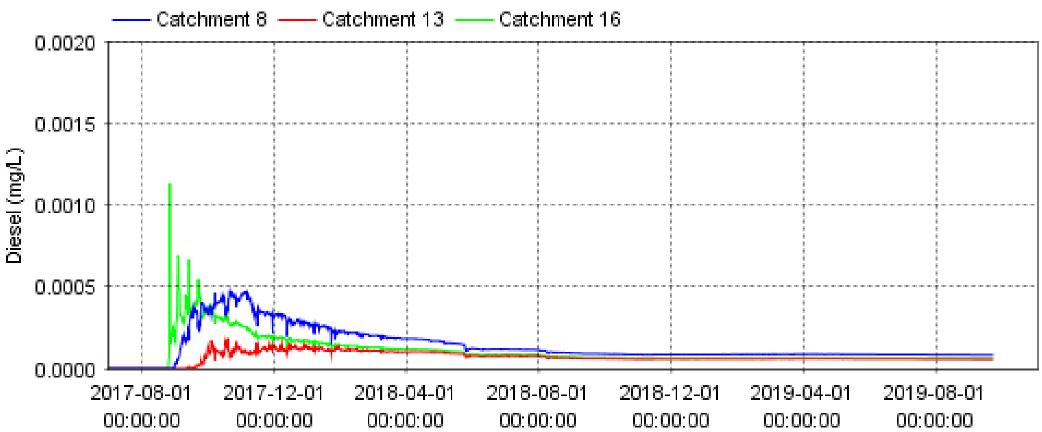

Figure 46 ***Diesel concentrations of Serpentine Main Dam (SMD) withdrawals of spills for the exisiting mining scenario over the 2017-2019 simulation period.***

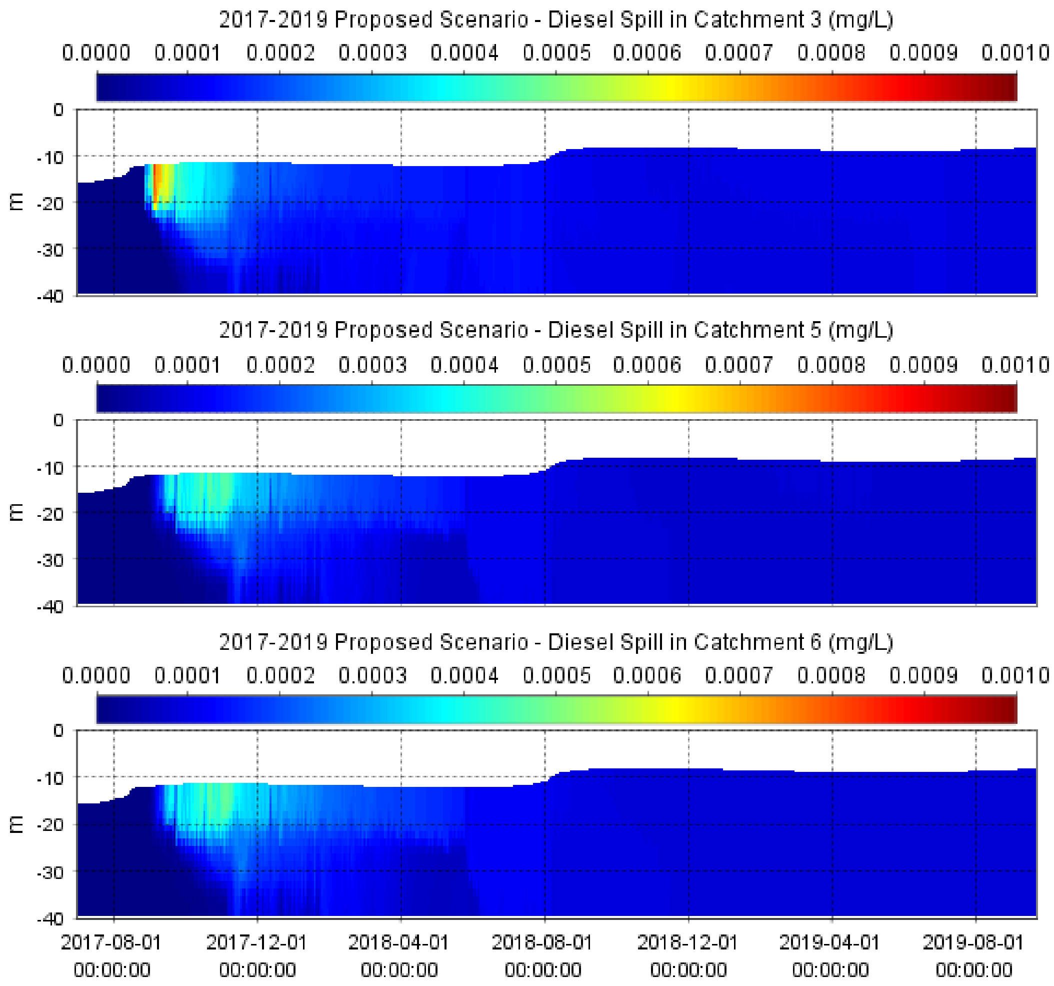

Figure 47 ***Isopleths of diesel concentrations near the Serpentine Main Dam (SMD) dam wall from spills for the proposed mining scenario over the 2017-2019 simulation period.***

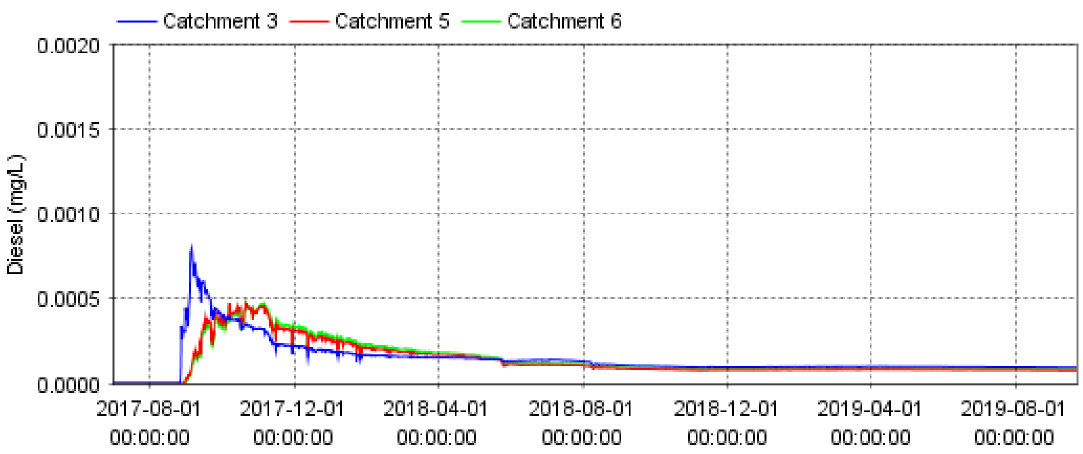

Figure 48 ***Diesel concentrations of Serpentine Main Dam (SMD) withdrawals of spills for the proposed mining scenario over the 2017-2019 simulation period.***

5.2.2 1% and 10% Annual Exceedance Period (AEP) Winter and Summer Inflow Events (Moderate Drainage Failure Inorganic Suspended Solids [SS] Levels)

Appendix A provides the 1% and 10% 7-day AEP flood event model inputs (discharge, SS_{clay} and SS_{silt} concentrations) for SMD assuming moderate drainage failure SS levels, which can be summarised as:

- The total baseline (i.e. un-mined, fully rehabilitated mining and no drainage failures in mined catchments) discharge over the 14 day inflow events was 28,706 ML and 13,503 ML for the 1% and 10% AEP scenarios, respectively. Both of these volumes are considerably larger than the 2017 and 2018 maximum 14-day totals of 10,245 and 10,291 ML, respectively.
- An additional 2,646 and 4,034 ML of discharge from drainage failures of the 1% AEP inflow event (75% drainage failures) was inputted for the existing and proposed scenarios, respectively. For the 10% AEP inflow event (30% drainage failures) an additional 979 and 1,492 ML of discharge was estimated for the existing and proposed scenarios, respectively.
- All of the baseline (no mining) scenarios had SS_{clay} and SS_{silt} catchment concentrations representative of the natural catchment of 5 and 15 mg/L, respectively, as no drainage failures with associated higher SS levels were assumed.
- Depending on the proportion of the catchment area for the existing and proposed scenarios, the SS_{Clay} catchment concentrations ranged from ~5.5-12.5 mg/L. Generally, the larger catchments (i.e. catchment 5 [39 Mile Brook], catchment 7 [Serpentine River] and catchment 13 [Big Brook]) had lower SS_{clay} concentrations as smaller proportions of the catchments were mined and thereby underwent greater stream dilution of SS prior to the reservoir.

Appendix B presents graphical summaries of the simulated SS_{clay} and SS_{silt} at the dam wall and up-reservoir locations, and in the withdrawals from the intake tower[8], which illustrate the following:

- The 1% and 10% AEP summer inflow events result in elevated concentrations for these rare events. The largest differences in SS throughout the reservoir and the withdrawals between the baseline, existing and proposed scenarios occurred for the summer 1% AEP inflow event. and to a lesser degree for the summer 10% AEP inflow event. Summer thermal stratification promotes higher SS levels in the upper portion of the water column coincident with the assumed 17 m below FSL withdrawal depth, thereby particle trapping above the seasonal thermocline generally leads to increased SS in water supply extractions. In contrast, during the winter there is a greater tendency for catchment inflows to be transported as underflows where elevated SS levels tend to occur deeper in the water column below the assumed withdrawal extraction level.
- Variations in SS between the three scenarios (i.e. baseline, existing and proposed) for the 1% and 10% AEP winter inflow events were very subtle.
- As with the 2017-2019 scenarios, elevated SS_{silt} for all scenarios was of short duration due to relatively rapid settling. The duration of elevated SS was primarily due to clay particles.
- The 10% AEP inflow events did not markedly increase maximum SS_{clay} levels above 1 mg/L. However, the simulated 1% AEP inflow events attained maximum SS_{clay} of ~2 mg/L.

A summary of the simulated total silt and clay SS in the SMD withdrawals is provided as time series in Figure 49 and percentile distributions over two 1 year periods (August 2017 to July 2018 for winter scenarios and January to December 2018 for summer scenarios) in Figure 50. The simulated SS (silt + clay) concentrations in the withdrawals are predicted to have minimal variations between the scenarios for the 10% AEP inflow event. Greater variations on the order of ~0.5 mg/L are predicted between the three scenarios for the rare 1% AEP summer inflow events, though the difference is considerably less (~0.2-0-3 mg/L) for the more common 1% AEP winter inflow event. In short, SS variations (and hence also turbidity variations) from mining activity are predicted to not cause large relative changes in SS (or turbidity) between the existing and proposed mining scenarios, even for the 1% AEP inflow events with effective drainage turbidity management.

[8] Appendix B also shows the simulated water levels for the scenario and monthly Water Corporation measurements for comparison (not verification).

The relative changes to the baseline SMD withdrawal SS (SS_{clay}+ SS_{silt}) concentrations over 1 year after the winter and summer 1% and 10% AEP inflow events are summarised in Table 11. This summary table provides the predicted relative changes to SMD withdrawal SS from the existing and proposed mining scenarios with moderate drainage failure SS levels to inform the GHD (2021a) drinking water risk assessment.

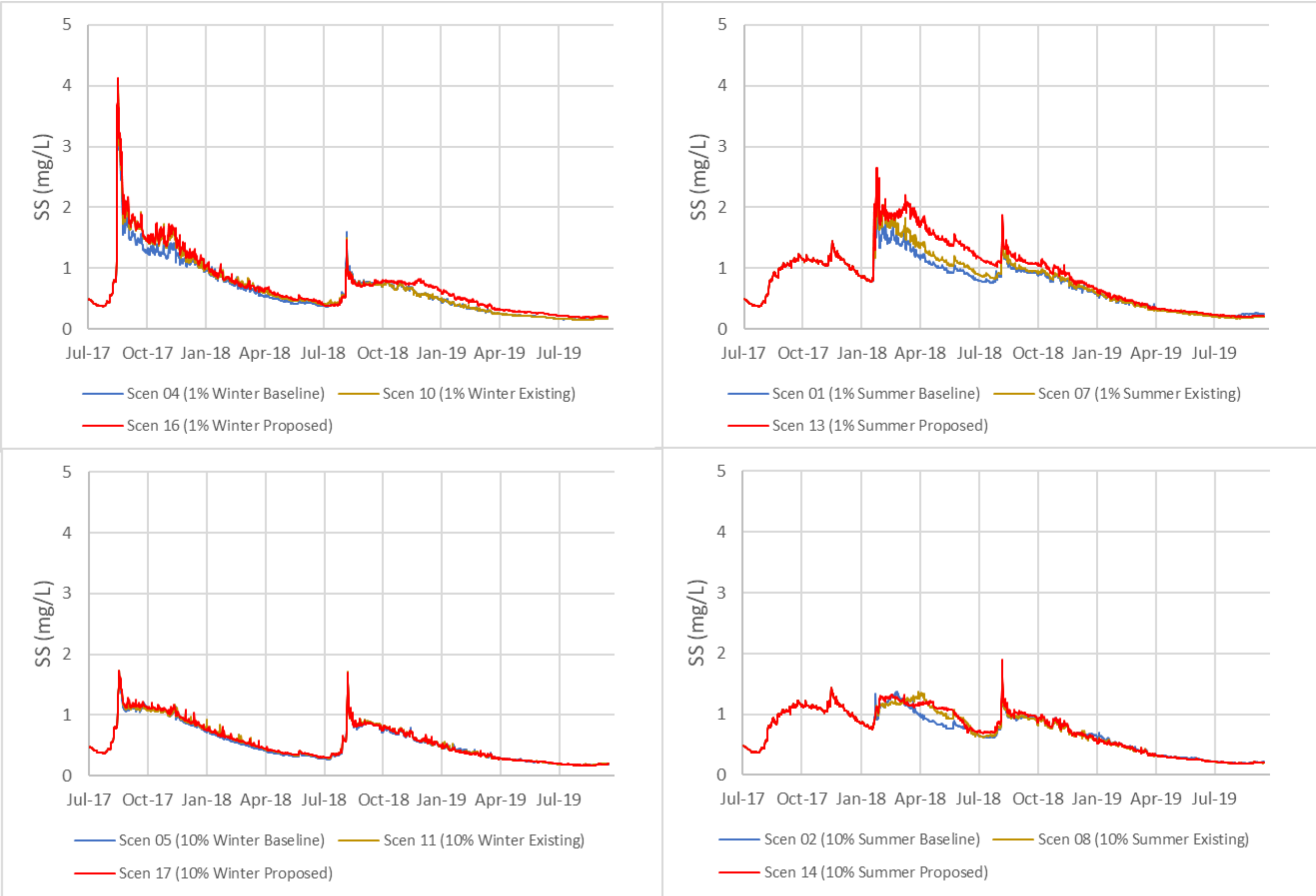

Figure 49 ***Time series of simulated Serpetine Main Dam (SMD) withdrawal inorgnaic suspended solids (SS [silt + clay]) of winter and summer 1% and 10% Annual Exceedanc Period (AEP) inflow event scenarios with moderate drainage failure SS levels.***

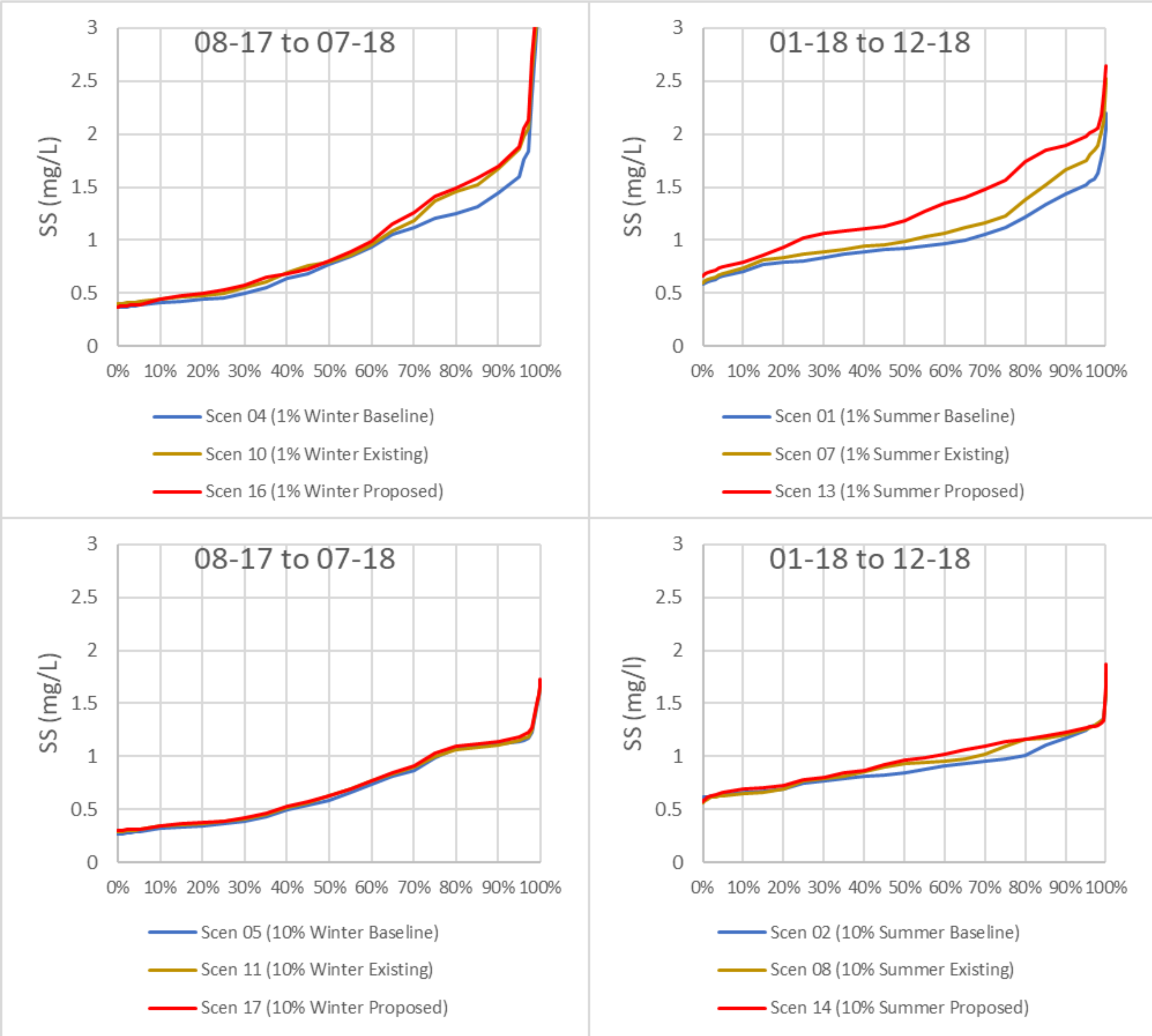

Figure 50 ***Percentile plots of simulated Serpentine Main Dam (SMD) withdrawal inorganic suspended solids (SS [silt + clay]) of winter[9] and summer[10] 1% and 10% Annual Exceedance Period (AEP) inflow event scenarios with moderate drainage failure SS levels.***

[9] Percentiles over 1 year from 1 August 2017 to 31 July 2018.
[10] Percentiles over 1 yar from 1 January to 31 December 2018.

Table 11 Summary of simulated increases in Serpentine Main Dam (SMD) withdrawal inorganic suspended solids (SS) (mg/L) for existing and proposed mining scenarios relative to baseline scenarios over 1 year after winter and summer 1% and 10% Annual Exceedance Period (AEP) inflow events with moderate drainage failure SS levels.

Statistic	1% AEP Summer Existing Scenario	10% AEP Summer Existing Scenario	1% AEP Winter Existing Scenario	1% AEP Winter Existing Scenario	1% AEP Summer Proposed Scenario	10% AEP Summer Proposed Scenario	1% AEP Winter Proposed Scenario	1% AEP Winter Proposed Scenario
Maximum	0.54	0.40	0.36	0.20	1.09	0.34	0.56	0.23
99^{th} percentile (~4 cumulative days over 1 year)	0.31	0.32	0.29	0.08	0.64	0.32	0.37	0.10
95^{th} percentile (~20 cumulative days over 1 year)	0.20	0.19	0.22	0.04	0.52	0.25	0.26	0.05
80^{th} percentile (~70 cumulative days over 1 year)	0.10	0.01	0.05	0.03	0.33	0.06	0.14	0.03

5.2.3 1% and 10% Annual Exceedance Period (AEP) Winter and Summer Inflow Events (High Drainage Failure Inorganic Suspended Solids [SS] Levels)

Appendix C provides the 1% and 10% 7-day AEP flood event model inputs (discharge, SS_{clay} and SS_{silt} concentrations) for SMD assuming high drainage failure SS levels (i.e. higher drainage SS of 63 mg/L rather than 31.5 mg/L for the existing and proposed scenarios). Appendix D presents graphical summaries of the simulated SS_{clay} and SS_{silt} at the dam wall and up-reservoir locations, and in the withdrawals[11] for these four scenarios with high drainage failure SS levels.

A summary of the simulated total silt and clay SS in the SMD withdrawals is provided as time series in Figure 51 and percentile distributions over two one year periods (August 2017 to July 2018 for winter scenarios and January to December 2018 for summer scenarios) in Figure 52 for the existing and proposed scenarios with high drainage failure SS levels. The simulated SS (silt + clay) concentrations in the withdrawals have minimal variations between the scenarios for the 10% AEP inflow event. Greater variations on the order of ~1 mg/L are simulated between the three scenarios for the rare 1% AEP summer inflow events, larger than the ~0.5 mg/L predicted with moderate drainage failure SS levels. The 1% AEP winter inflow event was predicted to increase from ~0.2-0.3 mg/L over baseline to ~0.3-0.4 mg/L over baseline for the moderate and high drainage failure SS levels scenarios. Further, a notable increase is also simulated under the high drainage failure SS level scenarios for the 10% AEP summer inflow event, though the differences between scenarios are negligible for the 10% AEP winter inflow event. In short, SS variations of the withdrawals from mining activity are predicted to cause larger relative changes with high drainage failure SS levels than with low drainage failure SS levels (Section 5.2.2), but differences between the existing and proposed scenarios are only substantive (~0.3-0.5 mg/L) for the rare 1% AEP summer inflow events.

The relative changes to the baseline SMD withdrawal SS (SS_{clay}+ SS_{silt}) concentrations over 1 year after the winter and summer 1% and 10% AEP inflow events are summarised in Table 12. This summary table provides the

[11] Appendix D also shows the simulated water levels for the scenario and monthly Water Corporation measurements for comparison (not verification).

predicted relative changes to SMD withdrawal SS from the existing and proposed mining scenarios with high drainage failure SS levels to inform the GHD (2021a) drinking water risk assessment.

Table 12 ***Summary of simulated increases in Serpentine Main Dam (SMD) withdrawal inorganic suspended solids (SS) (mg/L) for existing and proposed mining scenarios relative to baseline scenarios over 1 year after winter and summer 1% and 10% Annual Exceedance Period (AEP) inflow events with high drainage failure SS levels.***

Statistic	1% AEP Summer Existing Scenario	10% AEP Summer Existing Scenario	1% AEP Winter Existing Scenario	1% AEP Winter Existing Scenario	1% AEP Summer Proposed Scenario	10% AEP Summer Proposed Scenario	1% AEP Winter Proposed Scenario	1% AEP Winter Proposed Scenario
Maximum	0.92	0.52	1.03	0.31	1.80	0.53	0.79	0.62
99th percentile (~4 cumulative days over 1 year)	0.51	0.43	0.45	0.11	1.04	0.49	0.64	0.19
95th percentile (~20 cumulative days over 1 year)	0.40	0.29	0.37	0.08	0.86	0.43	0.50	0.15
80th percentile (~70 cumulative days over 1 year)	0.22	0.06	0.14	0.06	0.59	0.17	0.21	0.10

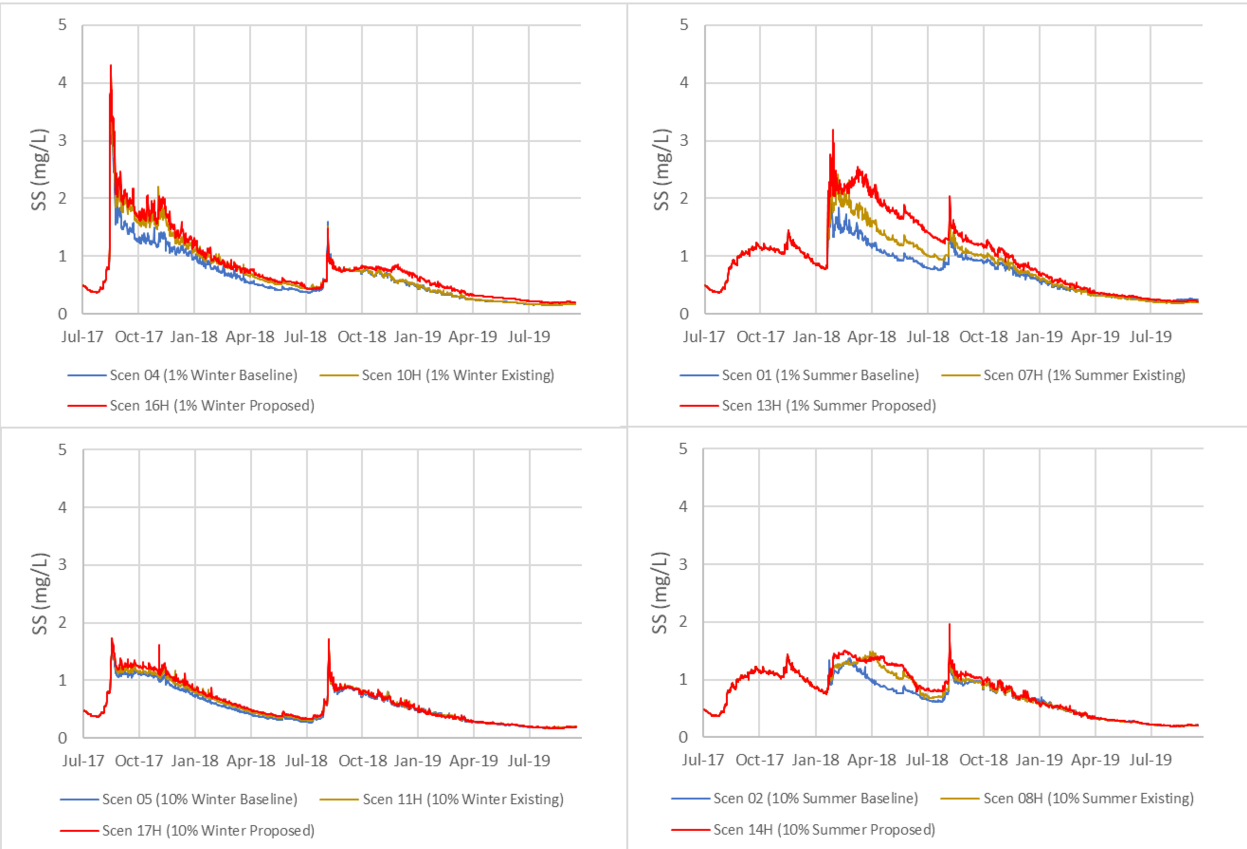

Figure 51 ***Time series of simulated Serpetine Main Dam (SMD) withdrawal inorgnaic suspended solids (SS [silt + clay]) of winter and summer 1% and 10% Annual Exceedanc Period (AEP) inflow event scenarios with high drainage failure SS levels.***

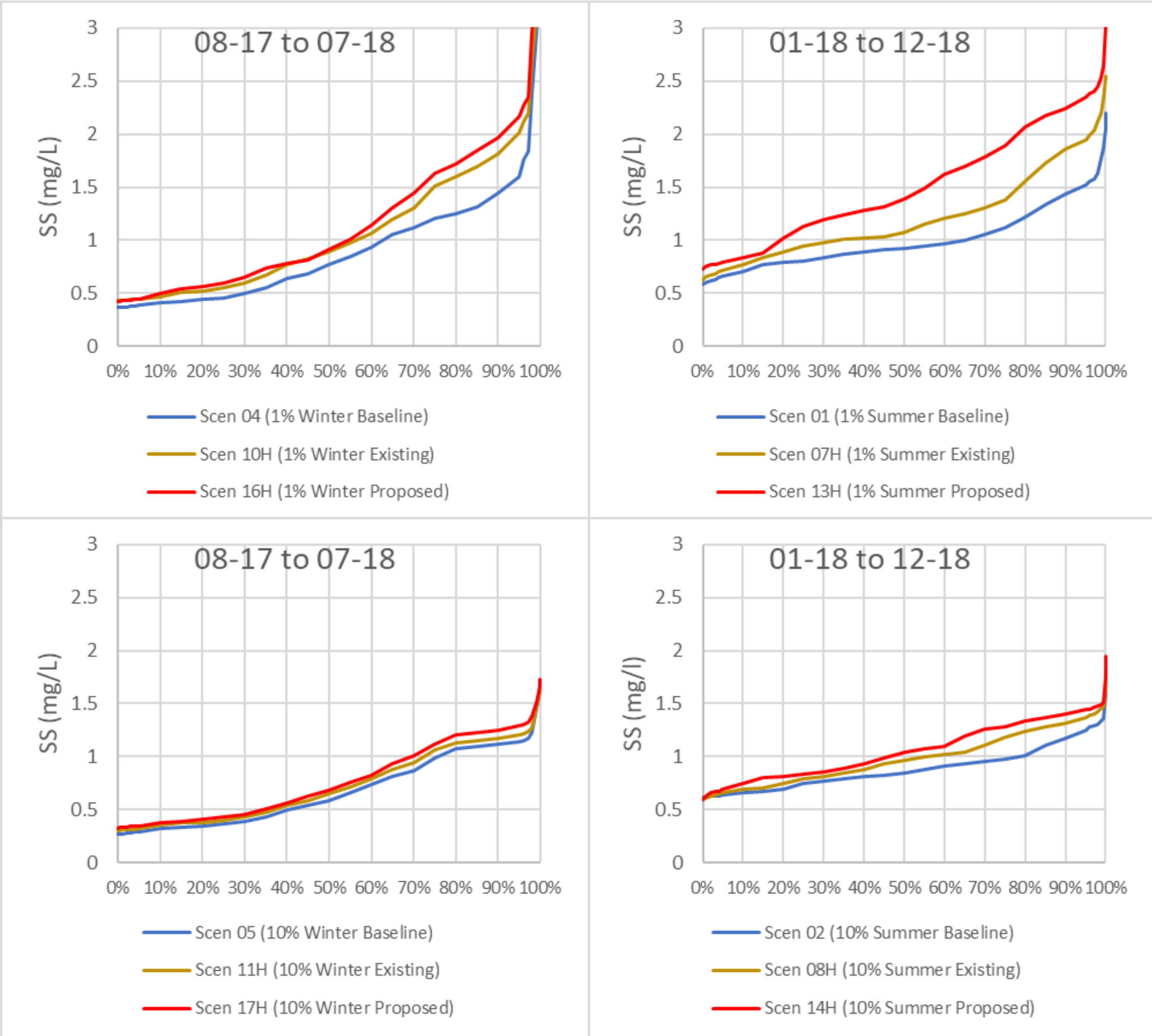

Figure 52 ***Percentile plots of simulated Serpentine Main Dam (SMD) withdrawal inorganic suspended solids (SS [silt + clay]) of winter[12] and summer[13] 1% and 10% Annual Exceedance Period (AEP) inflow event scenarios with high drainage failure SS levels.***

[12] Percentiles over 1 year from 1 August 2017 to 31 July 2018.
[13] Percentiles over 1 yar from 1 January to 31 December 2018.

5.3 South Dandalup Dam (SDD)

5.3.1 Proposed 2017-2019 Scenarios (Cryptosporidium and Hydrocarbon Spill Assessment)

Suspended Solids

Patterns of suspended inorganic solids (SS) in SDD are described in Section 4.3.2 for this scenario.

Cryptosporidium

Simulated cryptosporidium concentrations along the SDD thalweg at 4 day intervals over the first 3 weeks of reference hazard scenario 4D (i.e. mobilisation of infected human stool from catchment 30 closest to the dam wall) is illustrative of the potential risk from this pathogen (Figure 53). Unlike reference hazard 4D for SMD that had variations in the spatial patterns of pathogen between years, spatial patterns of simulated cryptosporidium levels of this hazard scenario for SDD were similar between the 2017 and 2018 inflow events with vertical mixing distributing this pathogen through the water column. However, large scale transport processes did not distribute pathogens to the same degree throughout the up-reservoir volume in SDD as for the SMD simulations, in part due to the smaller inflow to reservoir volume ratio during these hydrological events.

Isopleths of cryptosporidium concentration near the dam of hazards 1, 2, 3, 4A and 4D for the proposed scenario over the 2017-2019 simulation period is summarised in Figure 54. These figures illustrate the relative magnitude and duration of the risks from these incidents. For example, hazards 1 (STP overflow), 2 (STP irrigation area washout) and 3 (STP irrigation area subsurface drainage) are predicted to yield relatively low cryptosporidium levels at the dam (~$<3\times10^{-6}$ oocysts/L) similar to the SMD scenarios for loading of an infected stool from proposed mining catchments (hazards 4A-4C) (~$<1\times10^{-4}$ oocysts/L) and the reference un-mined catchment closest to the dam (reference hazard 4D) (~$<1\times10^{-3}$ oocysts/L). Characteristics of the simulated cryptosporidium incidents include:

– The typical timescale of elevated cryptosporidium levels is ~3-4 months.
– Over these ~3-4 months the oocysts occur throughout the water column.

Simulated cryptosporidium levels in the withdrawals to the IWSS over the 2+ year simulation of the proposed mining scenario are presented in Figure 55. As with the SMD scenarios, there are considerably higher concentrations for infected human stool hazards 4A-4D than those for STP hazards 1-3 for the SDD proposed mining scenario over the 2017-2019 simulation period. Because of the reduced horizontal transport in SDD, withdrawal cryptosporidium concentrations for hazards 4A-4C were ~2-4 fold lower than SMD and those for hazard 4D were ~2 fold greater than SMD.

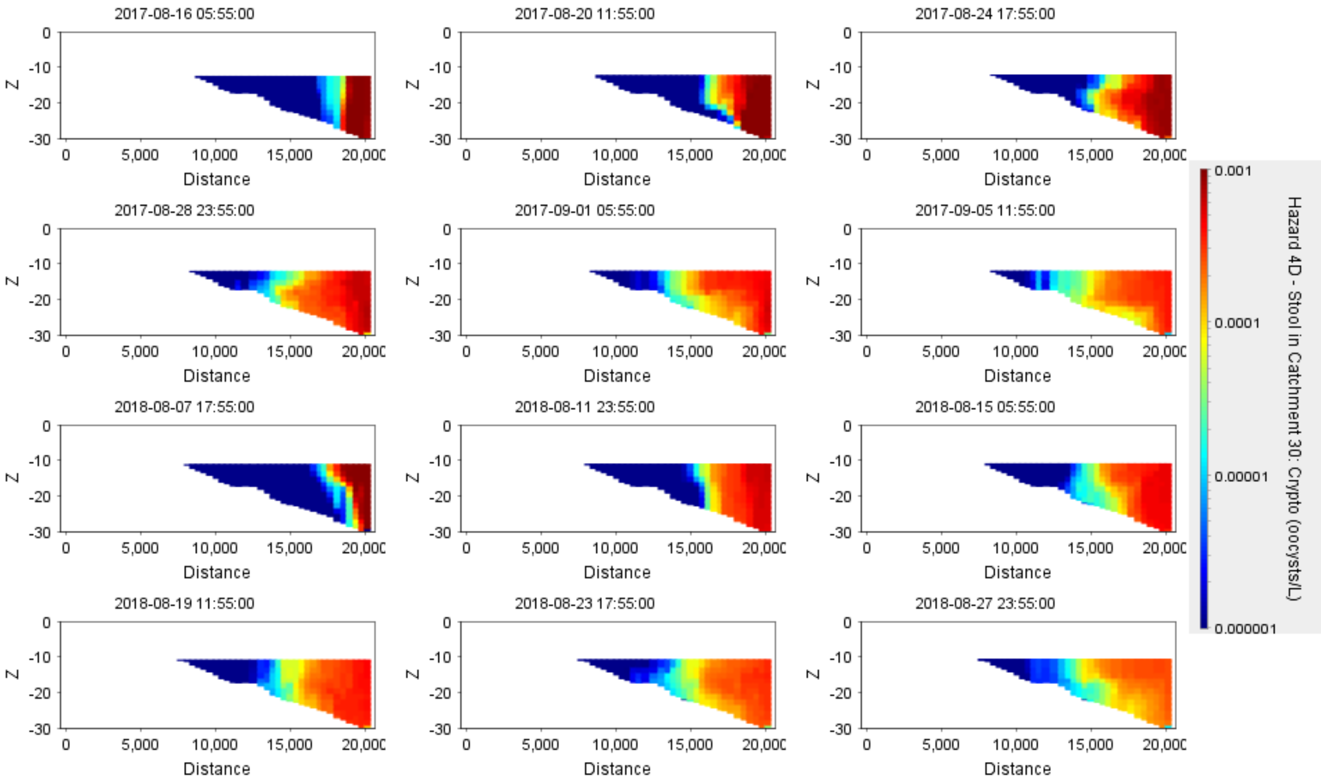

Figure 53 ***Cryptosporidium concentrations along the South Dandalup Dam (SDD) thalweg over 4 day intervals at the onset of hazard 4D during the 2017 (top 2 panels) and 2018 (bottom 2 panels) winter inflow events.***

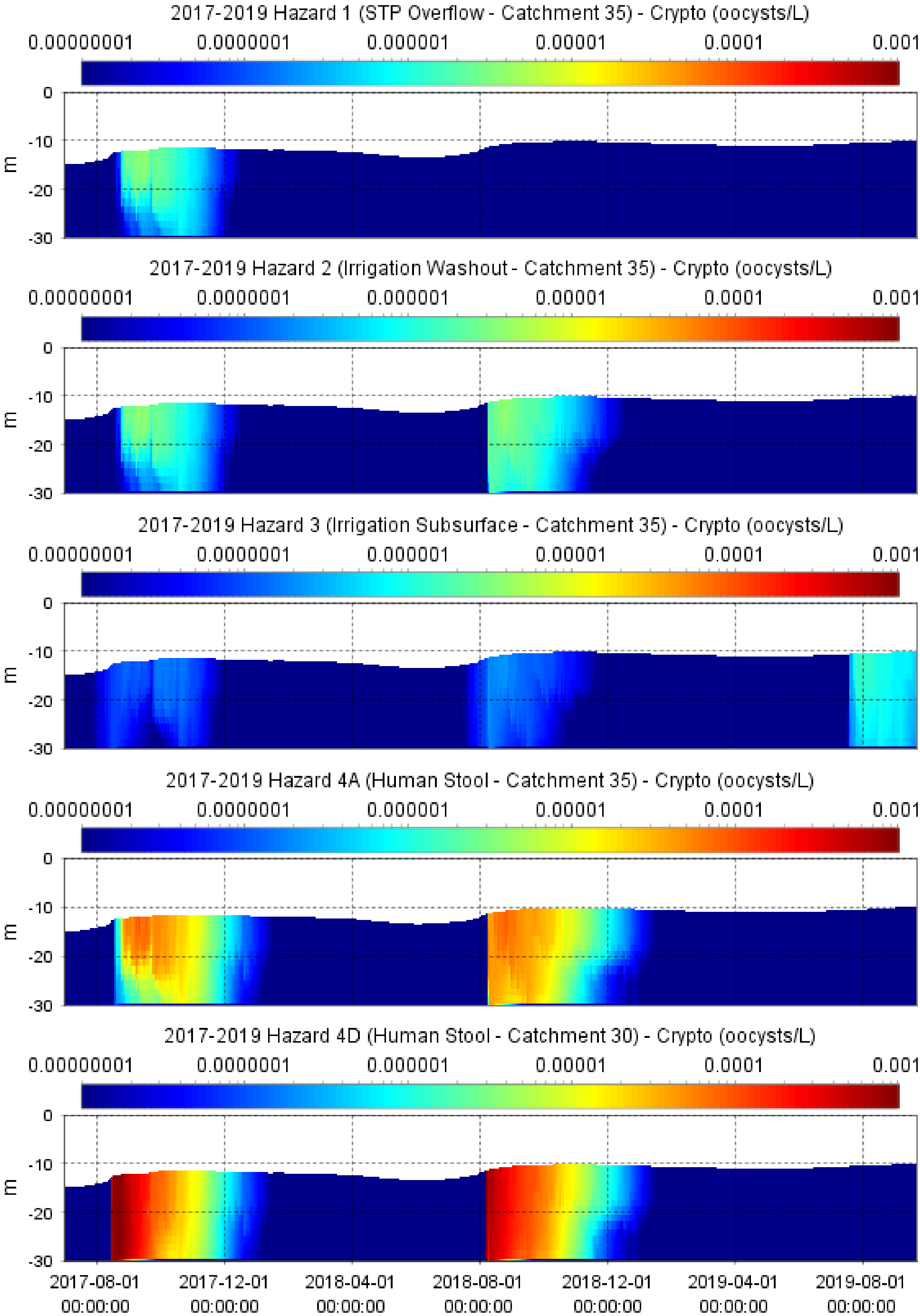

Figure 54 *Isopleths of cryptosporidium concentrations near the South Dandalup Dam (SDD) dam wall for selected hazards for the proposed mining scenario over the 2017-2019 simulation period.*

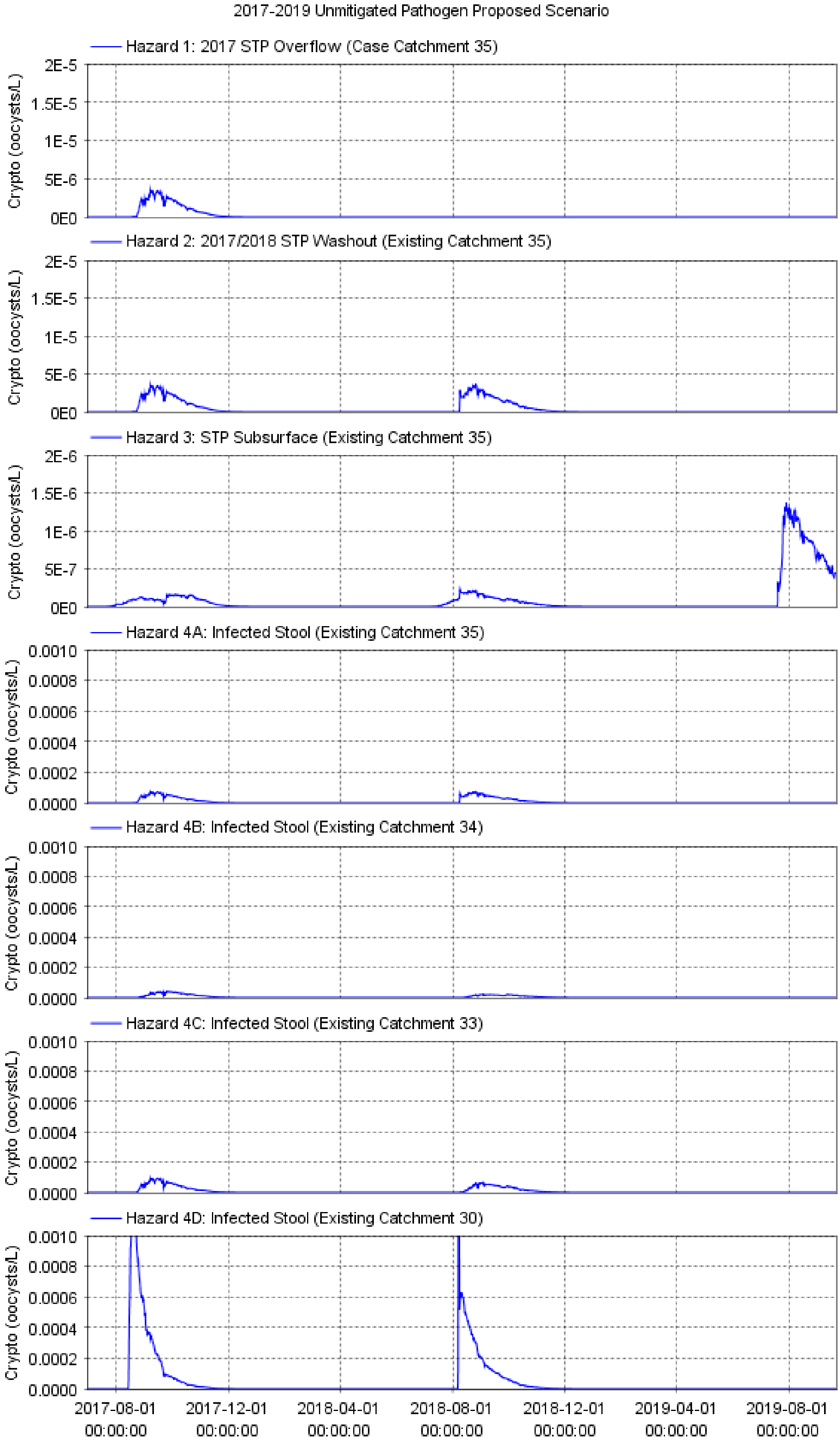

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Figure 55 *Simulated South Dandalup Dam (SDD) cyrptosporidium withdrawal concentrations of the seven hazards for the proposed mining scenario over the 2017-2019 simulation period.*

Diesel Spill

Diesel concentrations at the dam wall and withdrawals from spills in the selected SDD proposed mining catchments (i.e. haul roads with stream crossings) had similar patterns and concentrations (Figure 56 and Figure 57). As with SMD, peak diesel concentrations of up to 1 µg/L were predicted with all levels below 0.4 µg/L within 6-7 months of the spill. As noted in section 5.1.2, simulated diesel concentrations do not account for any fate losses due to volatilisation, degradation or settling to adhered particles (i.e. diesel modelled as a conservative tracer in the reservoir).

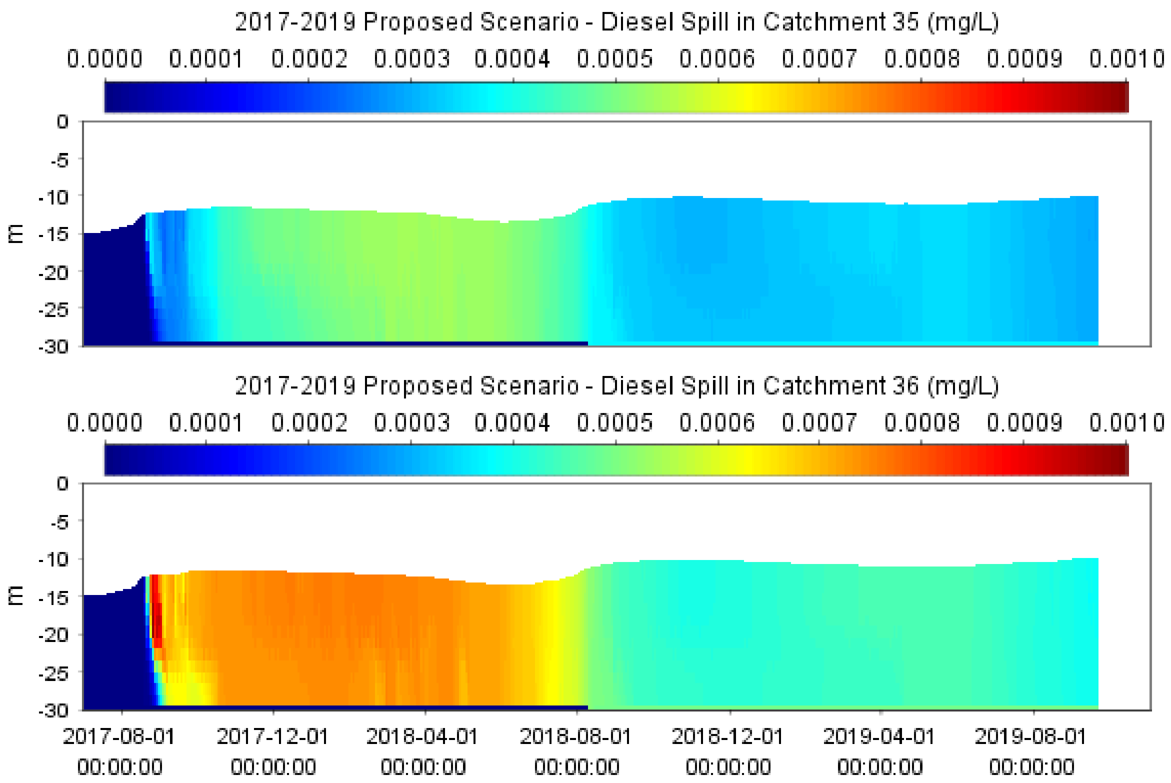

Figure 56 *Isopleths of diesel concentration near the South Dandalup (SDD) dam wall of spills for the proposed mining scenario over the 2017-2019 simulation period.*

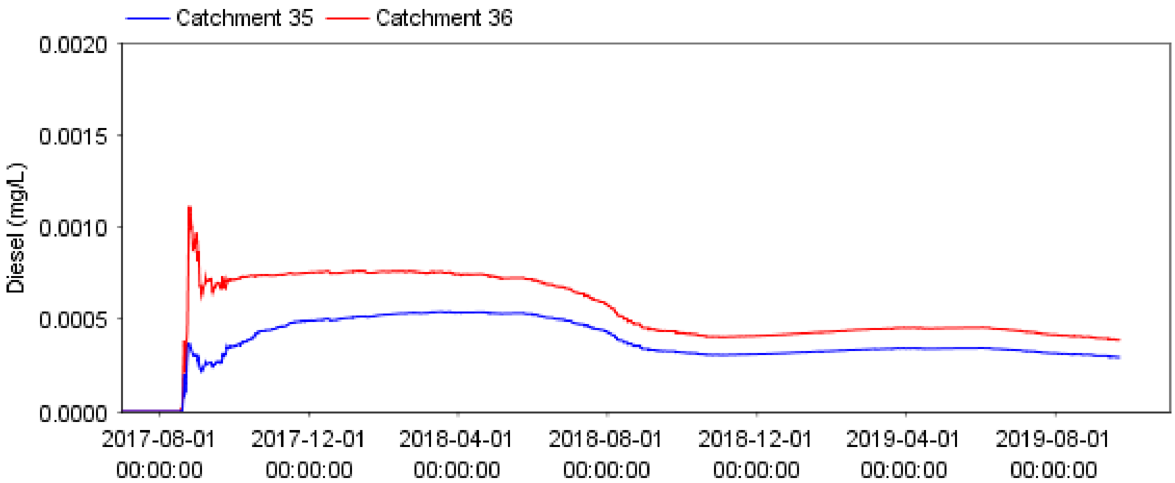

Figure 57 *Diesel concentrations of South Dandalup Dam (SDD) withdrawals of spills for the proposed mining scenario over the 2017-2019 simulation period.*

5.3.2 1% and 10% Annual Exceedance Period (AEP) Winter and Summer Inflow Events (Moderate Drainage Failure Inorganic Suspended Solids [SS] Levels)

Appendix E provides the 1% and 10% AEP flood event model inputs (discharge, SS_{clay} and SS_{silt} concentrations) for SDD assuming moderate drainage failure SS levels, which can be summarised as:

- The total baseline (i.e. un-mined, fully rehabilitated mining and no drainage failures in mined catchments) discharge over the 14 day inflow events were 13,503 ML and 5,791 ML for the 1% and 10% AEP scenarios, respectively. Both of these volumes are larger than the 2017 and 2018 maximum 14-day totals of 5,335 and 4,500 ML, respectively.
- An additional 864 ML of discharge was inputted from drainage failures of the 1% AEP inflow event (75% drainage failures) for the proposed scenario. For the 10% AEP inflow event (30% drainage failures) an additional 319 ML of discharge was estimated for the proposed scenario.
- All of the baseline (no mining) scenarios had SS_{clay} and SS_{silt} catchment concentrations representative of the natural catchment of 5 and 15 mg/L, respectively, as no drainage failures with associated higher SS levels were assumed.
- Depending on the proportion of the catchment area for the proposed scenario, the SS_{clay} catchment concentrations ranged from ~5.5-10 mg/L. Generally, the larger catchment (i.e. catchment 35 [Serpentine River]) had lower SS_{clay} concentrations as a smaller proportion of the catchment was mined and more substantive discharge caused greater stream dilution of SS prior to reservoir insertion.

Inspection of the scenario simulations at the upper, mid- and near-dam locations in Appendix F[14] illustrate the following:

- Unlike the SMD scenarios, the SDD scenarios did not predict any material differences in the 1% and 10% AEP summer and winter inflow events between the baseline and proposed scenarios (note no existing mining scenario for SDD). The relatively small proportion of the catchment that will undergo mining does not generate sufficient additional SS loads over the baseline (no mining) scenario to cause a substantive increase in SS of the proposed scenarios.
- As with the 2017-2019 scenarios, elevated SS_{silt} for all scenarios was of short duration due to relatively rapid settling. The duration of elevated SS was primarily due to clay particles.

A summary of the simulated total silt and clay SS in the SDD withdrawals is provided as time series in Figure 58 and percentile distributions over two one year periods (August 2017 to July 2018 for winter scenarios and January to December 2018 for summer scenarios) in Figure 59. The simulated SS (silt + clay) concentrations in the withdrawals predict minimal variations between the baseline and proposed scenarios for the 1% and 10% AEP inflow events. In short, SS variations from proposed SDD mining activity are predicted to not cause large relative changes between the baseline and proposed scenarios, even for the 1% AEP inflow events. The larger reservoir volume to catchment inflow ratio for SDD provides a greater volumetric barrier to elevated SS relative to SMD, which has a similar volume, but substantially larger catchment discharge.

The relative changes to the baseline SDD withdrawal SS (SS_{clay}+ SS_{silt}) concentrations over 1 year after the winter and summer 1% and 10% AEP inflow events are summarised in Table 13. This summary table provides the predicted relative changes to SDD withdrawal SS from the proposed mining scenarios with moderate drainage failure SS levels to inform the GHD (2012a) drinking water risk assessment.

[14] Appendix F shows the simulated water levels for the scenario and monthly Water Corporation measurements for comparison (not verification).

Table 13 *Summary of simulated increases in South Dandalup Dam (SDD) withdrawal inorganic suspended solids (SS) (mg/L) for existing and proposed mining scenarios relative to baseline scenarios over 1 year after winter and summer 1% and 10% Annual Exceedance Period (AEP) inflow events with moderate drainage failure SS levels.*

Statistic	1% AEP Summer Proposed Scenario	10% AEP Summer Proposed Scenario	1% AEP Winter Proposed Scenario	1% AEP Winter Proposed Scenario
Maximum	0.21	0.04	0.11	0.11
99th percentile (~4 cumulative days over 1 year)	0.05	0.02	0.09	0.06
95th percentile (~20 cumulative days over 1 year)	0.03	0.02	0.08	0.05
80th percentile (~70 cumulative days over 1 year)	0.02	0.01	0.04	0.02

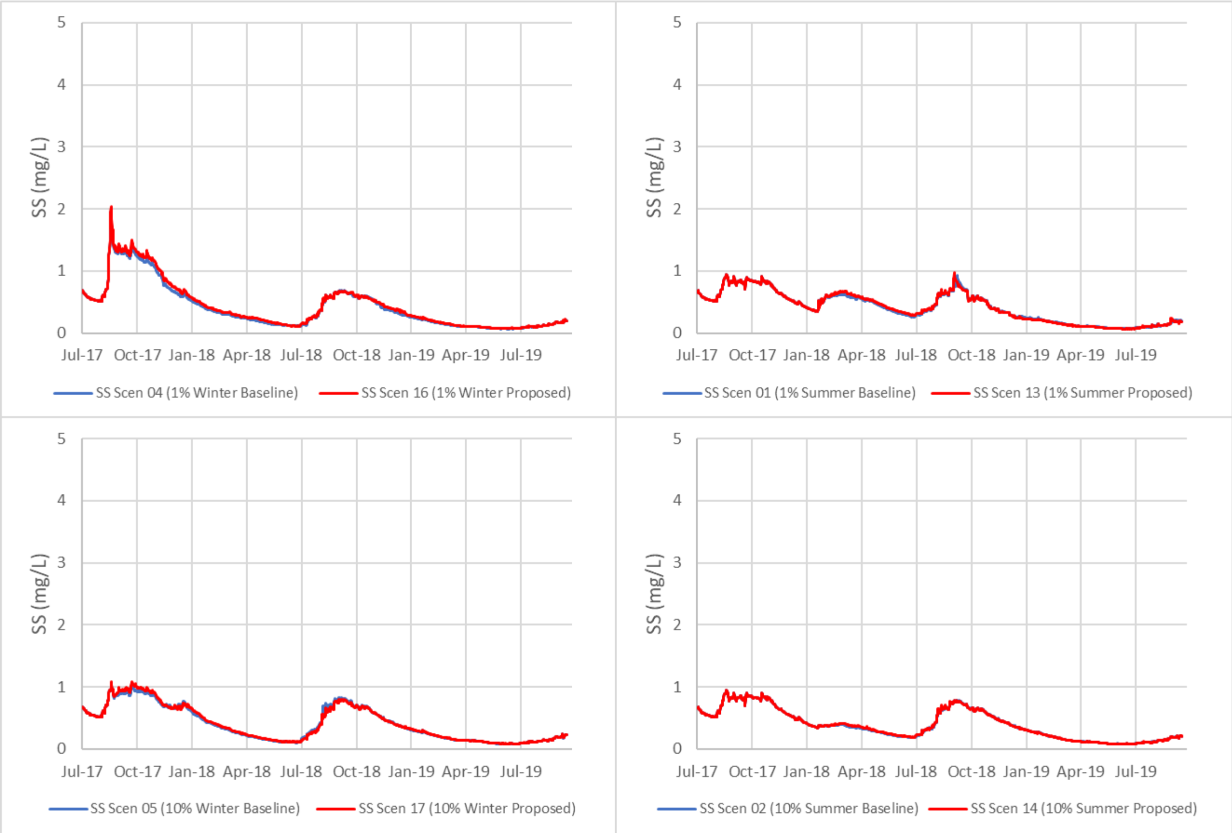

Figure 58 *Time series of simulated South Dandalup Dam (SDD) withdrawal inorganic suspended solids (SS [silt + clay]) of winter and summer 1% and 10% Annual Exceedance Period (AEP) inflow events with moderate drainage failure SS levels.*

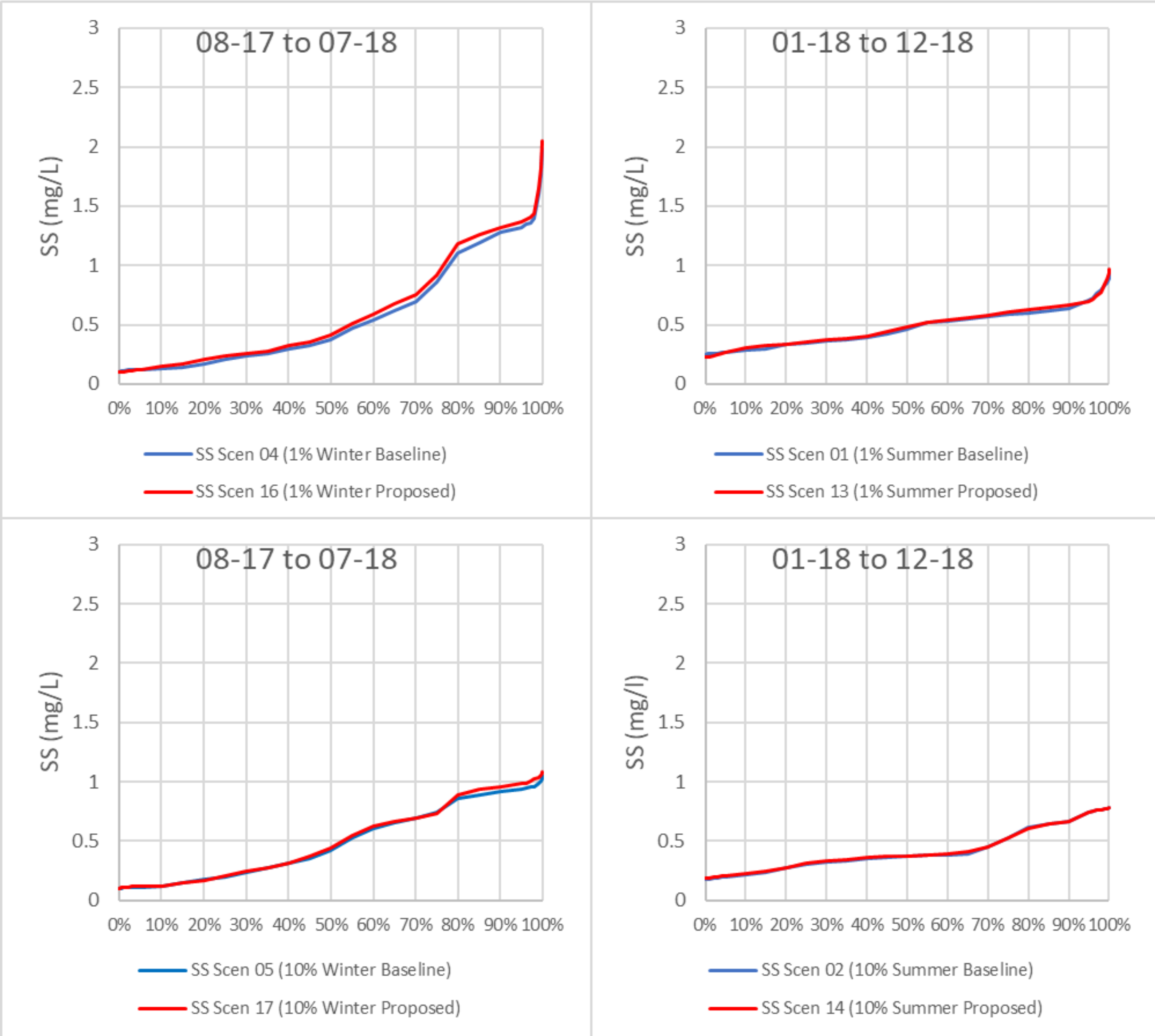

Figure 59 ***Percentile plots of simulated South Dandalup Dam (SDD) withdrawal inorganic suspended solids (SS [silt + clay]) of winter and summer 1% and 10% Annual Exceedance Period (AEP) inflow events with moderate drainage failure SS levels.***

5.3.3 1% and 10% Annual Exceedance Period (AEP) Winter and Summer Inflow Events (High Drainage Failure Inorganic Suspended Solids [SS] Levels)

Appendix G provides the 1% and 10% 7-day AEP flood event model inputs (discharge, SS_{clay} and SS_{silt} concentrations) for SDD assuming high drainage failure SS levels (i.e. higher drainage SS of 63 mg/L rather than 31.5 mg/L for the proposed scenarios). Appendix H presents graphical summaries of the simulated SS_{Clay} and SS_{Silt} at the dam wall and up-reservoir locations, and in the withdrawals[15] from the intake tower for these two scenarios with ineffective drainage turbidity management.

A summary of the simulated total silt and clay SS in the SDD withdrawals is provided as time series in Figure 60 and percentile distributions over two one year periods (August 2017 to July 2018 for winter scenarios and January to December 2018 for summer scenarios) in Figure 61 for the proposed scenarios with ineffective drainage turbidity management. The simulated SS (silt + clay) concentrations in the withdrawals predict minimal variations between the baseline and proposed scenarios of <0.2 mg/L. In short, SS variations of the withdrawals from mining activity are predicted to cause minimal changes to SS, even with ineffective drainage turbidity management.

The relative changes to the baseline SDD withdrawal SS (SS_{clay}+ SS_{silt}) concentrations over 1 year after the winter and summer 1% and 10% AEP inflow events are summarised in Table 14. This summary table provides the predicted relative changes to SDD withdrawal SS from the proposed mining scenarios with high drainage failure SS levels to inform the GHD (2012a) drinking water risk assessment.

Table 14 ***Summary of simulated increases in South Dandalup Dam (SDD) withdrawal inorganic suspended solids (SS) (mg/L) for existing and proposed mining scenarios relative to baseline scenarios over 1 year after winter and summer 1% and 10% Annual Exceedance Period (AEP) inflow events with high drainage failure SS levels.***

Statistic	1% AEP Summer Proposed Scenario	10% AEP Summer Proposed Scenario	1% AEP Winter Proposed Scenario	1% AEP Winter Proposed Scenario
Maximum	0.23	0.07	0.19	0.15
99th percentile (~4 cumulative days over 1 year)	0.09	0.04	0.17	0.10
95th percentile (~20 cumulative days over 1 year)	0.07	0.04	0.15	0.08
80th percentile (~70 cumulative days over 1 year)	0.04	0.02	0.06	0.03

15 Appendix H also shows the simulated water levels for the scenario and monthly Water Corporation measurements for comparison (not verification).

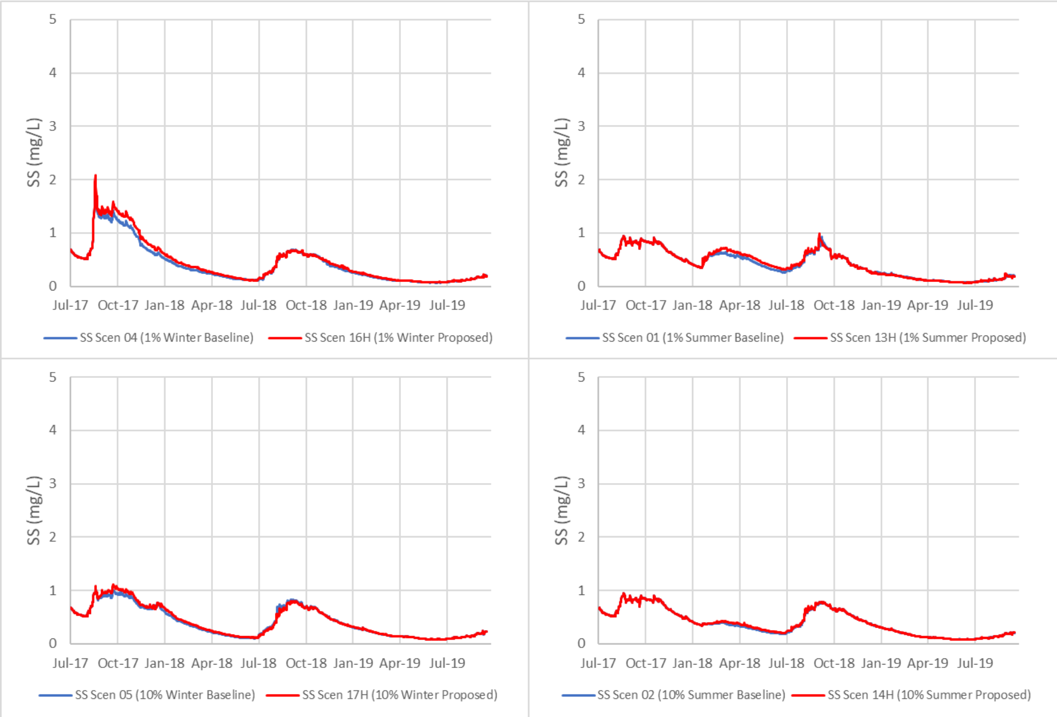

Figure 60 *Time series of simulated South Dandalup Dam (SDD) withdrawal inorganic suspended solids (SS [silt + clay]) of winter and summer 1% and 10% Annual Exceedance Period (AEP) inflow events with high drainage failure SS levels.*

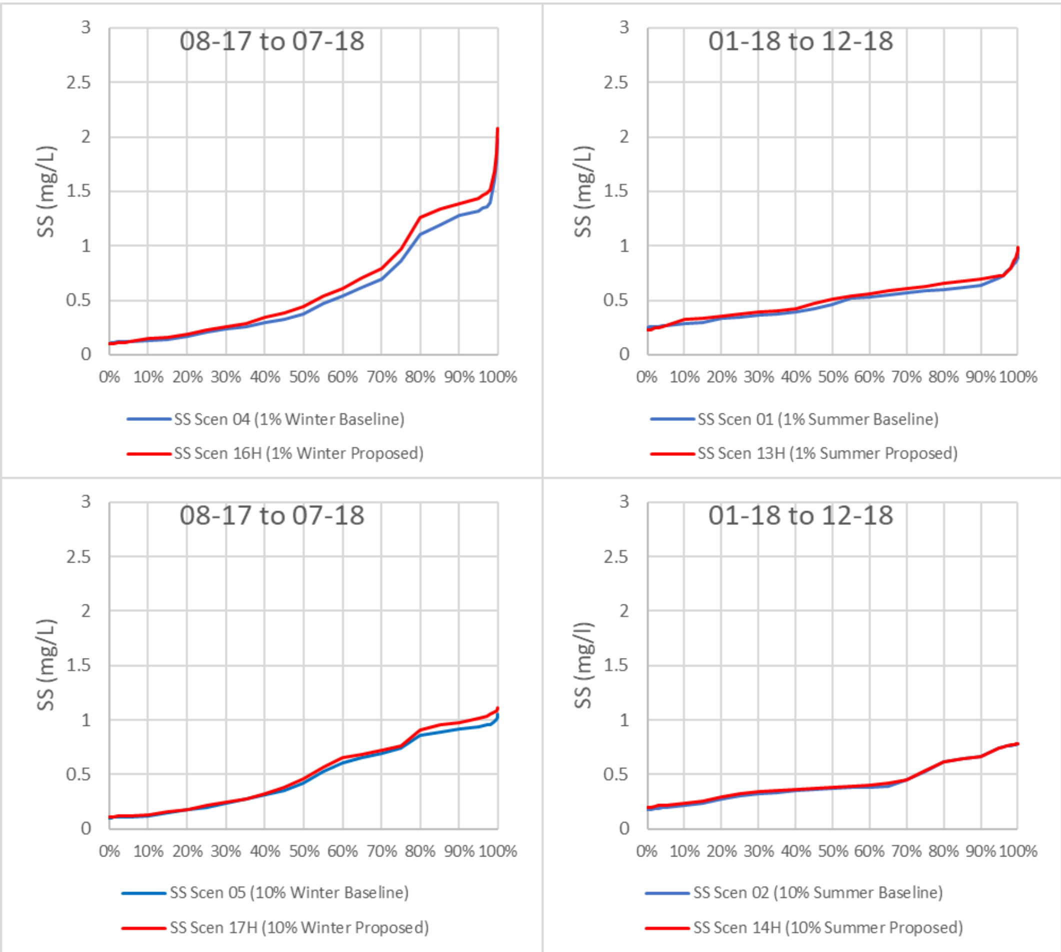

Figure 61 *Percentile plots of simulated South Dandalup Dam (SDD) withdrawal inorganic suspended solids (SS [silt + clay]) of winter and summer 1% and 10% Annual Exceedance Period (AEP) inflow events with high drainage failure SS levels.*

5.4 Serpentine Pipehead Dam (SPD)

5.4.1 Existing 2017-2019 Scenarios (Cryptosporidium and Hydrocarbon Spill Assessment)

Suspended Solids

Patterns of suspended inorganic solids (SS) in SPD are described in Section 4.3.2 for this scenario.

Cryptosporidium

Simulated cryptosporidium concentrations along the SPD thalweg at 4 day intervals over the first 3 weeks of reference hazard 4D (i.e. mobilisation of infected human stool from catchment 20 closest to the dam) is illustrative of the potential risk from this pathogen (Figure 62). Similar to SDD, spatial patterns of simulated cryptosporidium levels of this incident for SPD were similar between the 2017 and 2018 inflow events with vertical mixing distributing this pathogen through the water column. Further, as with SDD, large scale transport processes did not distribute pathogens to the same degree throughout the up-reservoir SPD volume.

Isopleths of cryptosporidium concentration near the dam of hazards 1, 2, 3, 4A and 4D for the existing scenario over the 2017-2019 simulation period is summarised in Figure 63. As no STP is located in any of the existing (same as proposed) SPD mining catchments, hazards 1, 2 and 3 are not relevant. Further, only two catchments have existing mining activity, and proposed mining activity is also to be limited to these two catchments. The two simulated two infected human stool incidents in the existing mining catchments (hazards 4A and 4B) have peak concentrations at the dam that span a large range wall from ~<1×10^{-5} oocysts/L (hazard 4A in catchment 23) to ~<1×10^{-3} oocysts/L (hazard 4B in catchment 24). Hazard 4D with cryptosporidium loads from catchment 20 closest to the dam has at least an order of magnitude greater simulated concentration (~<$1\text{-}2\times10^{-2}$ oocysts/L) than the other 2 hazards. Characteristics of simulated cryptosporidium concentrations during hazards 4A, 4B and 4D in SPD include:

– The typical timescale of elevated cryptosporidium levels is ~2-3 months, though it is considerable shorter and of much lower magnitude for hazard 4D in catchment 20.

– Over these ~2-3 months the oocysts occur throughout the water column.

– There is a delay in the arrival of elevated cryptosporidium concentrations for hazard 4A from uppermost catchment 23.

Cryptosporidium levels from hazards 4A, 4B and 4C in the SPD withdrawals to the IWSS for the existing (and proposed) mining scenario over the 2017-2019 simulation period are presented in Figure 64. The catchment from which an infected stool is mobilised has a large effect on the simulated cryptosporidium concentrations in the withdrawals. For hazard 4A in the uppermost catchment at the head of the reservoir, very low levels are predicted at the outlet in contrast with hazard 4D for the catchment closest to the dam wall.

The primary SPD water inputs and outputs are via external transfers and withdrawals, which are both in the vicinity of the dam and promote a high degree of short-circuiting between them. This has major implications on the spatial patterns of water age (i.e. duration a water parcel remains in the reservoir) throughout the SPD water body with much greater water retention in the upper portions of the reservoir relative to near proximity to the dam. This phenomenon induced by the operational configuration and management of the SPD induces a hydrodynamic barrier that decreases the transport of cryptosporidium (and any other contaminants) from catchment 23 to the dam as illustrated in Figure 65.

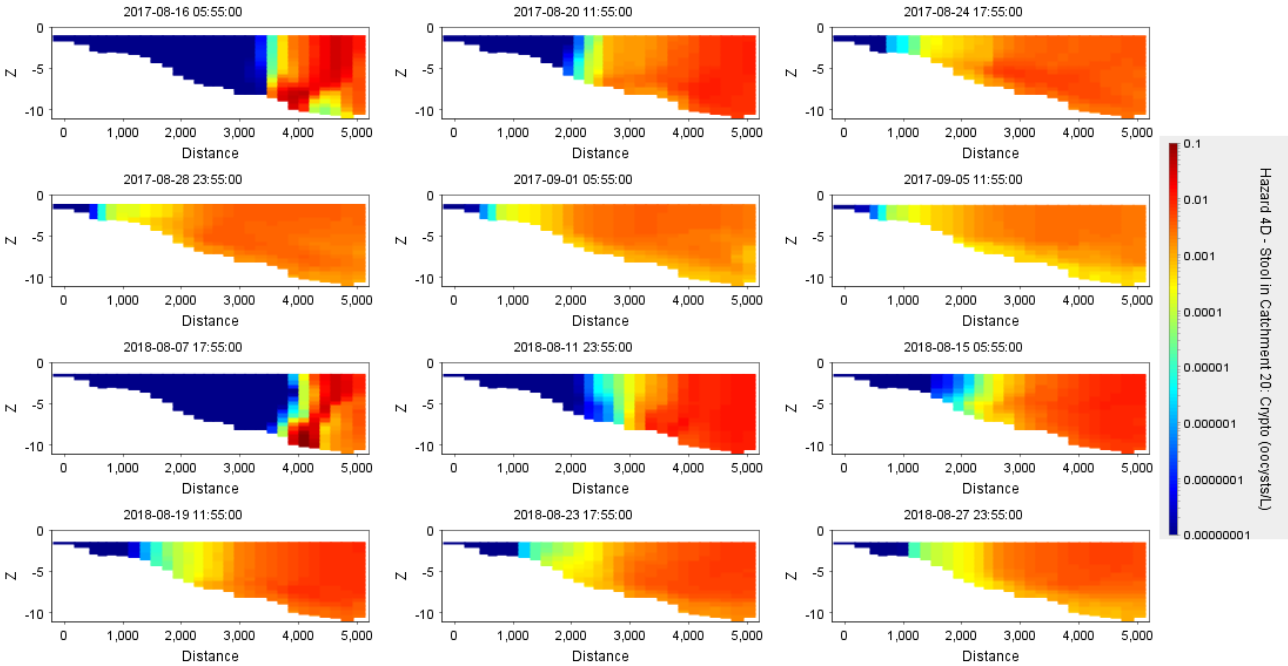

Figure 62 ***Cryptosporidium concentrations along the Serpentine Pipehead Dam (SPD) thalweg over 4 day intervals at the onset of hazard 4D during the 2017 (top 2 panels) and 2018 (bottom 2 panels) winter inflow events.***

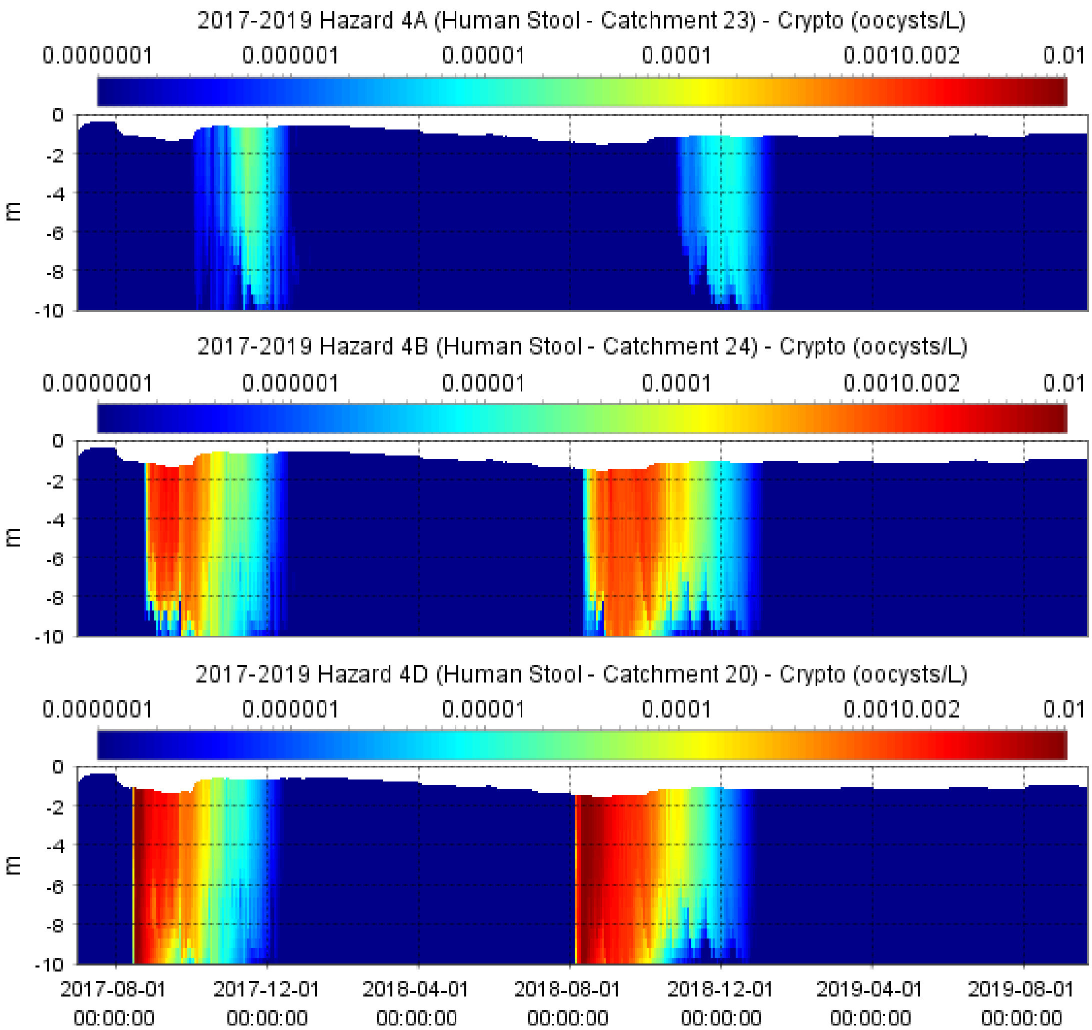

Figure 63 ***Isopleths of cryptosporidium concentrations near the Serpentine Pipehead Dam (SPD) dam wall for 3 relevant hazards for the existing mining scenario over the 2017-2019 simulation period.***

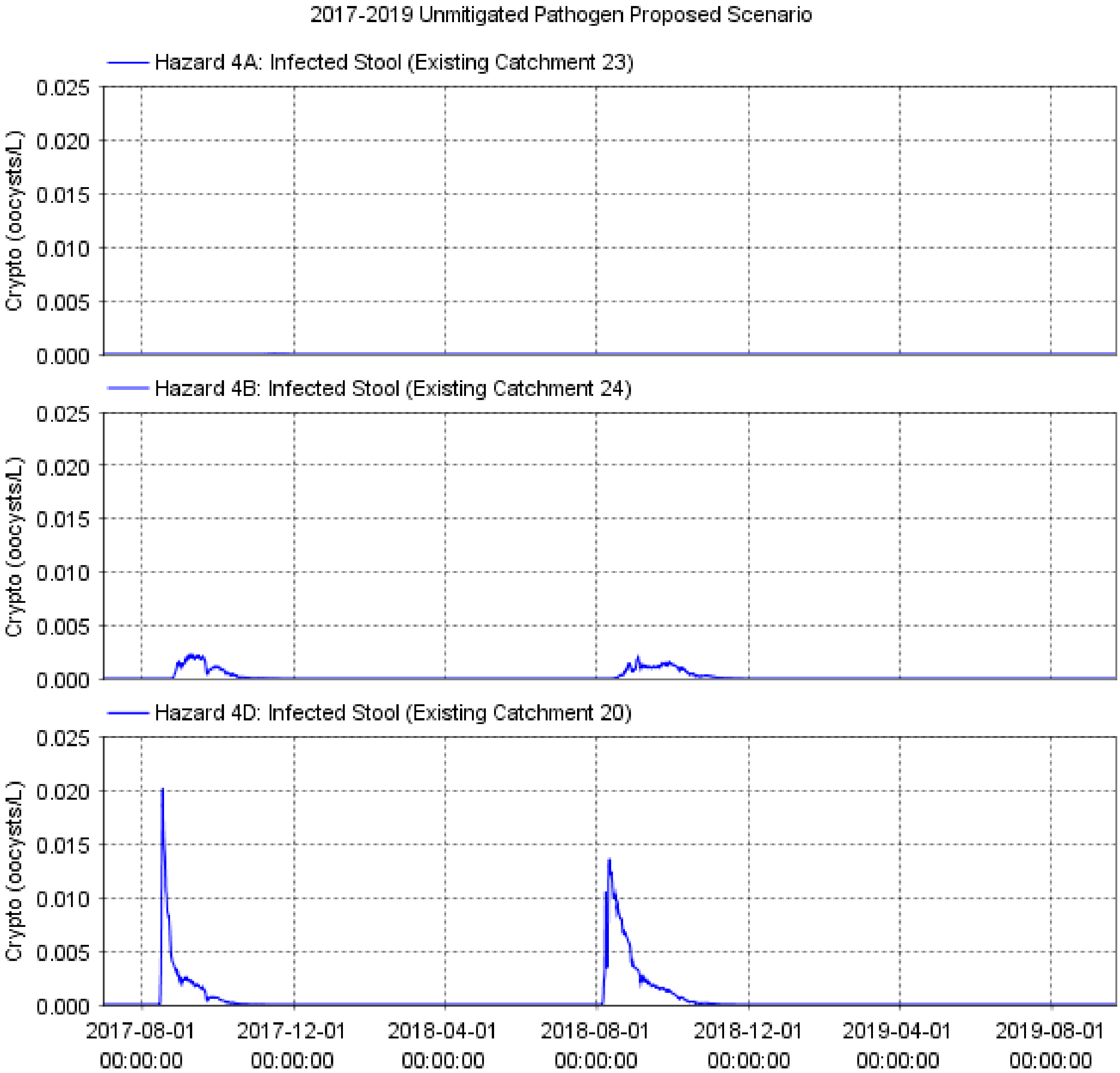

Figure 64 ***Simulated Serpentine Pipehead Dam (SPD) cyrptosporidium withdrawal concentrations of the three relevant incidents for the existing mining scenario over the 2017-2019 simulation period.***

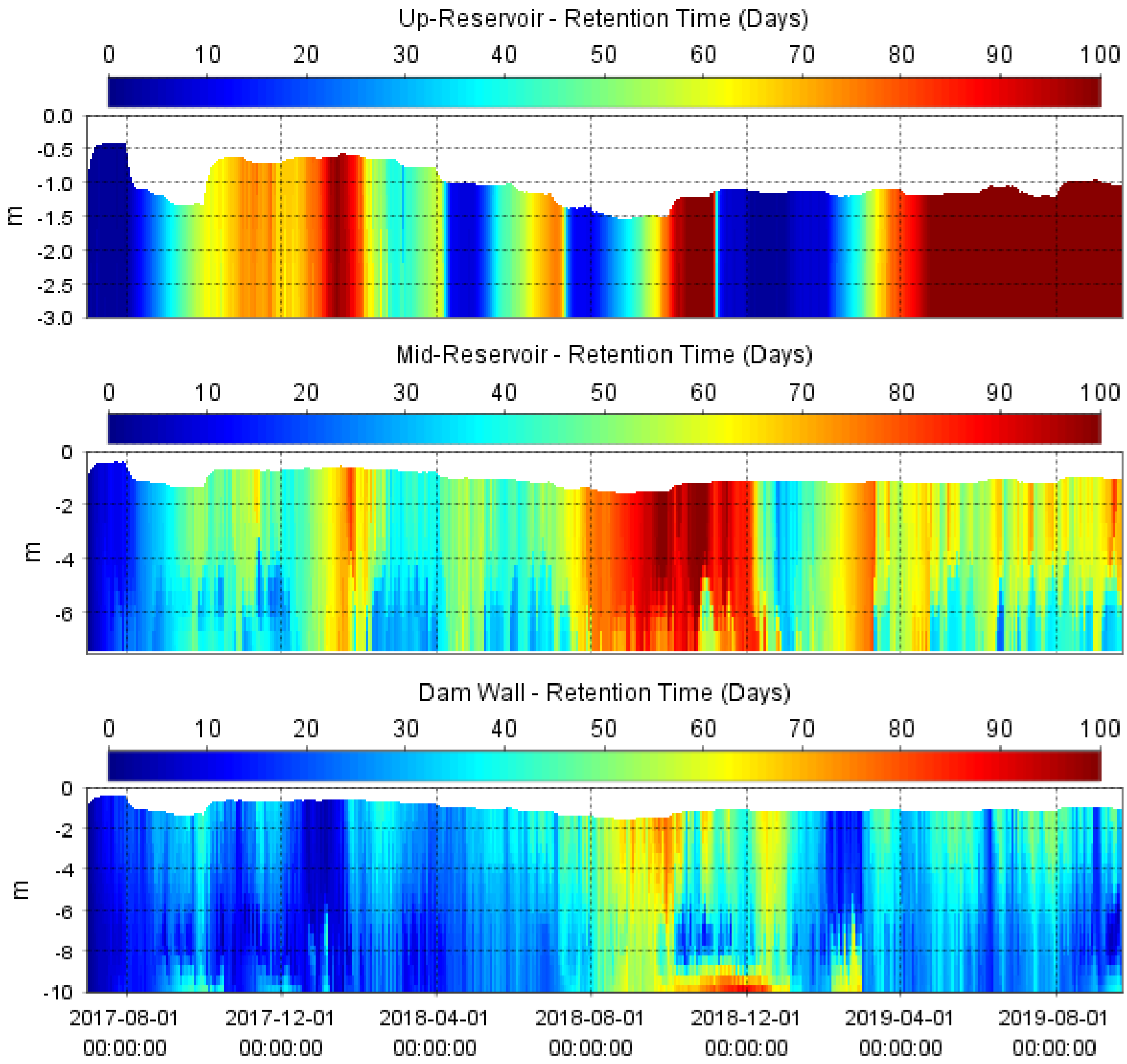

Figure 65 Simulated water age of upper, mid- and near dam Serpentine Pipehead Dam (SPD) assessment sites.

Diesel Spill

Diesel concentrations at the dam wall and withdrawals from spills in the selected SPD existing mining catchments (i.e. haul roads with stream crossings) had similar spatial and temporal patterns (Figure 66 and Figure 67) as the cryptosporidium predictions for hazards 4A (catchment 23) and 4B (catchment 24). The diesel concentrations from a spill in catchment 23 (upper reservoir) had much lower concentrations than those from catchment 24 (mid-reservoir), with the simulated arrival of diesel at the dam wall ~2 months later. As with variations in cryptosporidium, the hydrodynamic barrier effect induced by short-circuiting of the primary inflow (external transfers) and outflow (withdrawals) in the region of the dam effectively decreased the transport and dispersion of diesel from a spill in the upper reservoir catchment. Peak diesel concentrations from a spill in mid-reservoir catchment 24 of 5 µg/L was considerably greater than the peaks of ~1 µg/L for SMD and SDD. However, the spill in SPD catchment 23 had a similar peak of ~1.5 µg/L in the withdrawals as the much larger SMD and SDD reservoirs. Because of SPD's relatively small volume and high outflow, diesel levels were predicted to decrease to ~0 µg/L within ~10-12 months of the spill. As noted in section 5.1.2, simulated diesel concentrations do not account for any fate losses due to volatilisation, degradation or settling to adhered particles (i.e. diesel modelled as a conservative tracer in the reservoir).

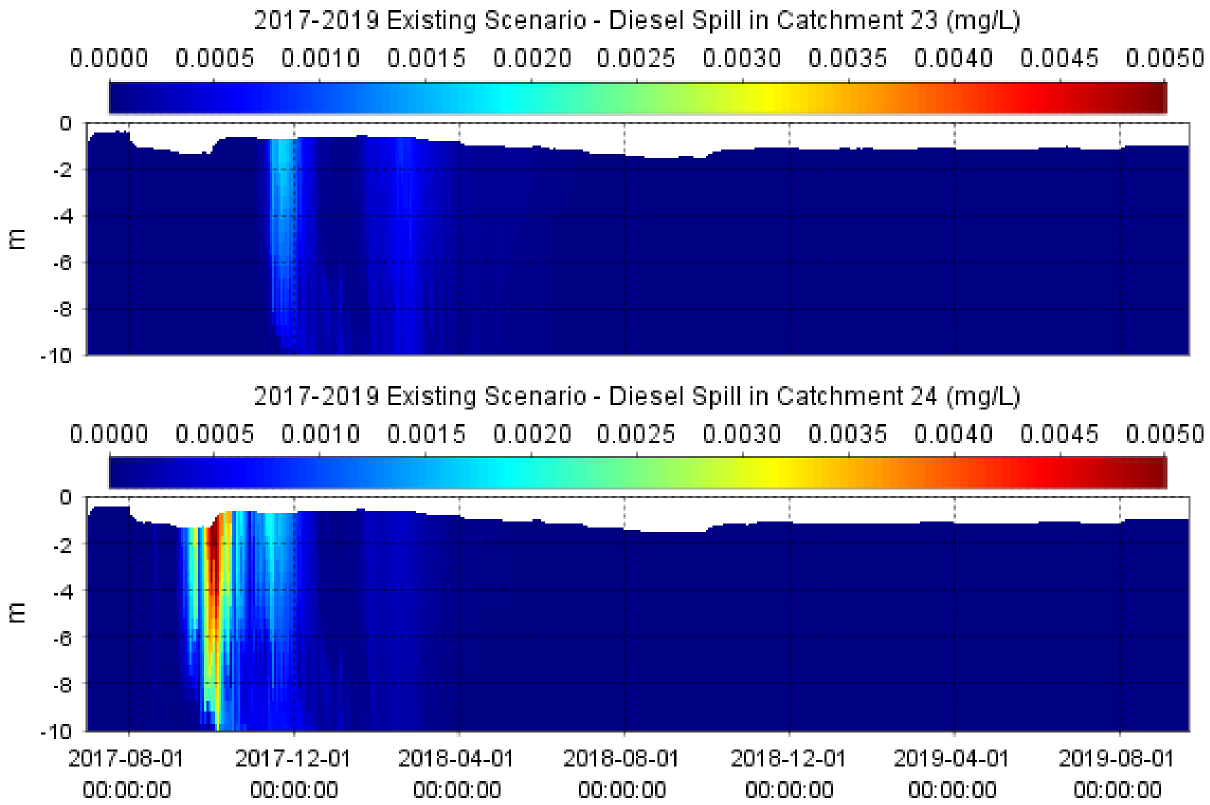

Figure 66 ***Isopleths of diesel concentration near the Serpentine Pipehead (SPD) dam wall of spills for the existing mining scenario over the 2017-2019 simulation period.***

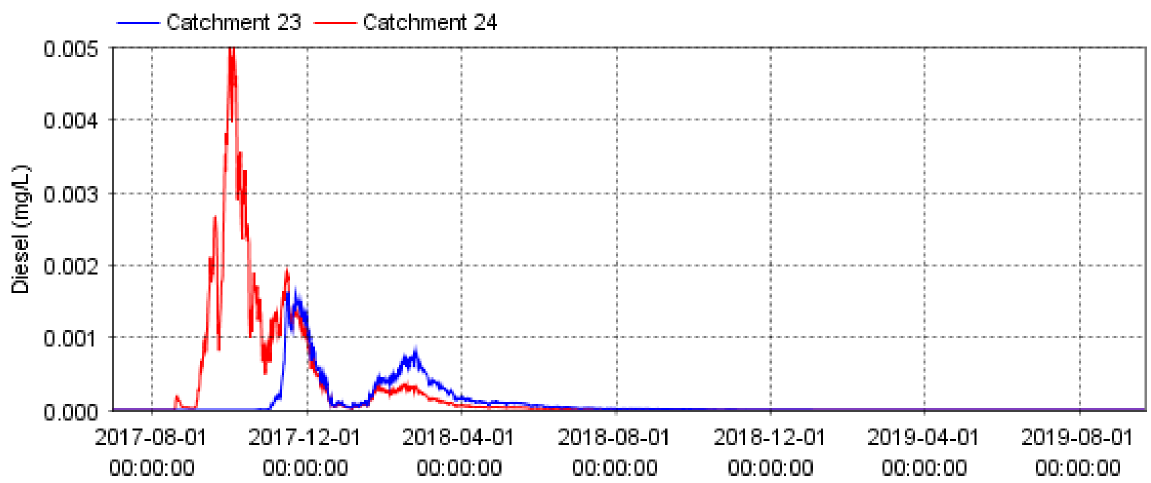

Figure 67 ***Diesel concentrations of Serpentine Pipehead Dam (SPD) withdrawals of spills occuring for the existing mining scenario over the 2017-2019 simulation period.***

5.4.2 1% and 10% Annual Exceedance Period (AEP) Winter and Summer Inflow Events (Moderate Drainage Failure Inorganic Suspended Solids [SS] Levels)

Appendix I provides the 1% and 10% AEP flood event model inputs (discharge, SS_{clay} and SS_{silt} concentrations) for SPD assuming moderate drainage failure SS levels, which can be summarised as:

- The total baseline (i.e. un-mined, fully rehabilitated mining and no drainage failures in mined catchments) discharge over the 14 day inflow events were 1,254 ML and 538 ML for the 1% and 10% AEP scenarios, respectively. Both of these volumes are considerably larger than the 2017 and 2018 maximum 14-day totals of 488 ML and 342 ML, respectively.
- An additional 128 ML of discharge was inputted from drainage failures of the 1% AEP inflow event (75% drainage failures) for the proposed mining scenario. For the 10% AEP inflow event (30% drainage failures) an additional 47 ML of discharge was estimated for the proposed mining scenario.
- All of the baseline (no mining) scenarios had SS_{clay} and SS_{silt} catchment concentrations representative of the natural catchment of 5 and 15 mg/L, respectively, as no drainage failures with associated higher SS levels were assumed.
- Depending on the proportion of the catchment area for the existing mining scenario, the SS_{clay} catchment concentrations ranged from ~6-12 mg/L.

Inspection of the scenario simulations at the upper, mid- and near-dam locations in Appendix J[16] illustrate the following:

- As the SDD scenarios, the SPD scenarios did not predict any material differences in the 1% and 10% AEP summer and winter inflow events between the baseline and existing scenarios (note no proposed mining scenario for SPD). The hydrodynamic barrier effect induced by the SPD primary inflow and outflow in proximity to the dam wall increases the duration for settling to occur prior to transport of the clay particles to the dam wall. Further, the high external transfers with assumed low SS levels effectively dilutes elevated catchment particles as they are transported to the dam wall.
- As with the 2017-2019 scenarios, elevated SS_{silt} for all scenarios was of short duration due to relatively rapid settling. The duration of elevated SS was primarily due to clay particles.

A summary of the simulated total silt and clay SS in the SPD withdrawals is provided as time series in Figure 68 and percentile distributions over two one year periods (August 2017 to July 2018 for winter scenarios and January to December 2018 for summer scenarios) in Figure 69. The simulated SS (silt + clay) concentrations in the withdrawals predict minimal variations between the baseline and proposed scenarios for the 1% and 10% AEP inflow events. In short, SS variations from existing SPD mining activity is predicted to not cause large relative changes between the baseline and existing scenarios, even for the 1% AEP inflow events. A combination of the hydrodynamic barrier effect discussed previously on retarding the transport of SS loads from the mid-reservoir (catchment 24) and upper reservoir (catchment 23) catchment confluences, and dilution with the low SS external transfers near the dam wall contribute to the predicted minimal effect on inorganic particle levels relative to the baseline.

The relative changes to the baseline SPD withdrawal SS (SS_{clay}+ SS_{silt}) concentrations over 1 year after the winter and summer 1% and 10% AEP inflow events are summarised in Table 15. This summary table provides the predicted relative changes to SPD withdrawal SS from the proposed mining scenarios with moderate drainage failure SS levels to inform the GHD (2012a) drinking water risk assessment.

[16] Appendix J shows the simulated water levels for the scenario and monthly Water Corporation measurements for comparison (not verification).

Table 15 ***Summary of simulated increases in Serpentine Pipehead Dam (SPD) withdrawal inorganic suspended solids (SS) (mg/L) for existing and proposed mining scenarios relative to baseline scenarios over 1 year after winter and summer 1% and 10% Annual Exceedance Period (AEP) inflow events with moderate drainage failure SS levels.***

Statistic	1% AEP Summer Existing Scenario	10% AEP Summer Existing Scenario	1% AEP Winter Existing Scenario	1% AEP Winter Existing Scenario
Maximum	0.23	0.07	0.19	0.15
99th percentile (~4 cumulative days over 1 year)	0.09	0.04	0.17	0.10
95th percentile (~20 cumulative days over 1 year)	0.07	0.04	0.15	0.08
80th percentile (~70 cumulative days over 1 year)	0.04	0.02	0.06	0.03

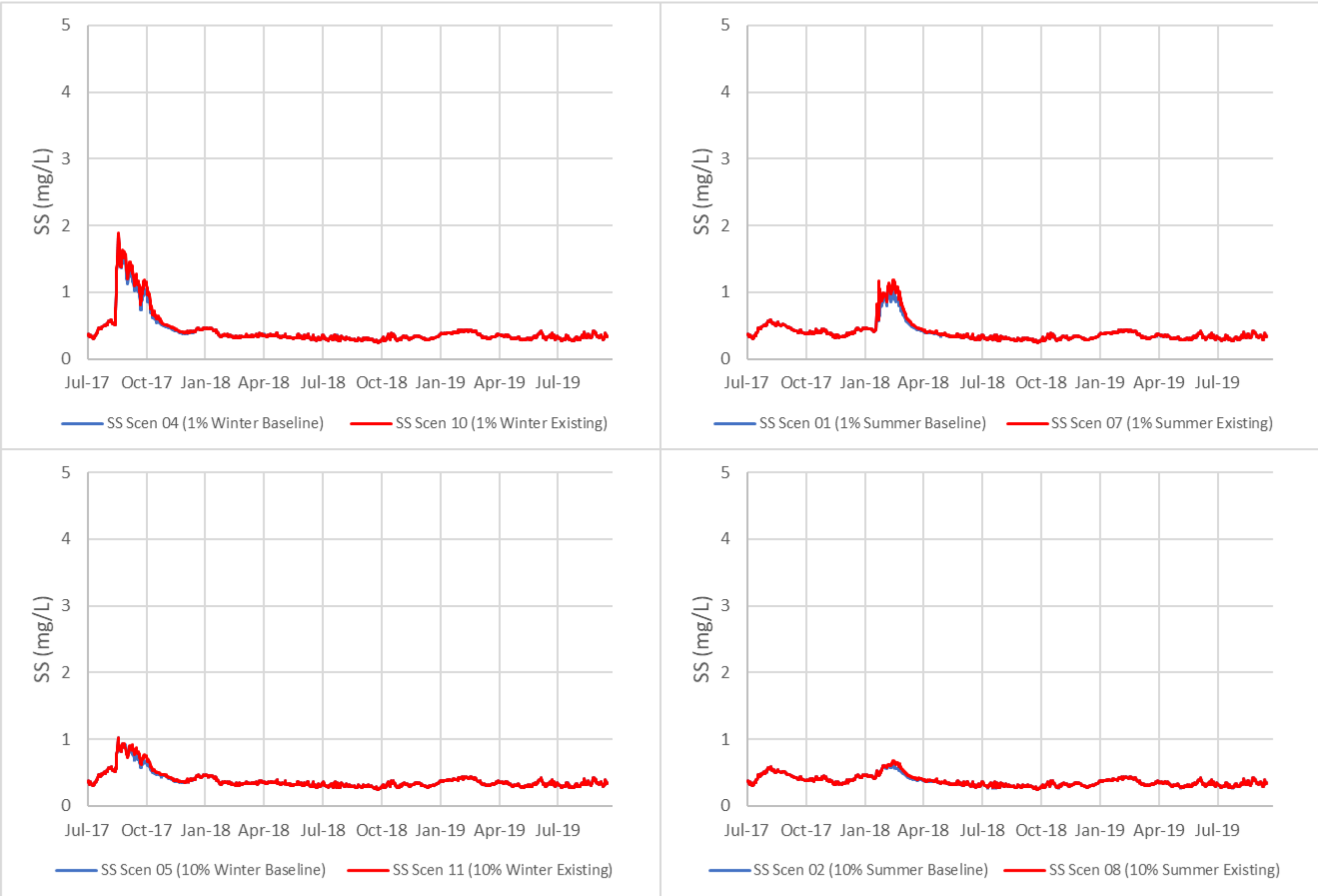

Figure 68 ***Time series of simulated Serpentine Pipehead Dam (SPD) withdrawal inorganic suspended solids (SS [silt + clay]) of winter and summer 1% and 10% Annual Exceedance Period [AEP] inflow events with moderate drainage failure SS levels.***

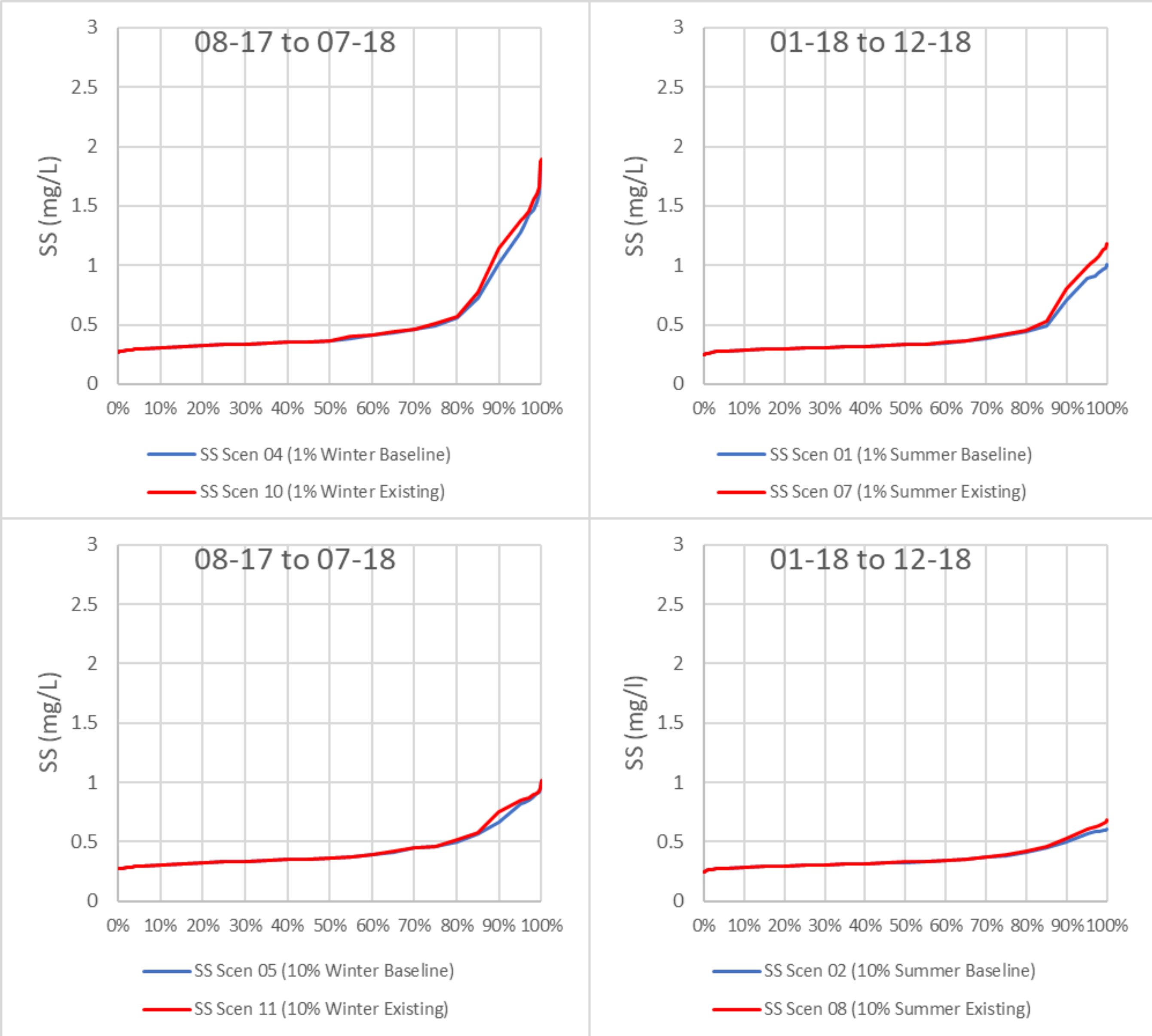

Figure 69 ***Percentile plots of simulated inorganic supended solids (SS [silt + clay]) of winter and summer 1% and 10% Annual Exceedance Period (AEP) inflow events with moderate drainage failure SS levels.***

5.4.3 1% and 10% Annual Exceedance Period (AEP) Winter and Summer Inflow Events (High Drainage Failure Inorganic Suspended Solids [SS] Levels)

Appendix K provides the 1% and 10% 7-day AEP flood model event inputs (discharge, SS_{clay} and SS_{silt} concentrations) for SPD assuming high drainage failure SS levels (i.e. higher drainage SS of 63 mg/L rather than 31.5 mg/L for the proposed scenarios). Appendix L presents graphical summaries of the simulated SS_{Clay} and SS_{Silt} at the dam wall and up-reservoir locations, and in the withdrawals from the intake tower[17] for these two scenarios with ineffective drainage turbidity management.

A summary of the simulated total silt and clay SS in the SPD withdrawals is provided as time series in Figure 70 and percentile distributions over two one year periods (August 2017 to July 2018 for winter scenarios and January to December 2018 for summer scenarios) in Figure 71 for the existing scenarios with ineffective drainage turbidity management. The simulated SS (silt + clay) concentrations in the withdrawals predict minimal variations between the baseline and existing scenarios. A combination of the hydrodynamic barrier of the mid-reservoir (catchment 24) and upper reservoir (catchment 23) catchment confluences and dilution with the low SS external transfers near the dam wall contribute to this prediction of minimal effect relative to the baseline.

The relative changes to the baseline SPD withdrawal SS (SS_{clay}+ SS_{silt}) concentrations over 1 year after the winter and summer 1% and 10% AEP inflow events are summarised in Table 16. This summary table provides the predicted relative changes to SPD withdrawal SS from the proposed mining scenarios with high drainage failure SS levels to inform the GHD (2012a) drinking water risk assessment.

Table 16 Summary of simulated increases in Serpentine Pipehead Dam (SPD) withdrawal inorganic suspended solids (SS) (mg/L) for existing and proposed mining scenarios relative to baseline scenarios over 1 year after winter and summer 1% and 10% Annual Exceedance Period (AEP) inflow events with high drainage failure SS levels.

Statistic	1% AEP Summer Existing Scenario	10% AEP Summer Existing Scenario	1% AEP Winter Existing Scenario	1% AEP Winter Existing Scenario
Maximum	0.23	0.07	0.19	0.15
99th percentile (~4 cumulative days over 1 year)	0.09	0.04	0.17	0.10
95th percentile (~20 cumulative days over 1 year)	0.07	0.04	0.15	0.08
80th percentile (~70 cumulative days over 1 year)	0.04	0.02	0.06	0.03

[17] Appendix L also shows the simulated water levels for the scenario and monthly Water Corporation measurements for comparison (not verification).

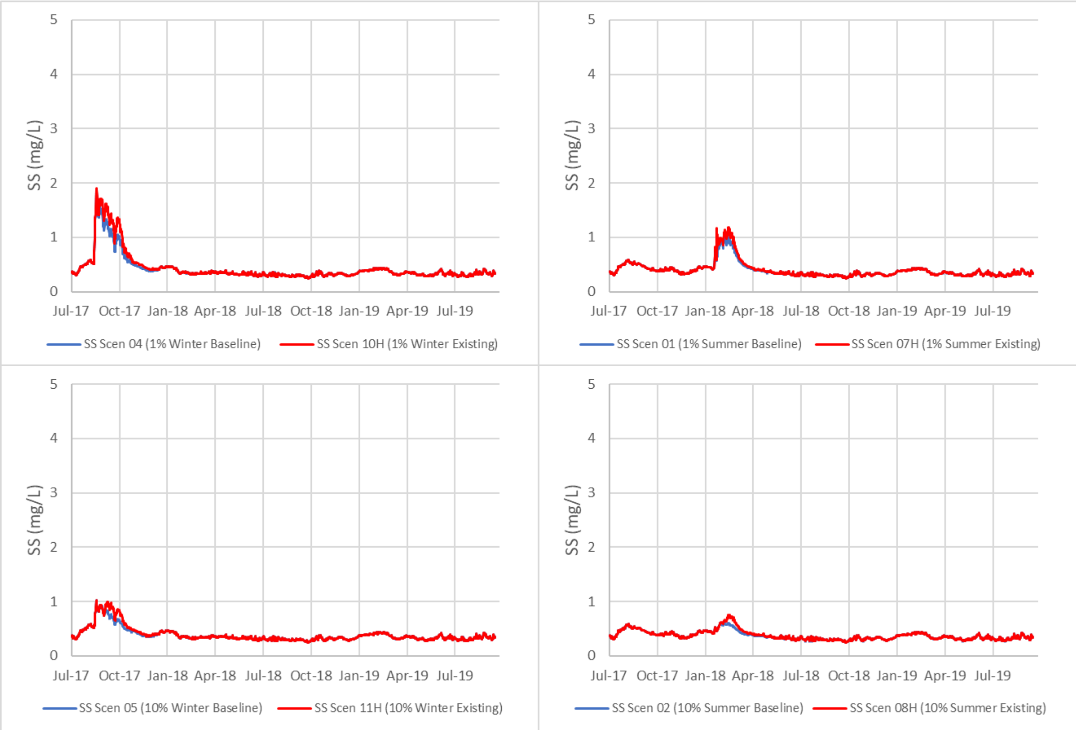

Figure 70 *Time series of simulated Serpentine Pipehead Dam (SPD) withdrawal inorganic suspended solids (SS [silt + clay]) of winter and summer 1% and 10% Annual Exceedance Period [AEP] inflow events with high drainage failure SS levels.*

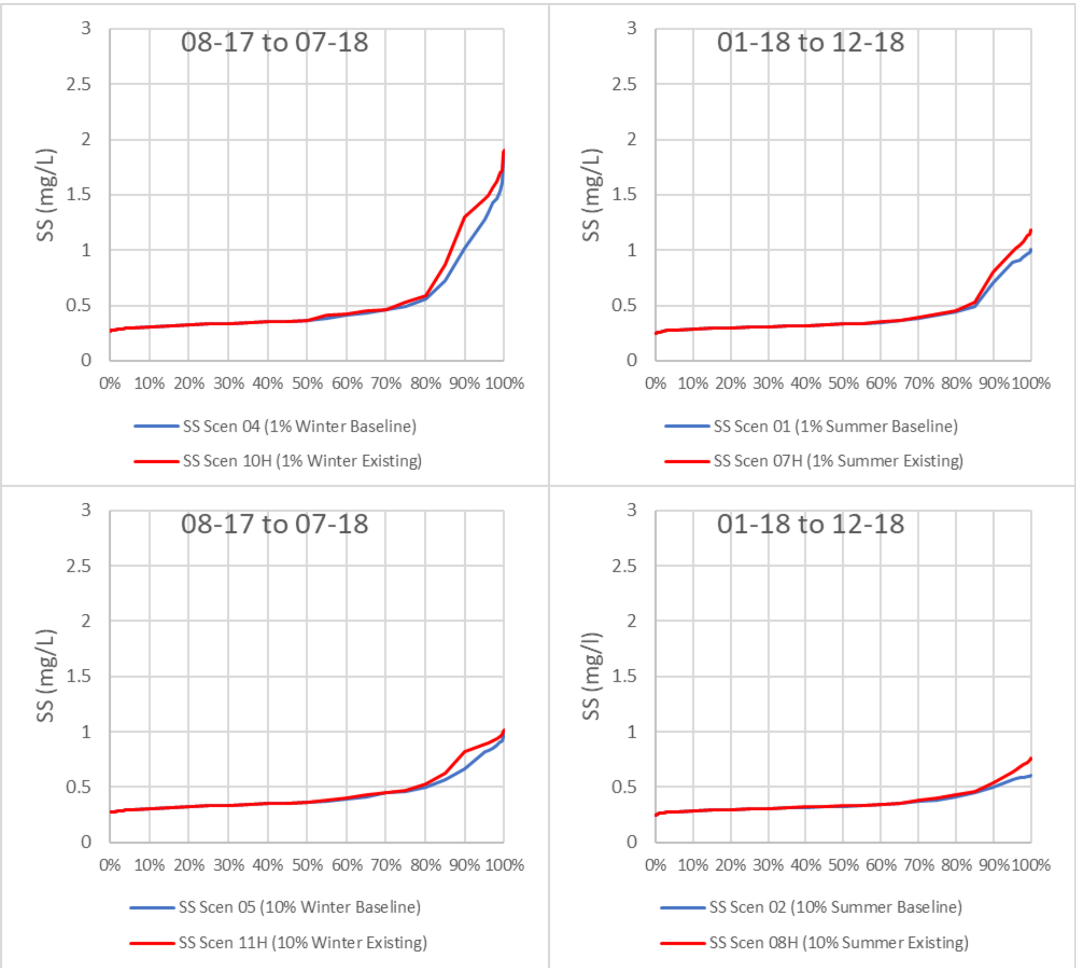

Figure 71 *Percentile plots of simulated inorganic supended solids (SS [silt + clay]) of winter and summer 1% and 10% Annual Exceedance Period (AEP) inflow events with high drainage failure SS levels.*

6. References

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Appendices

Appendix A

SMD: 1% and 10% AEP Flood Event Inputs (Moderate Drainage Failure SS Levels)

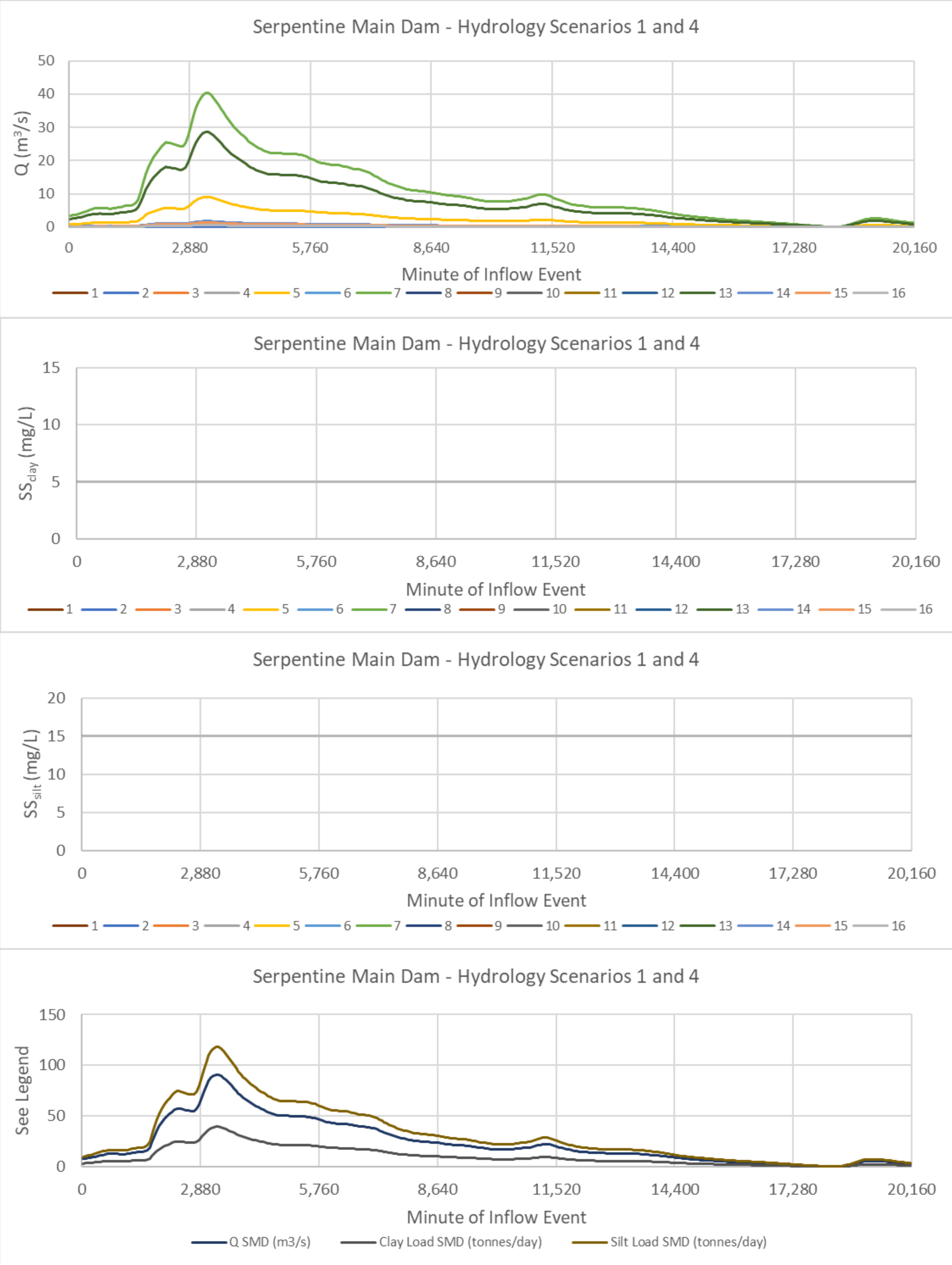

Figure 72 ***SMD hydrology and SS inputs for scenarios 1 and 4.***

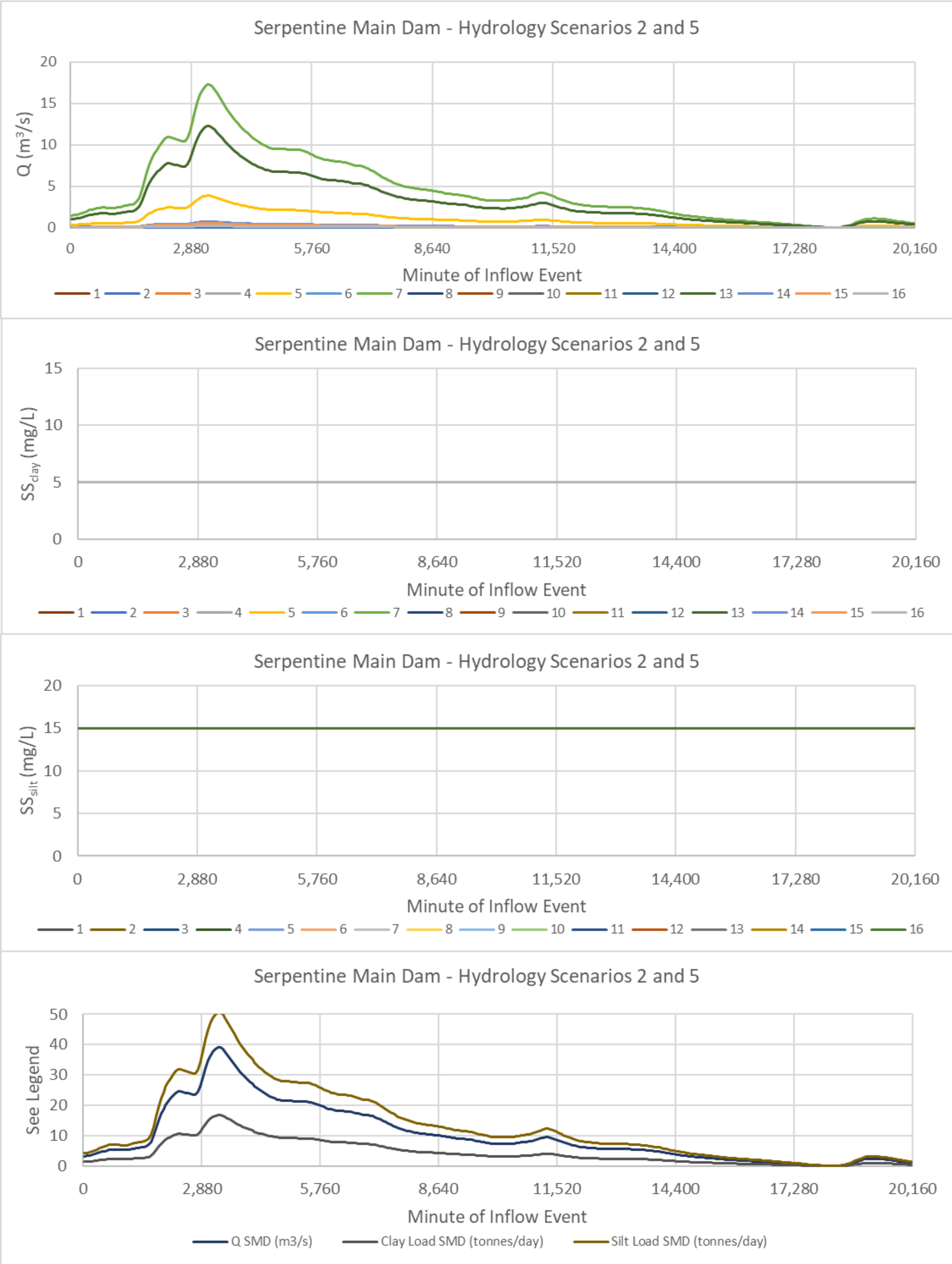

Figure 73 As Figure 72 for scenarios 2 and 5.

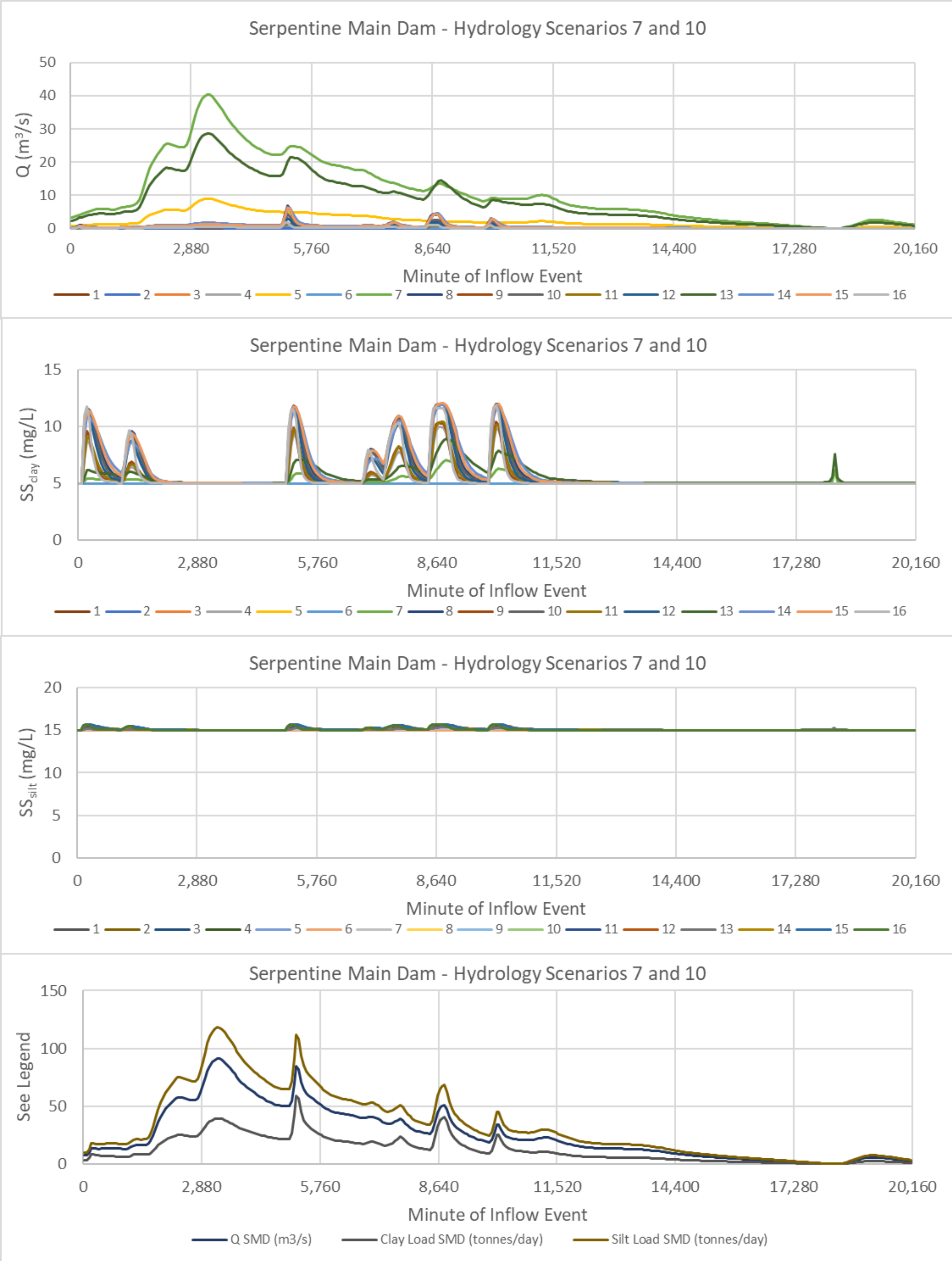

Figure 74 ***As Figure 72 scenarios 7 and 10 with moderate drainage failure SS levels.***

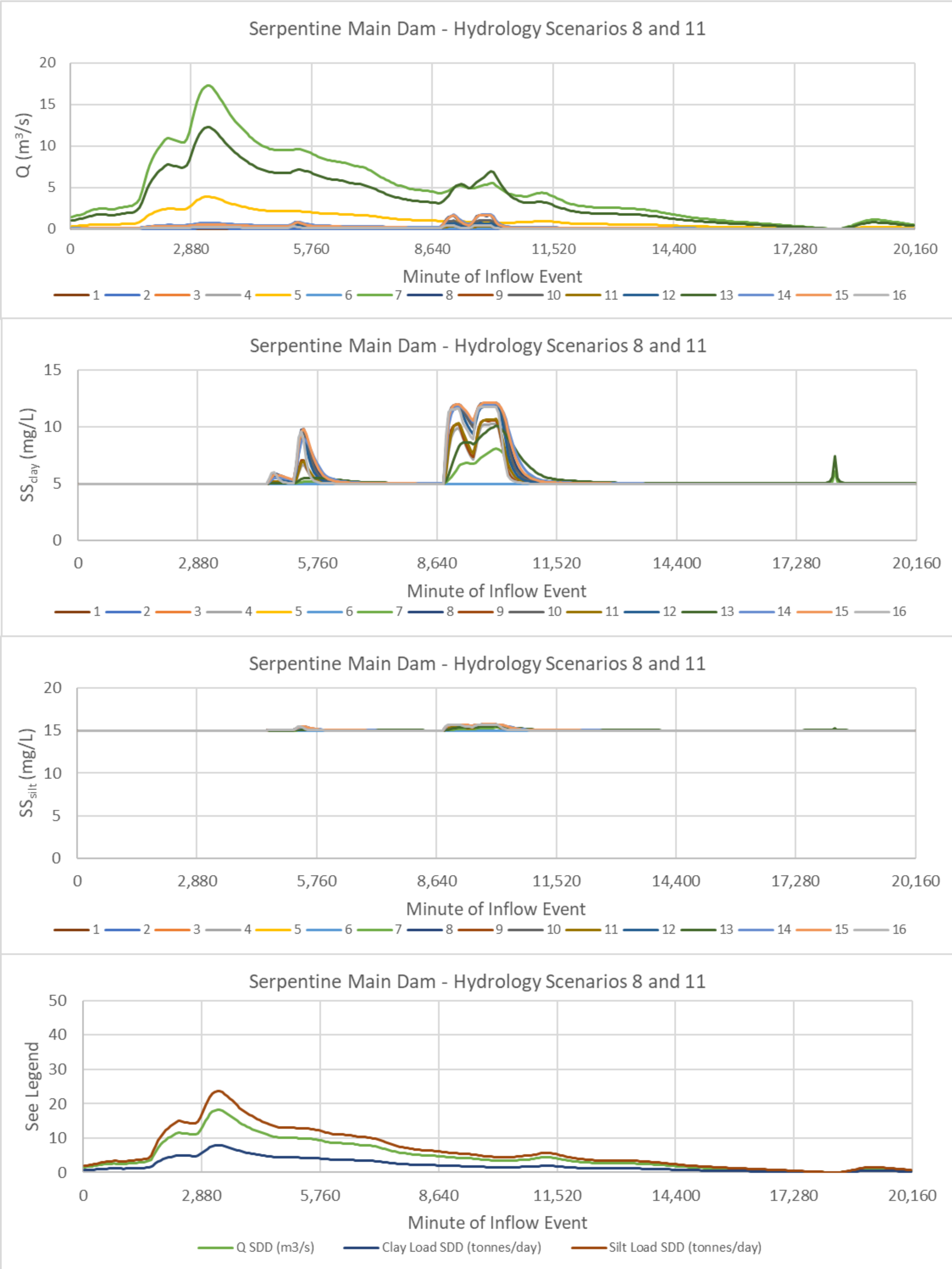

Figure 75 ***As Figure 72 for scenarios 8 and 11 with moderate drainage failure SS levels.***

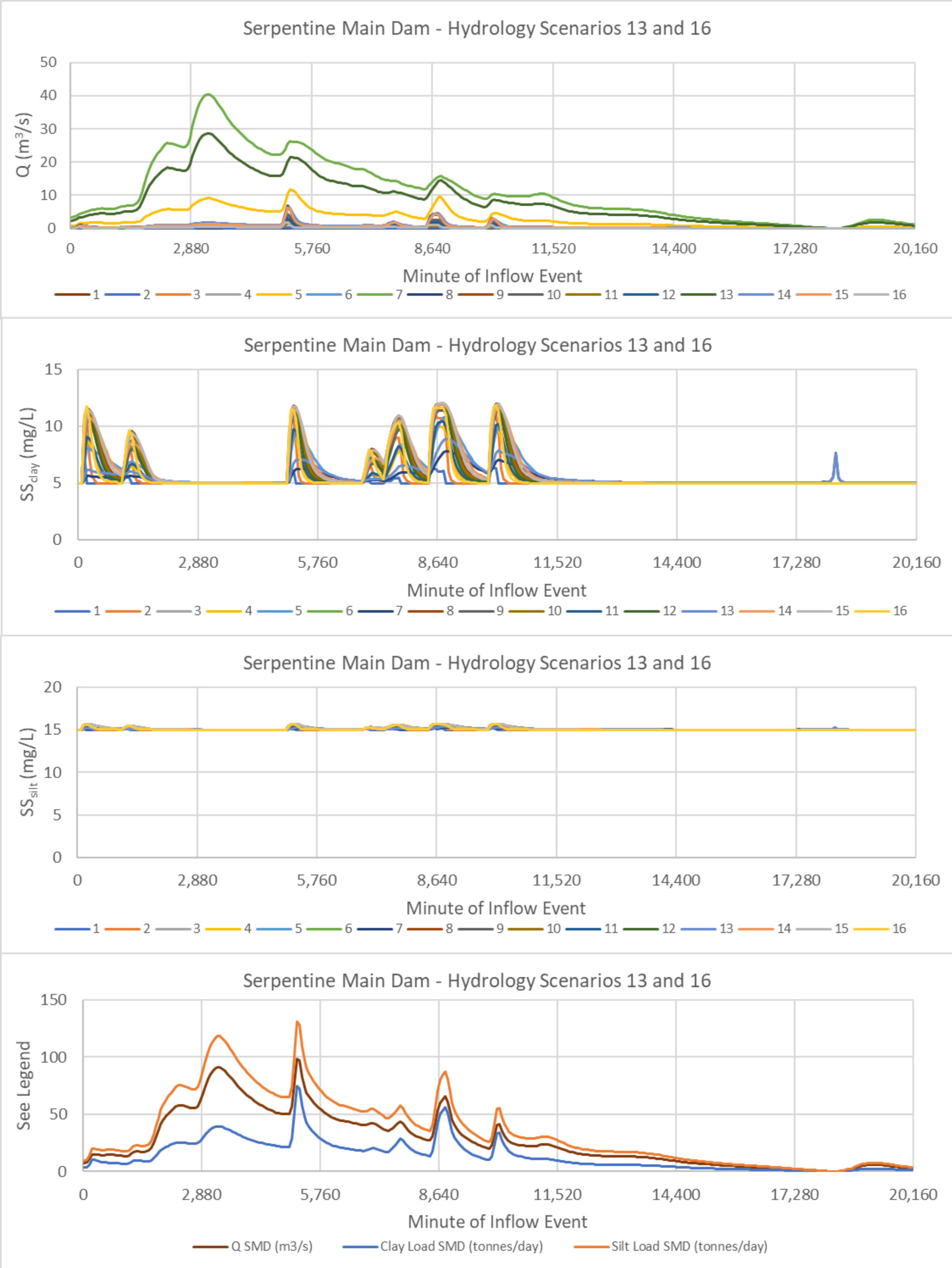

Figure 76 ***As Figure 72 for scenarios 13 and 16 with moderate drainage failure SS levels.***

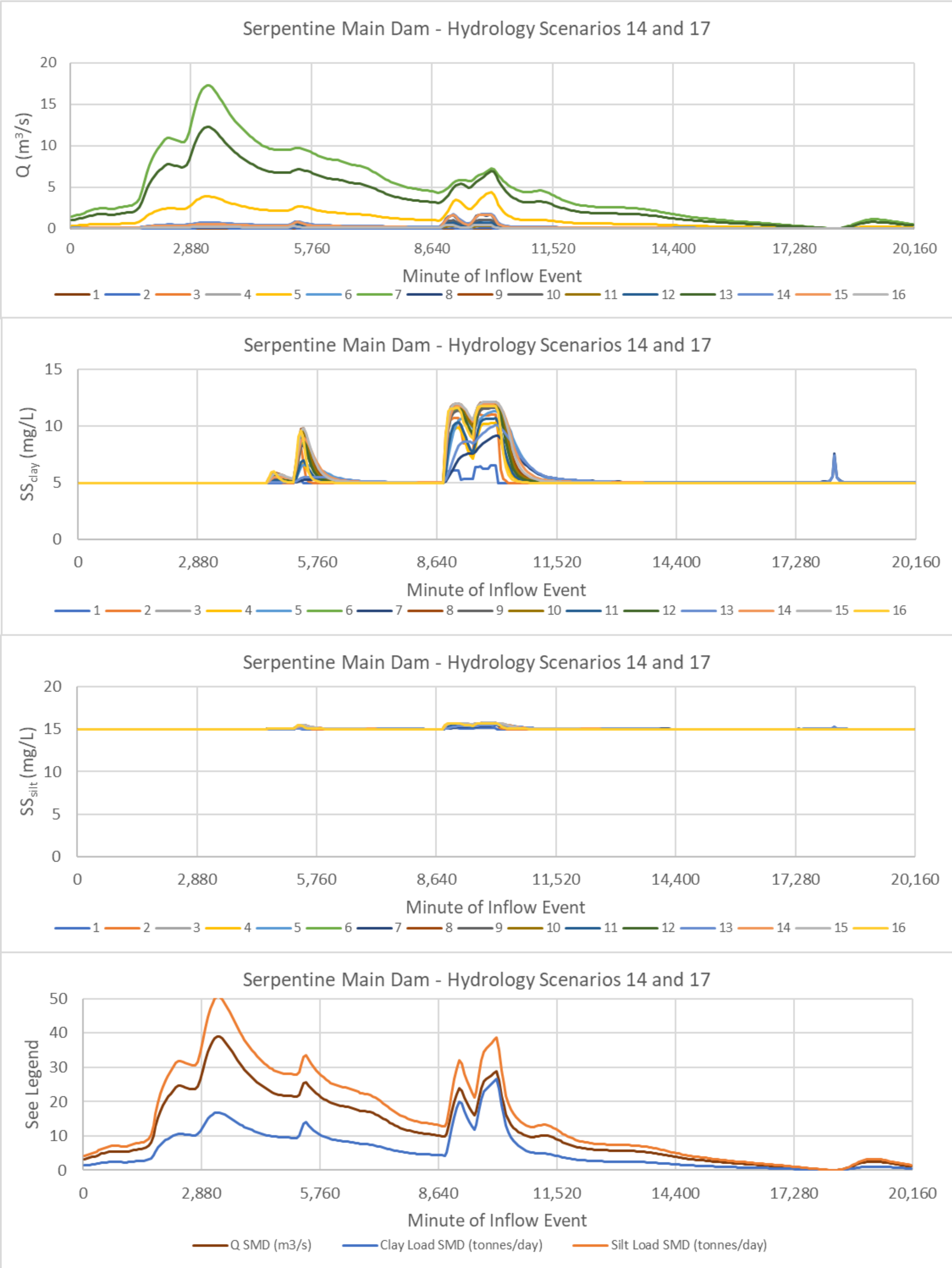

Figure 77 *As Figure 72 for scenarios 14 and 17 with moderate drainage failure SS levels.*

Appendix B

SMD: 1% and 10% AEP Flood Event Simulations (Moderate Drainage Failure SS Levels)

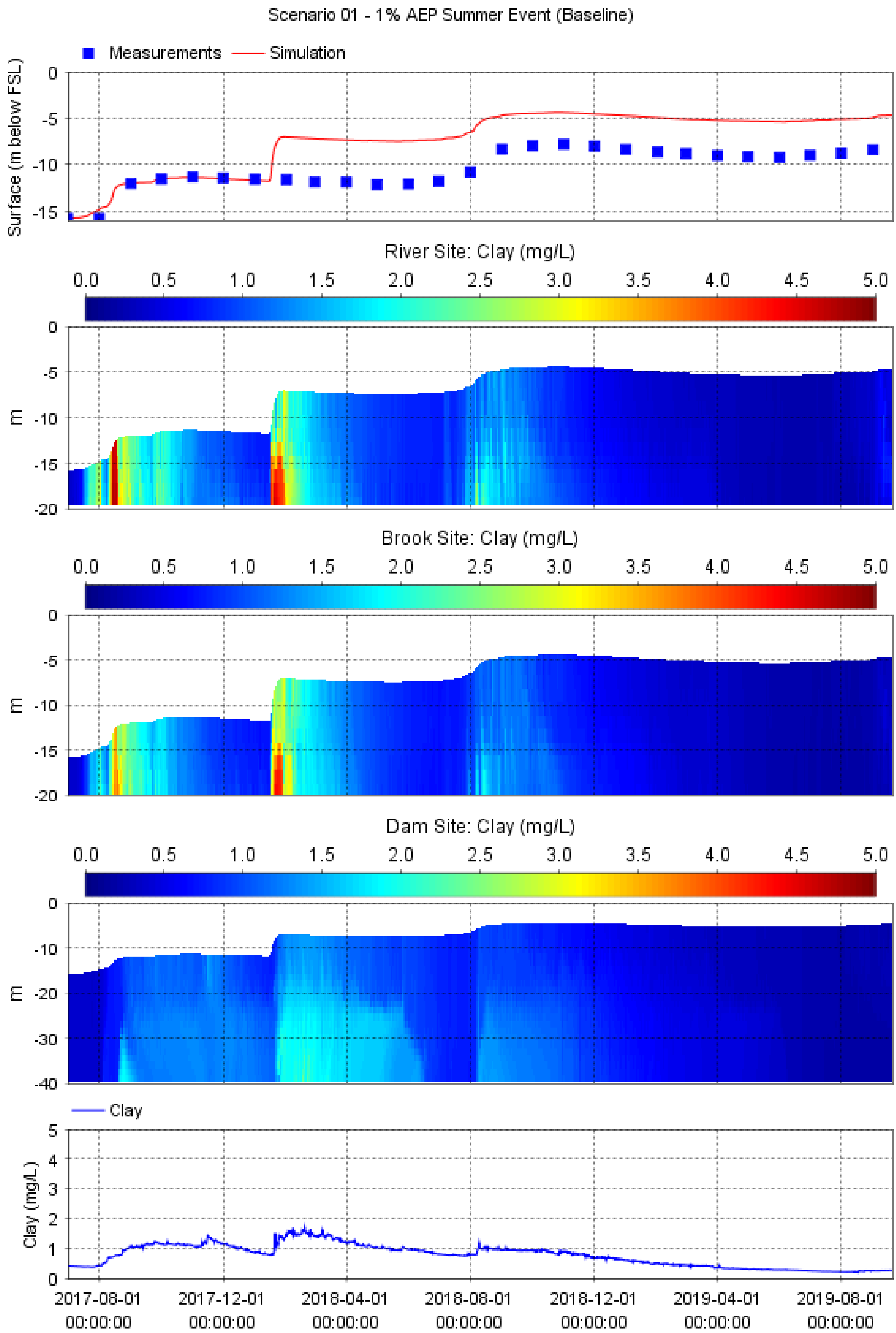

Figure 78 *SMD simulated levels of clay for scenario 1 (summer baseline case 1% AEP flood event).*

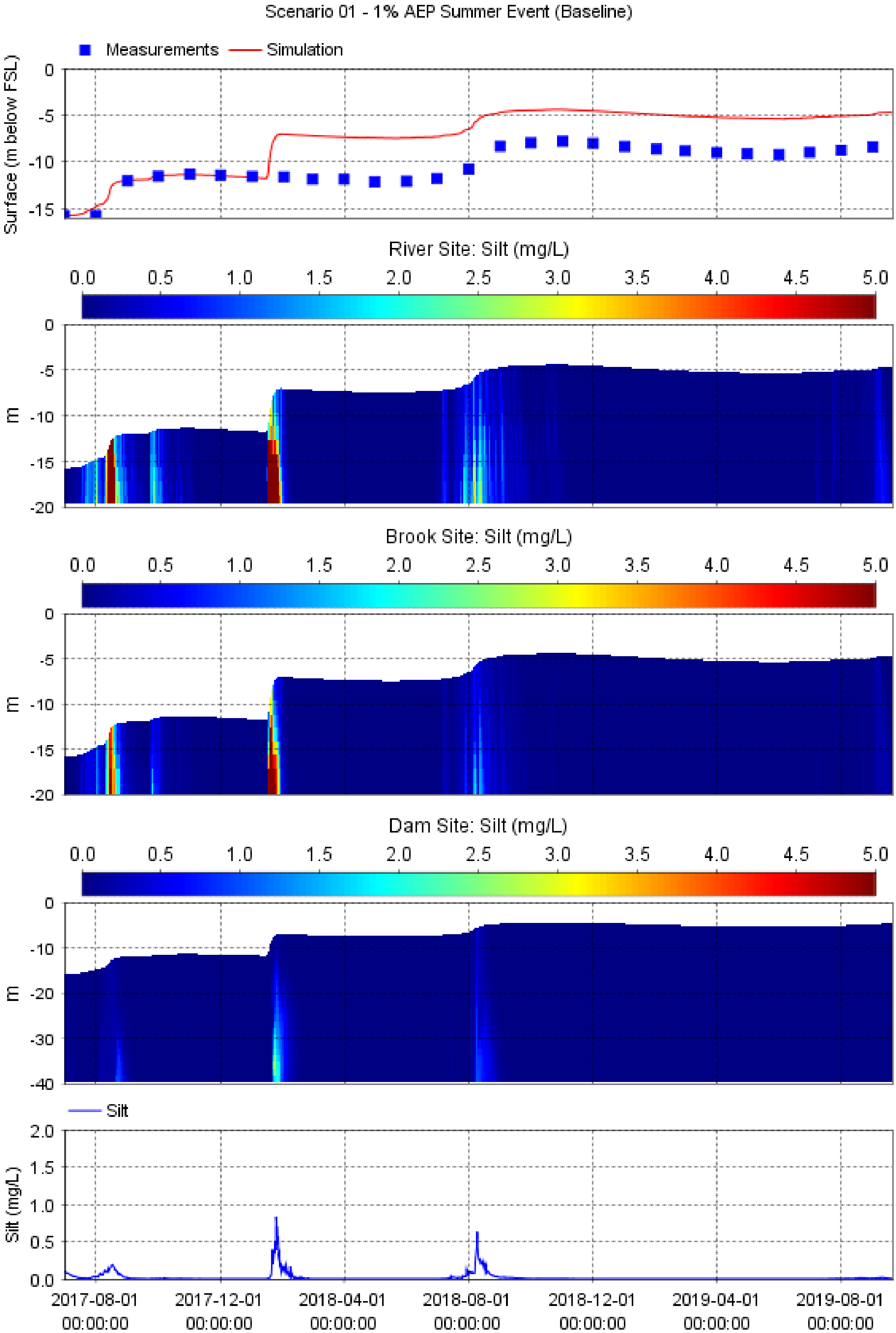

Figure 79 SMD simulated levels of silt for scenario 1 (summer baseline case 1% AEP flood event).

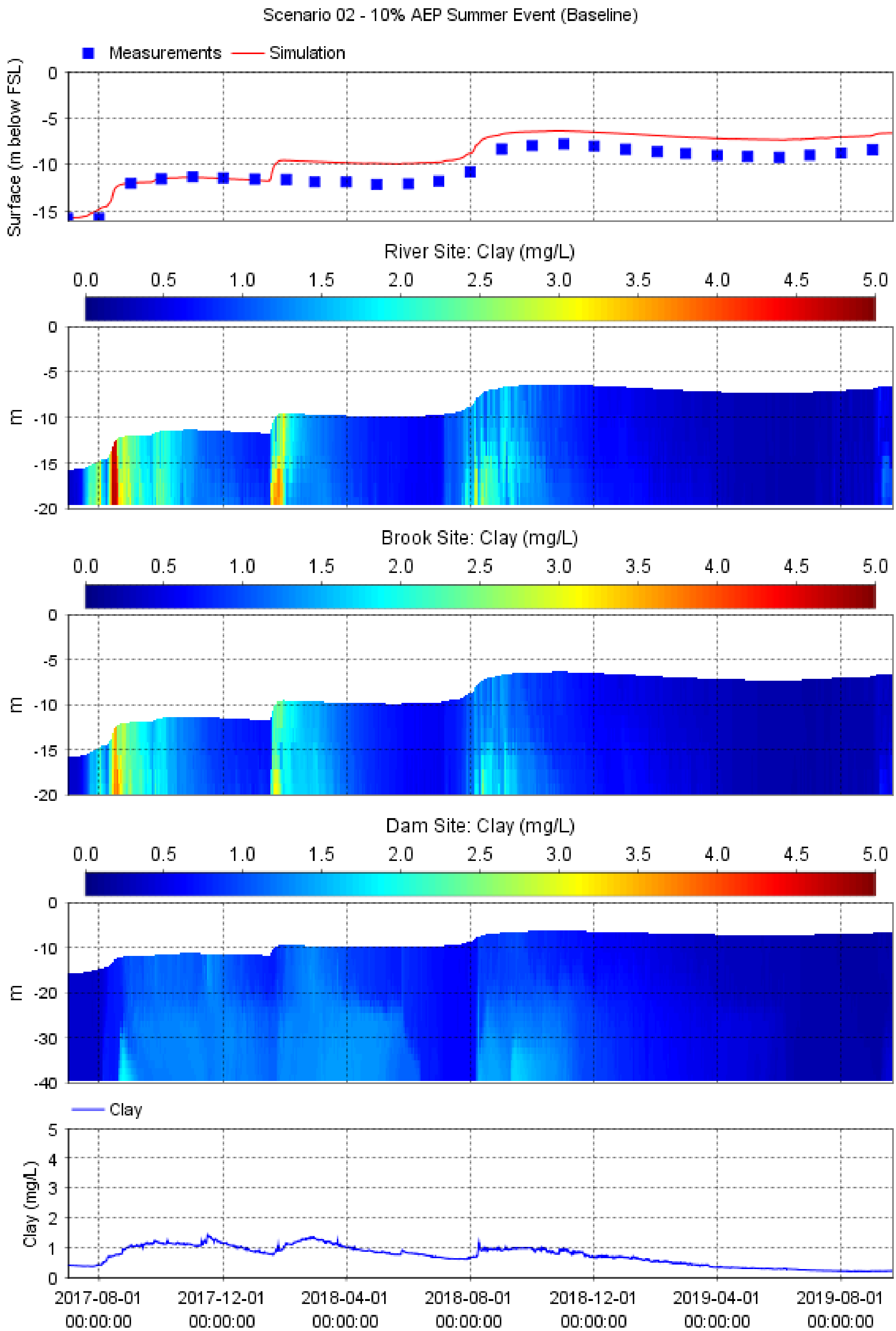

Figure 80 SMD simulated levels of clay for scenario 2 (summer baseline case 10% AEP flood event).

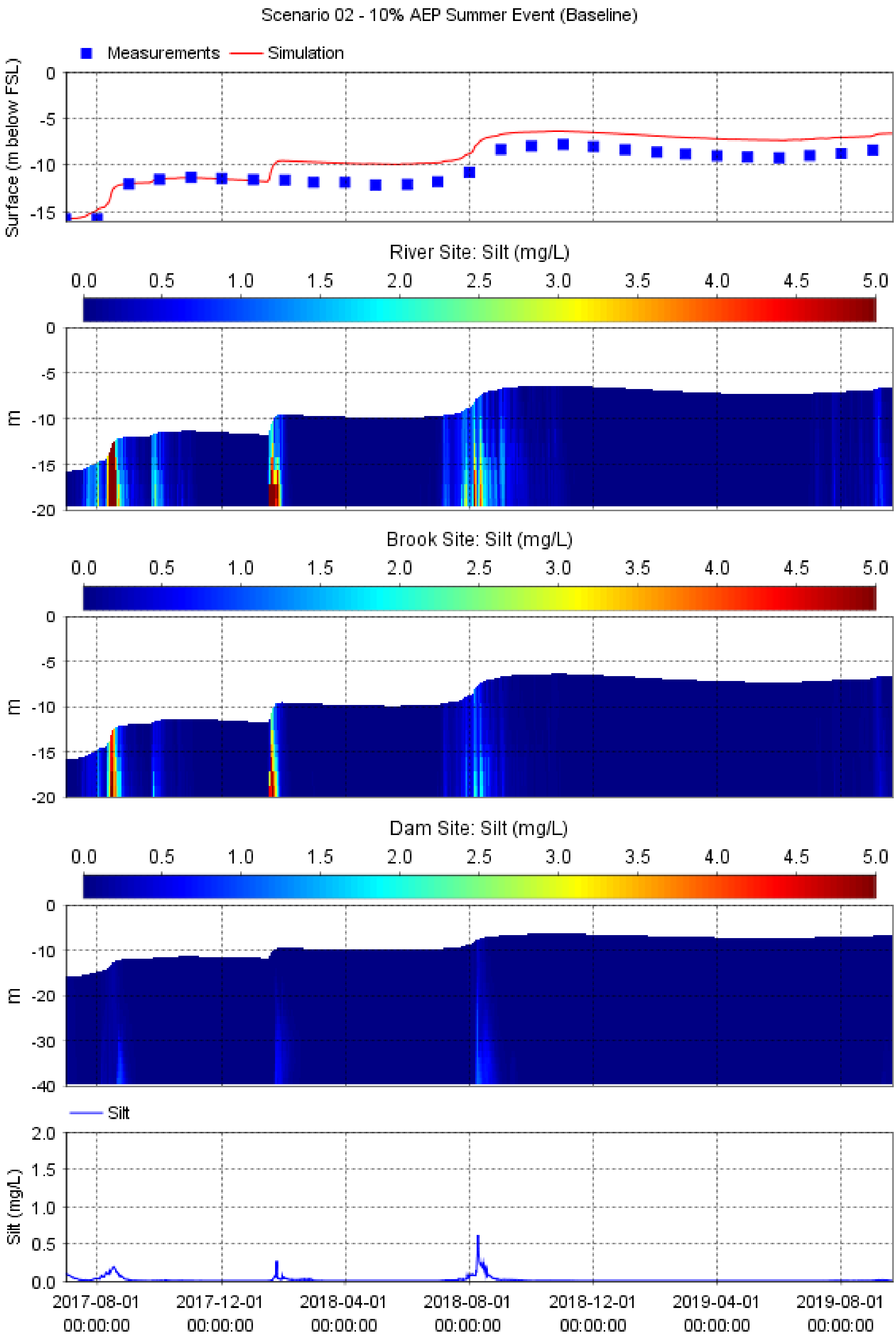

Figure 81 ***SMD simulated levels of silt for scenario 2 (summer baseline case 10% AEP flood event).***

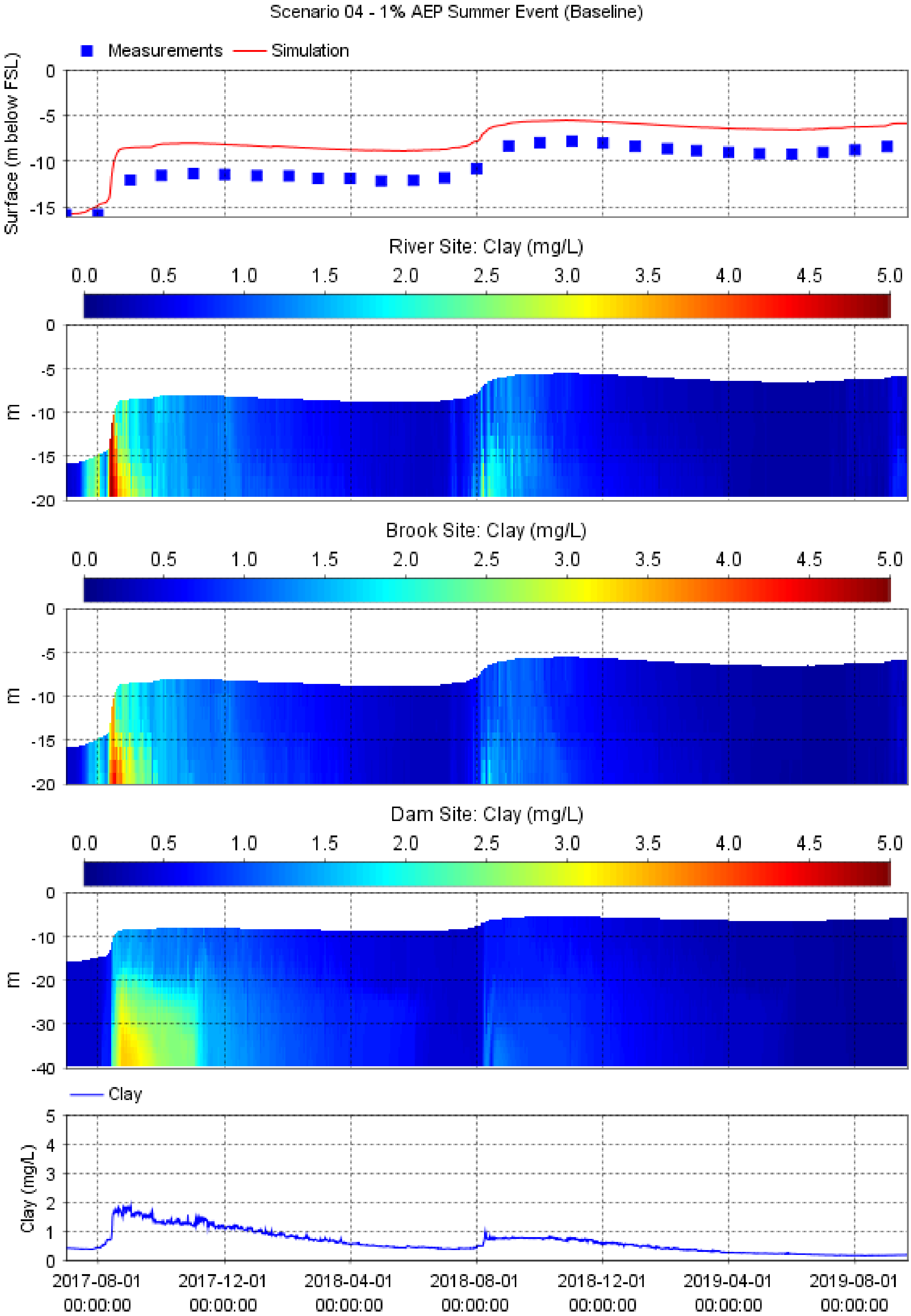

Figure 82 ***SMD simulated levels of clay for scenario 4 (winter baseline case 1% AEP flood event).***

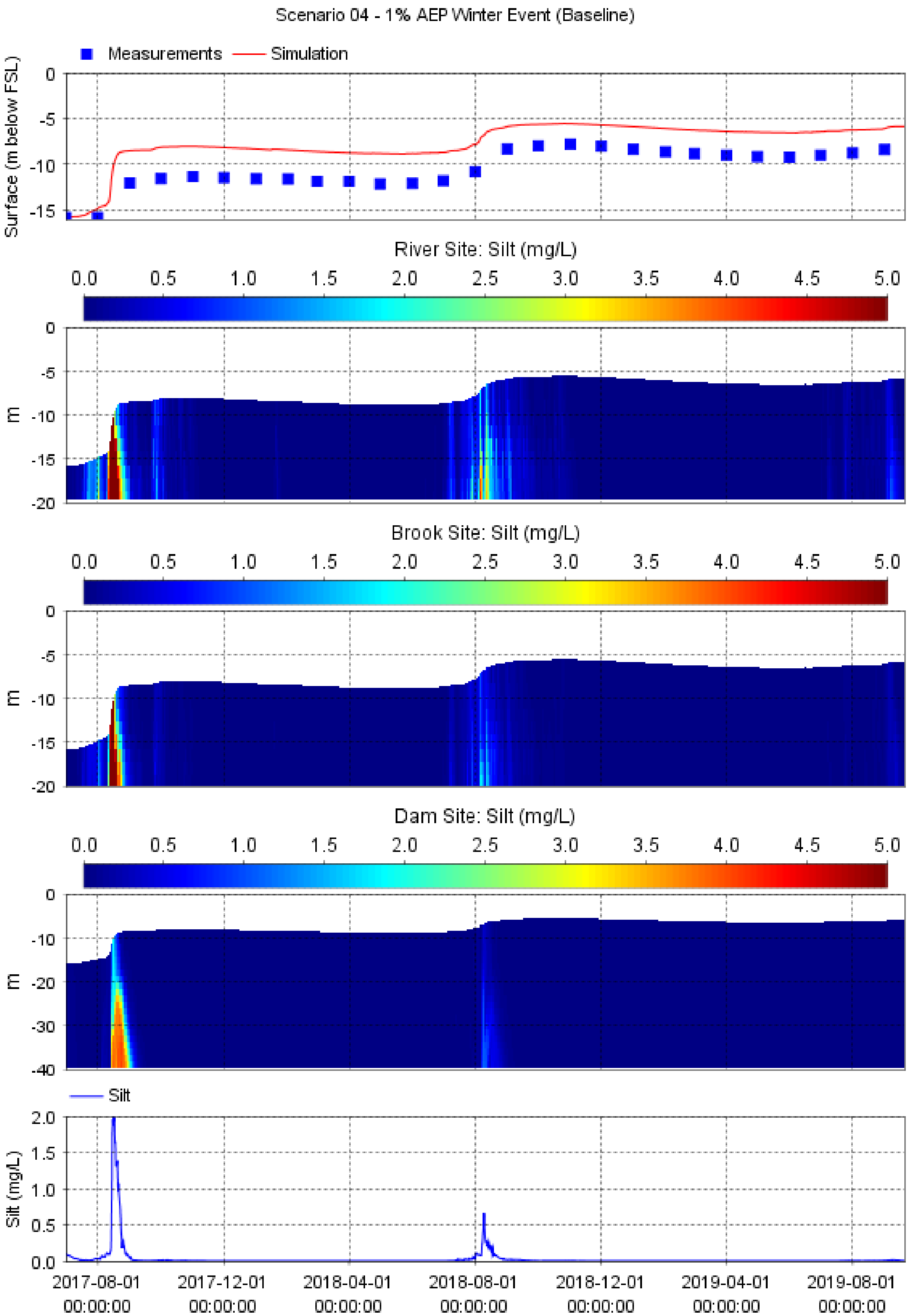

Figure 83 SMD simulated levels of silt for scenario 4 (winter baseline case 1% AEP flood event).

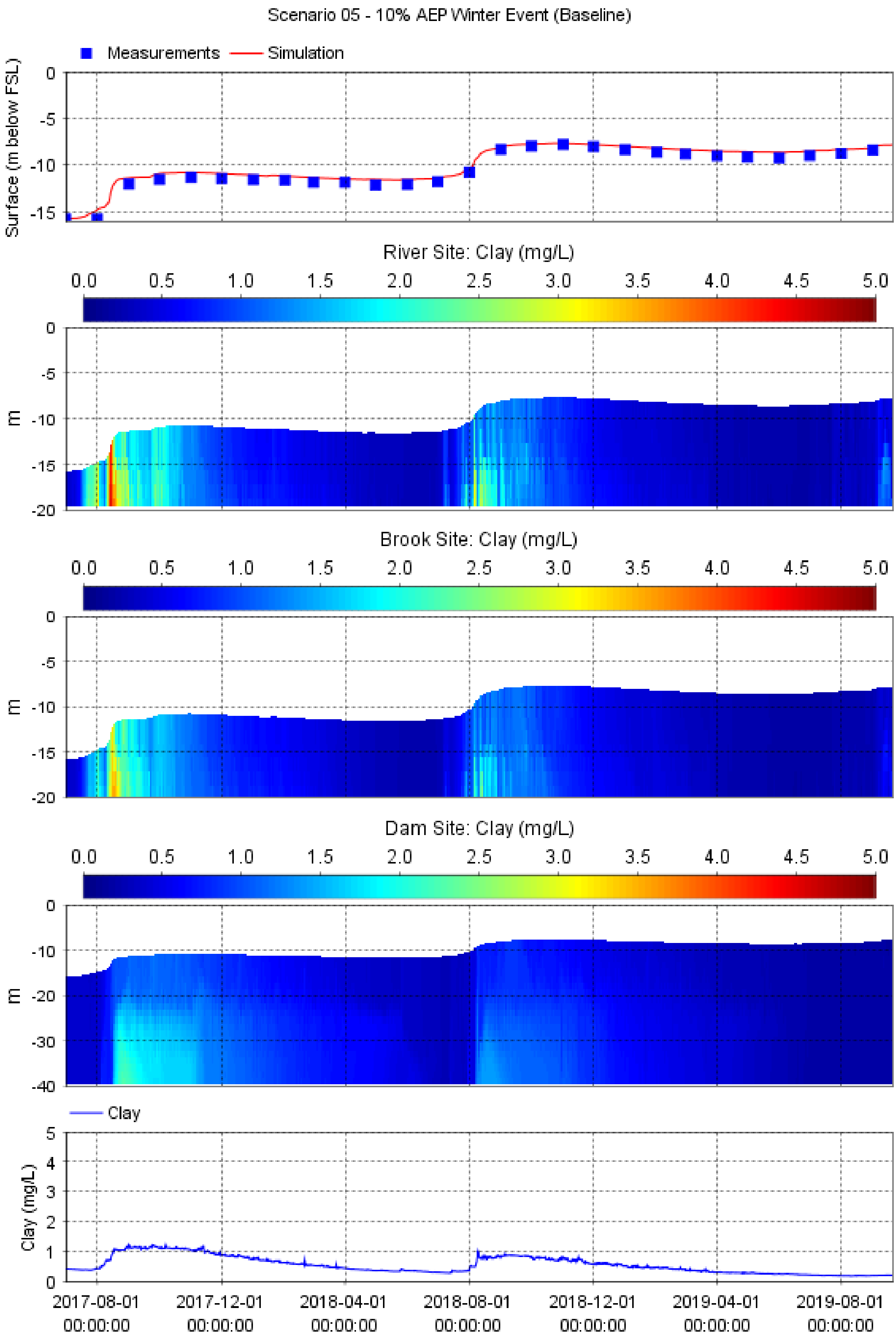

Figure 84 ***SMD simulated levels of clay for scenario 5 (winter baseline case 10% AEP flood event).***

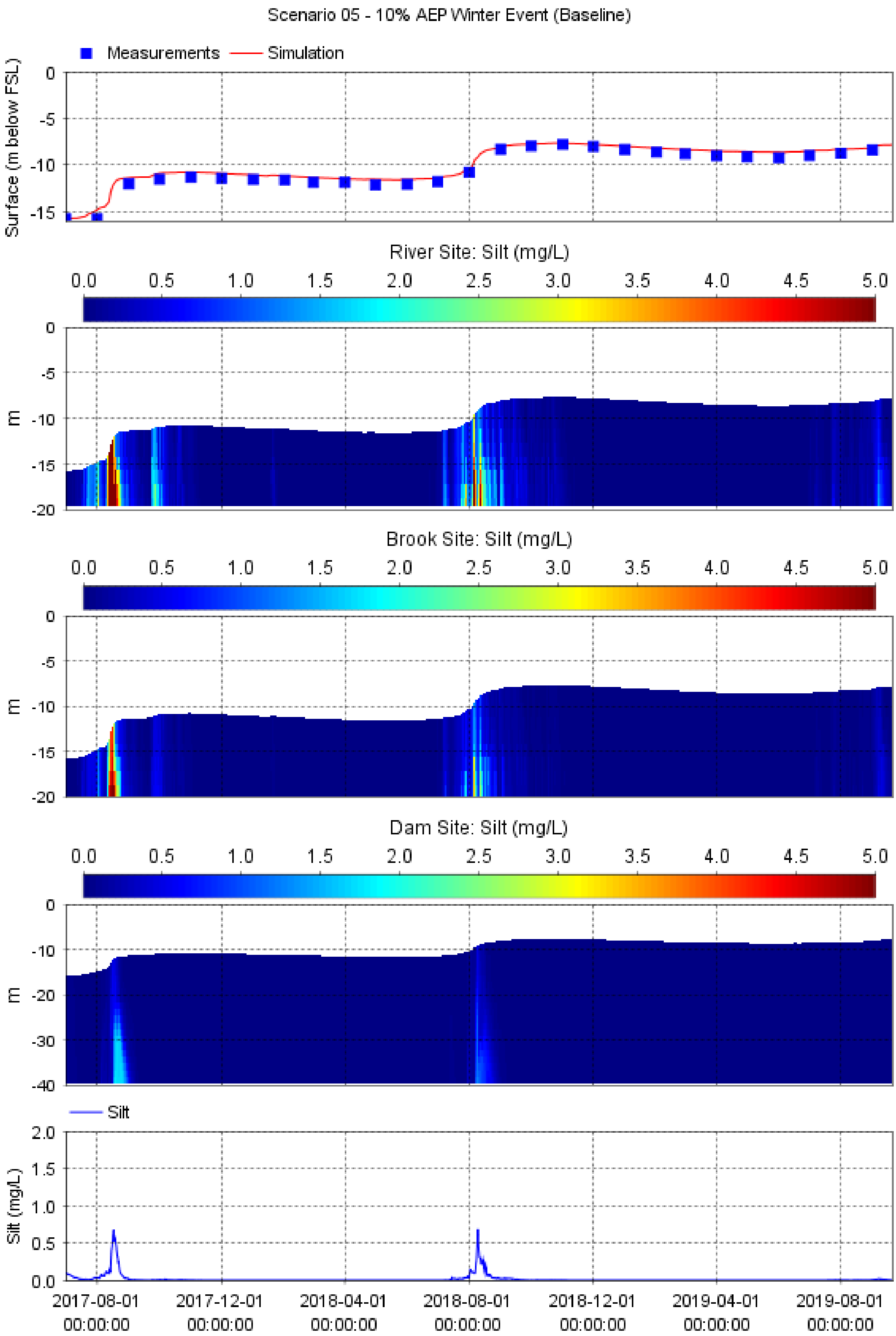

Figure 85 SMD simulated levels of silt for scenario 5 (winter baseline case 10% AEP flood event).

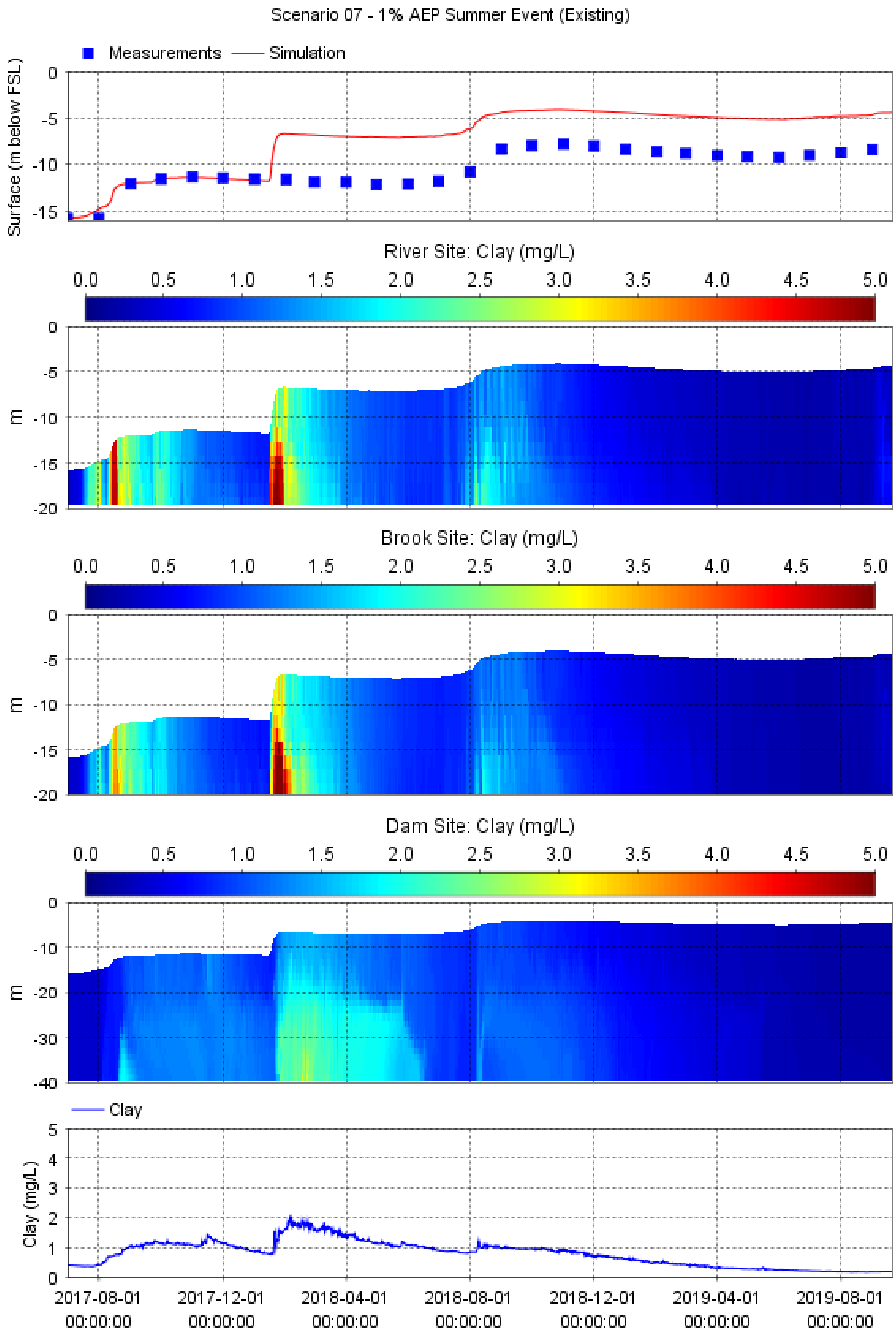

Figure 86 *SMD simulated levels of clay for scenario 7 (summer existing case 1% AEP flood event) with moderate drainage failure SS levels.*

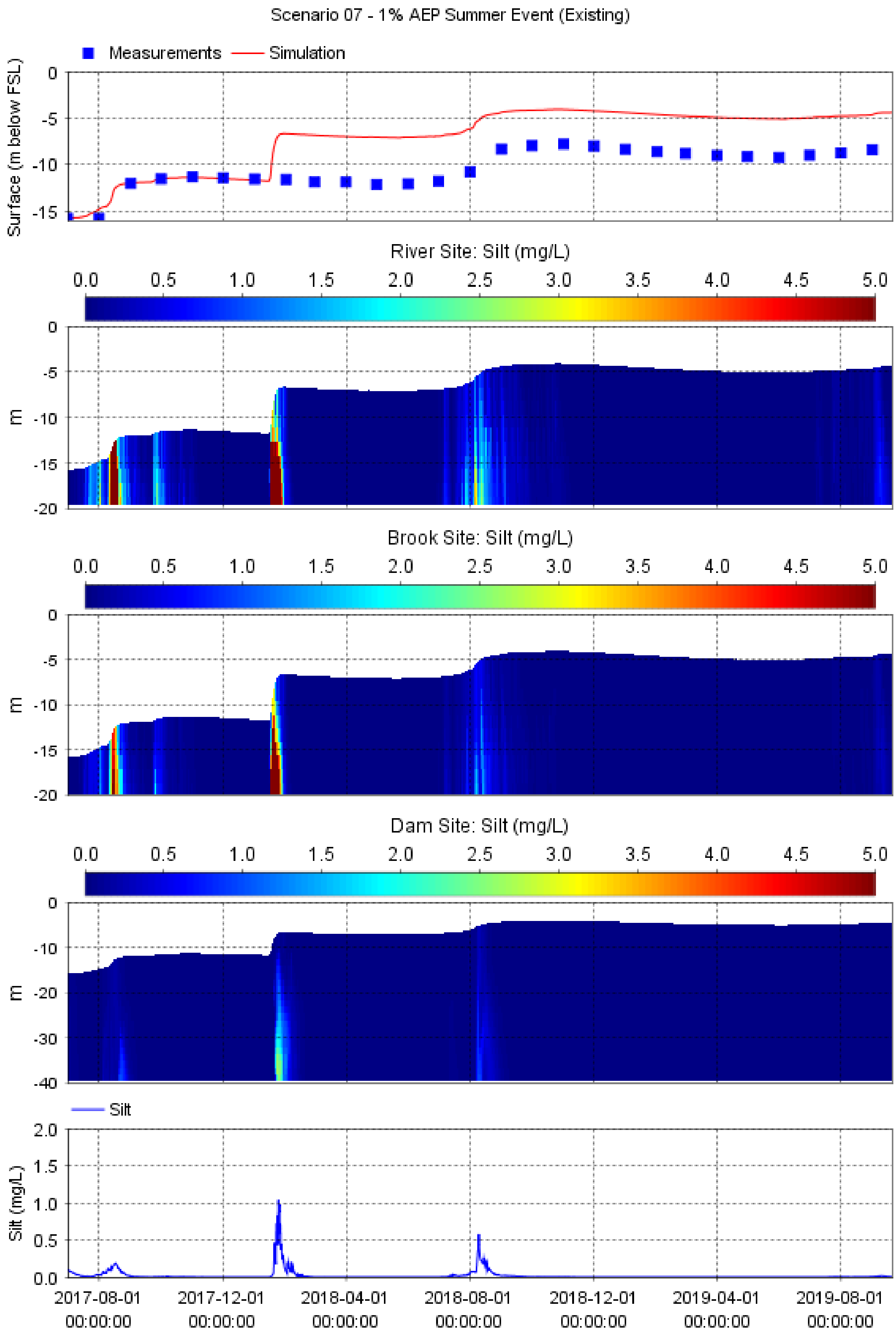

Figure 87 *SMD simulated levels of silt for scenario 7 (summer existing case 1% AEP flood event) with moderate drainage failure SS levels.*

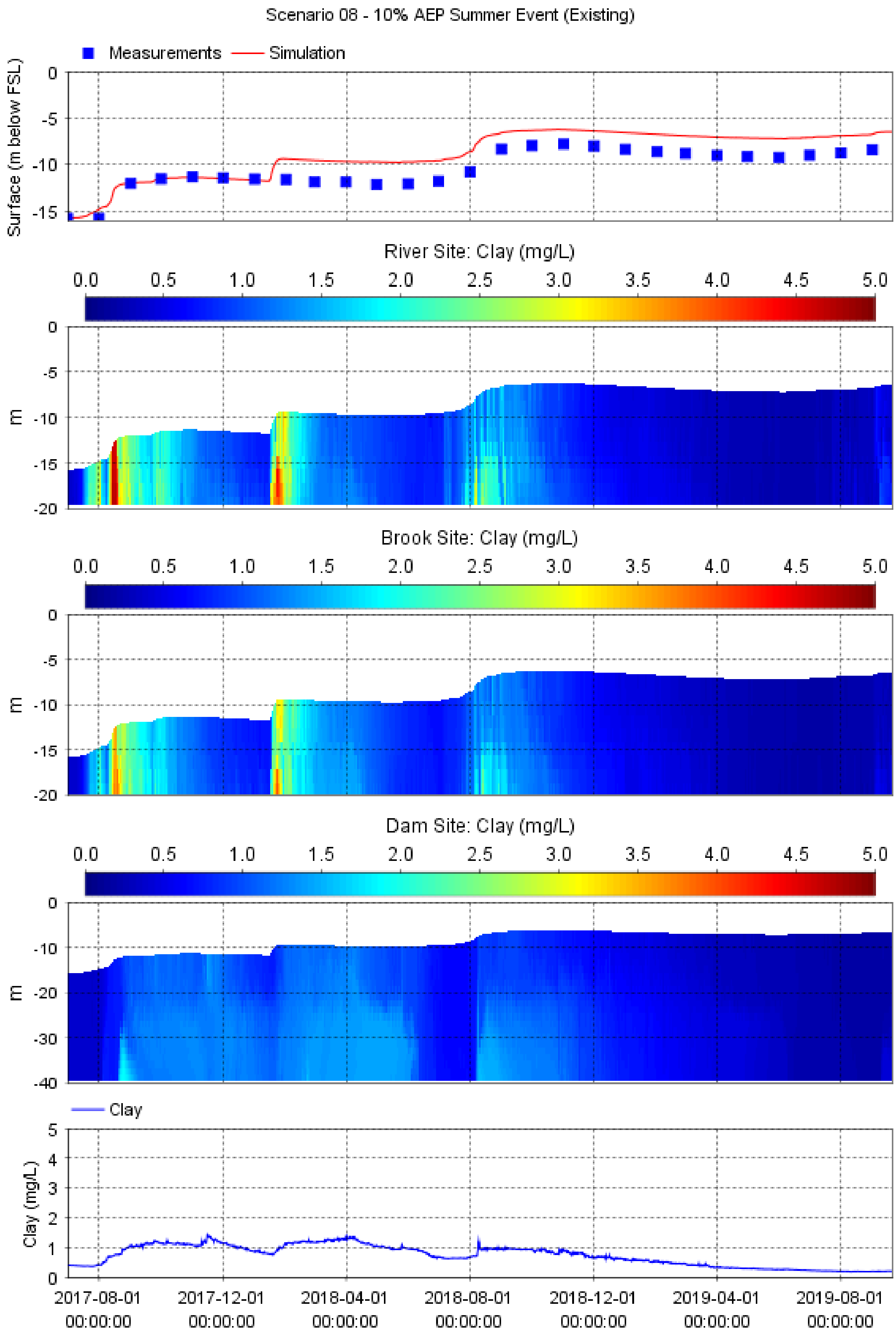

Figure 88 ***SMD simulated levels of clay for scenario 8 (winter existing case 10% AEP flood event) with moderate drainage failure SS levels.***

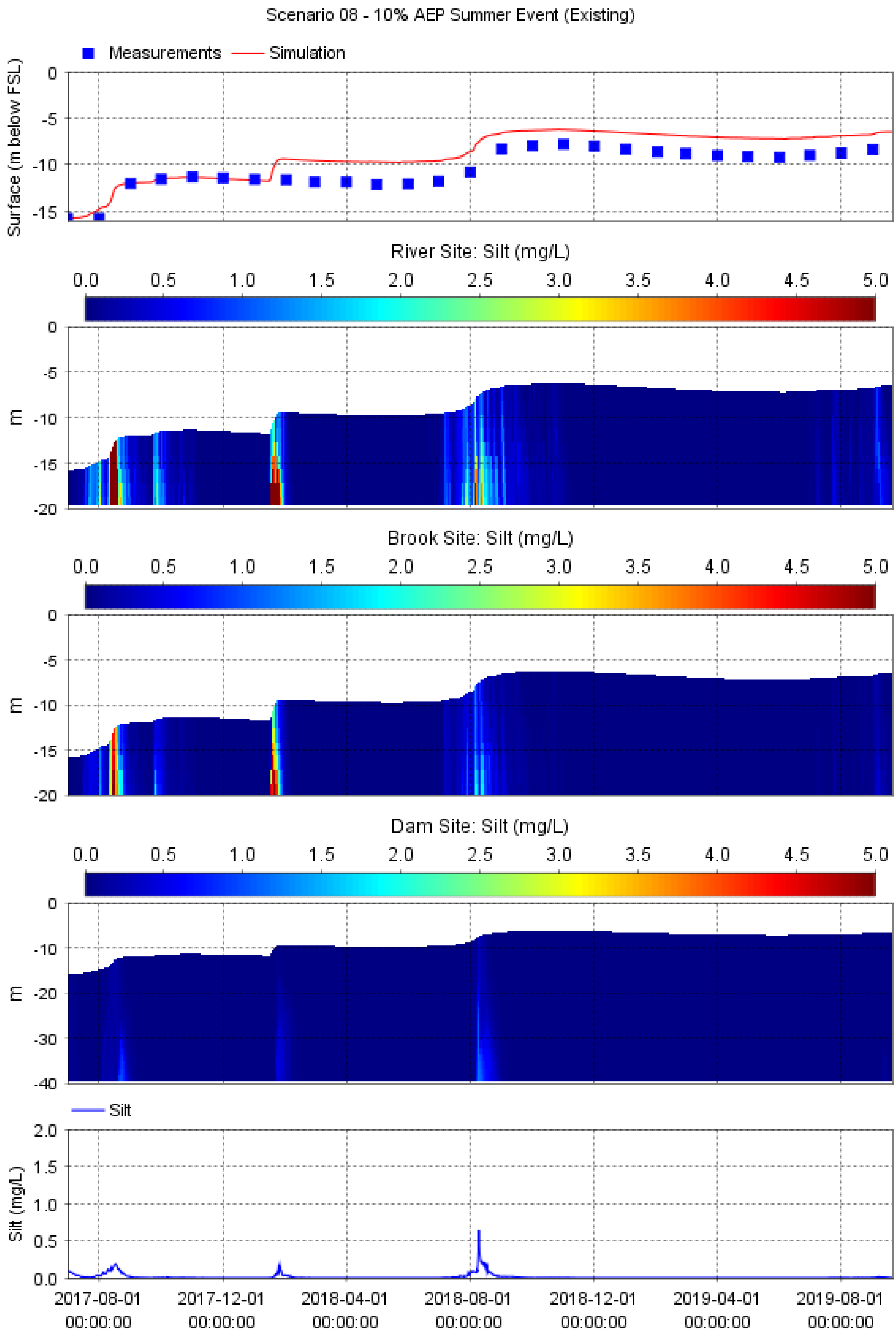

Figure 89 ***SMD simulated levels of silt for scenario 8 (summer existing case 10% AEP flood event) with moderate drainage failure SS levels.***

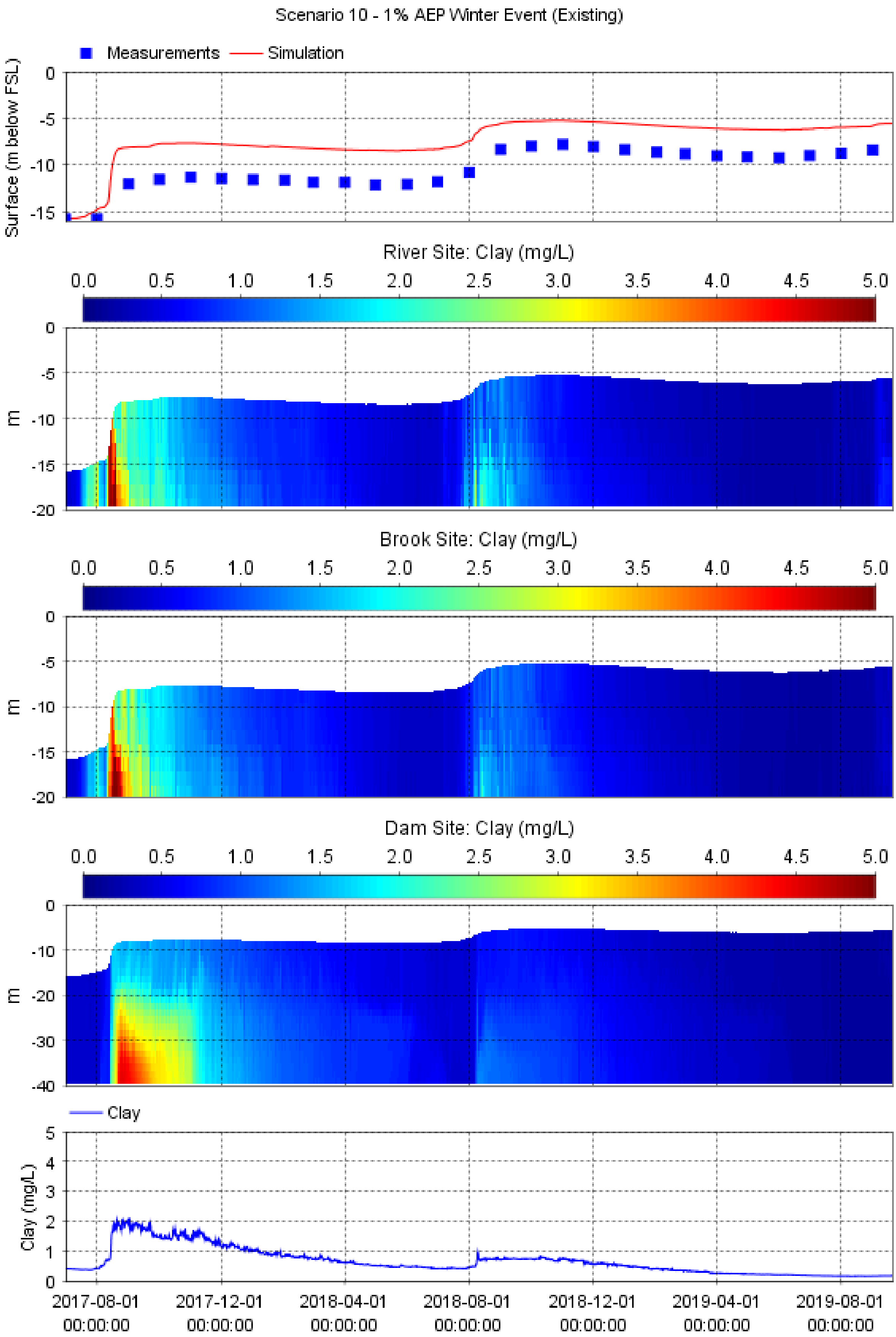

Figure 90 ***SMD simulated levels of clay for scenario 10 (winter existing case 1% AEP flood event) with moderate drainage failure SS levels.***

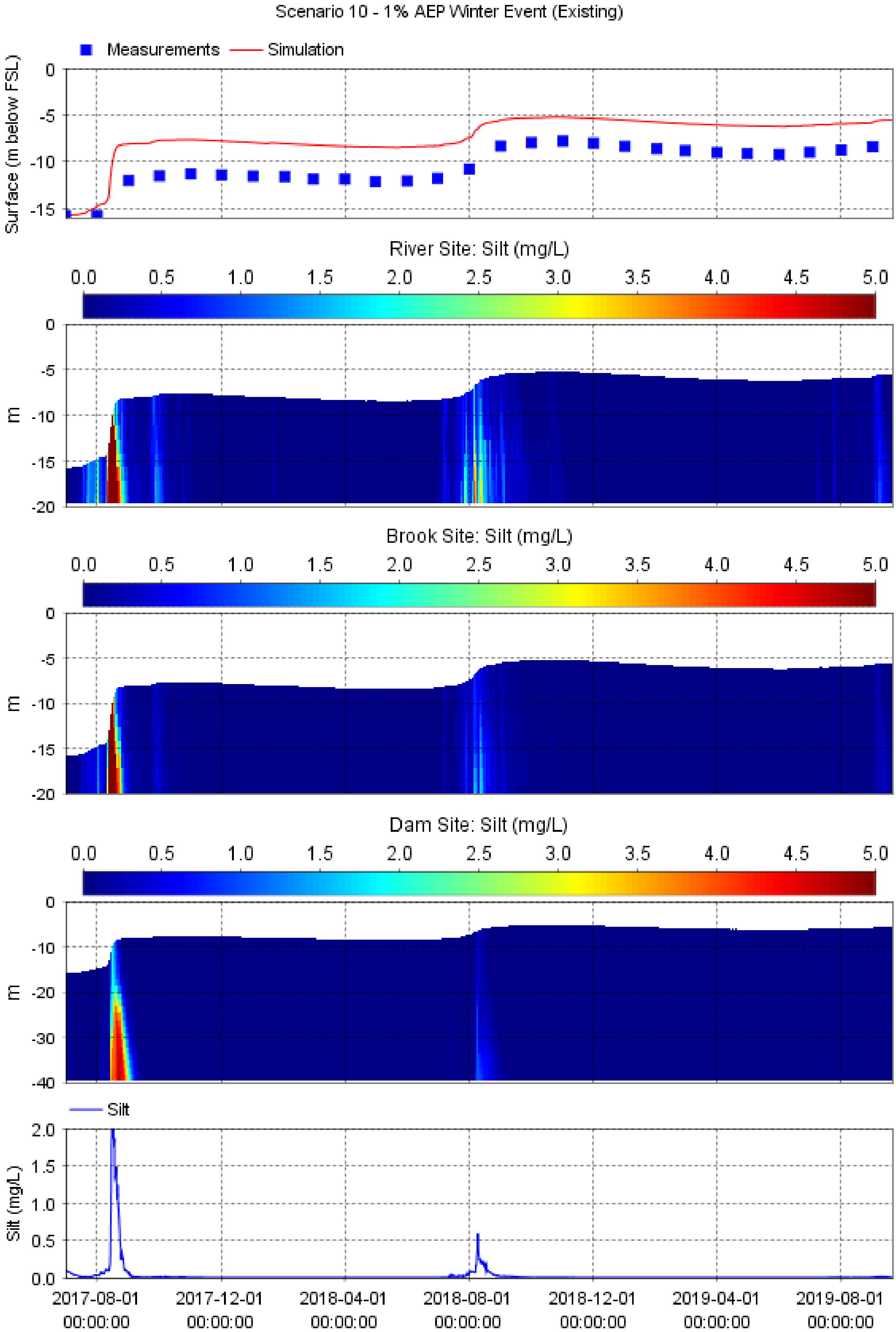

Figure 91 ***SMD simulated levels of silt for scenario 10 (winter existing case 1% AEP flood event) with moderate drainage failure SS levels.***

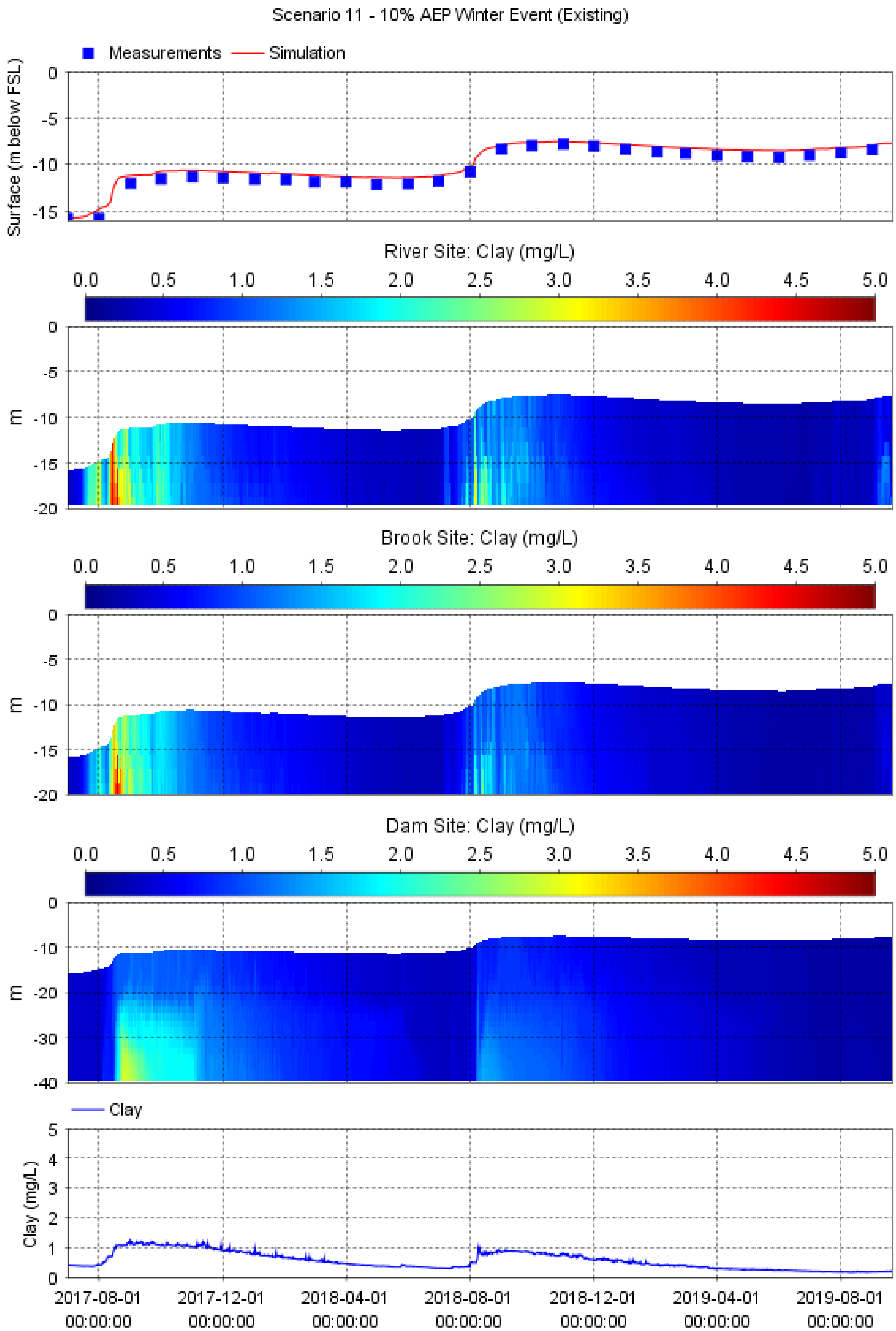

Figure 92 ***SMD simulated levels of clay for scenario 11 (winter existing case 10% AEP flood event) with moderate drainage failure SS levels.***

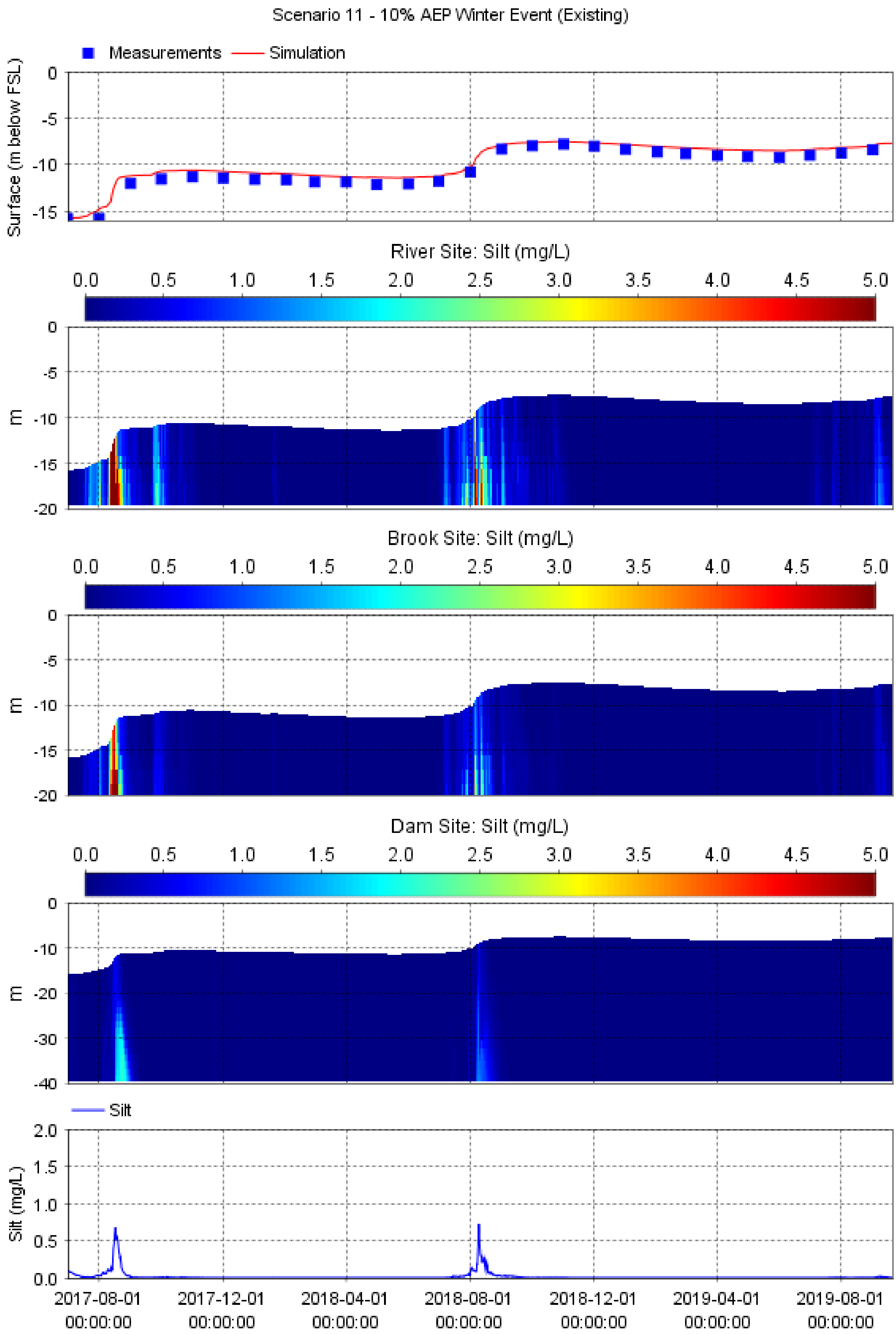

Figure 93 ***SMD simulated levels of silt for scenario 11 (winter existing case 10% AEP flood event) with moderate drainage failure SS levels.***

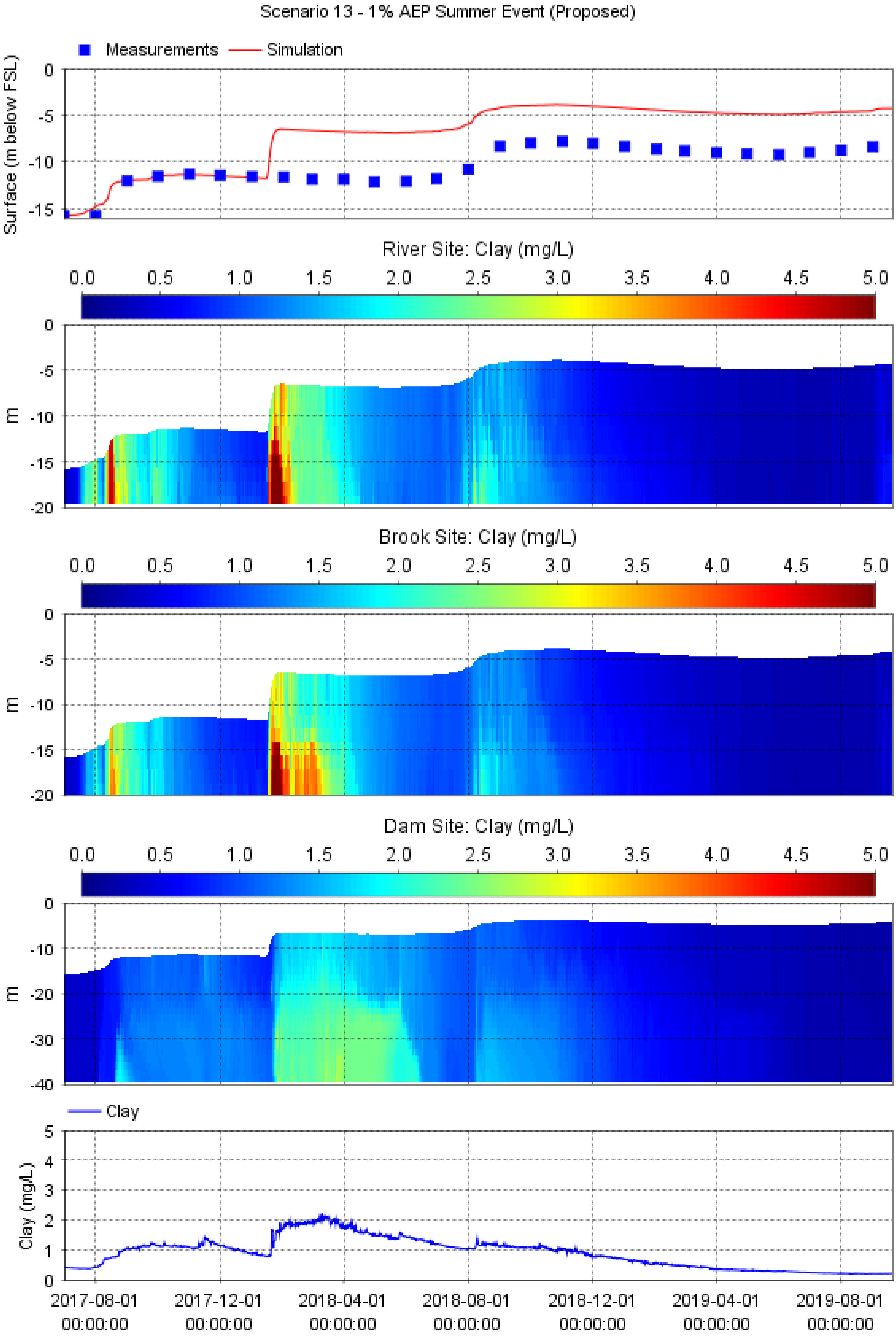

Figure 94 ***SMD simulated levels of clay for scenario 13 (summer proposed case 1% AEP flood event) with moderate drainage failure SS levels.***

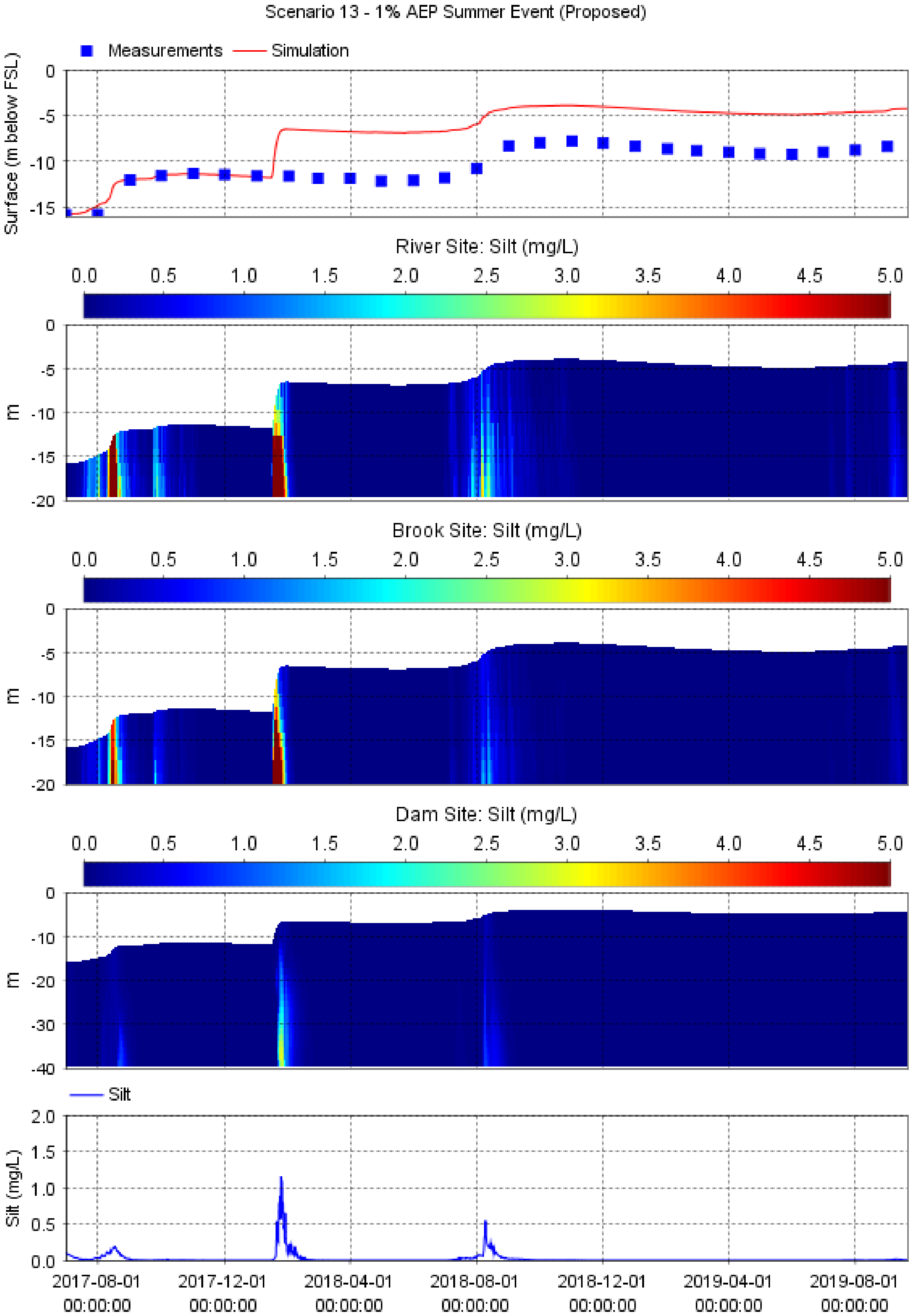

Figure 95 *SMD simulated levels of silt for scenario 13 (summer proposed case 1% AEP flood event) with moderate drainage failure SS levels.*

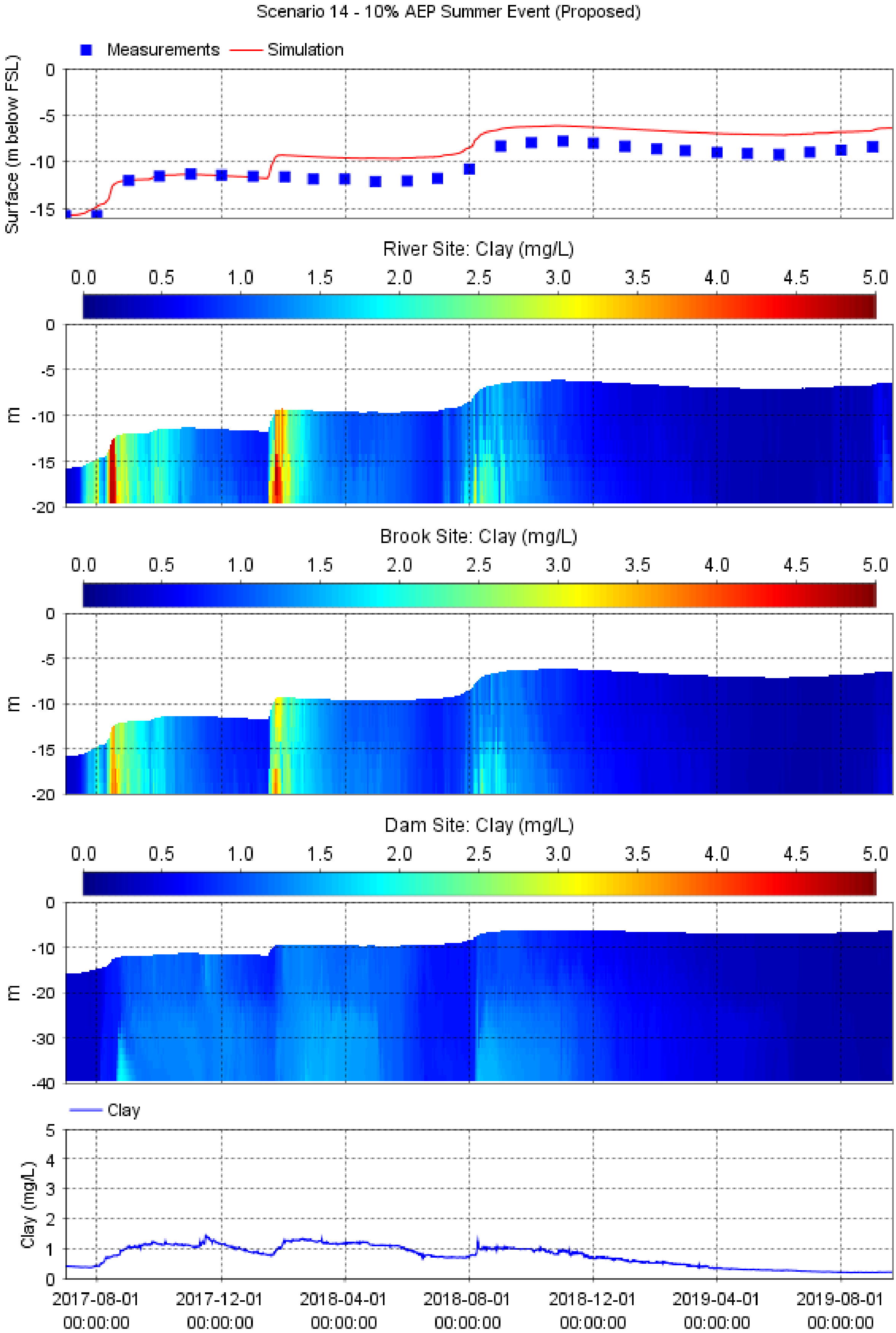

Figure 96 ***SMD simulated levels of clay for scenario 14 (summer proposed case 10% AEP flood event) with moderate drainage failure SS levels.***

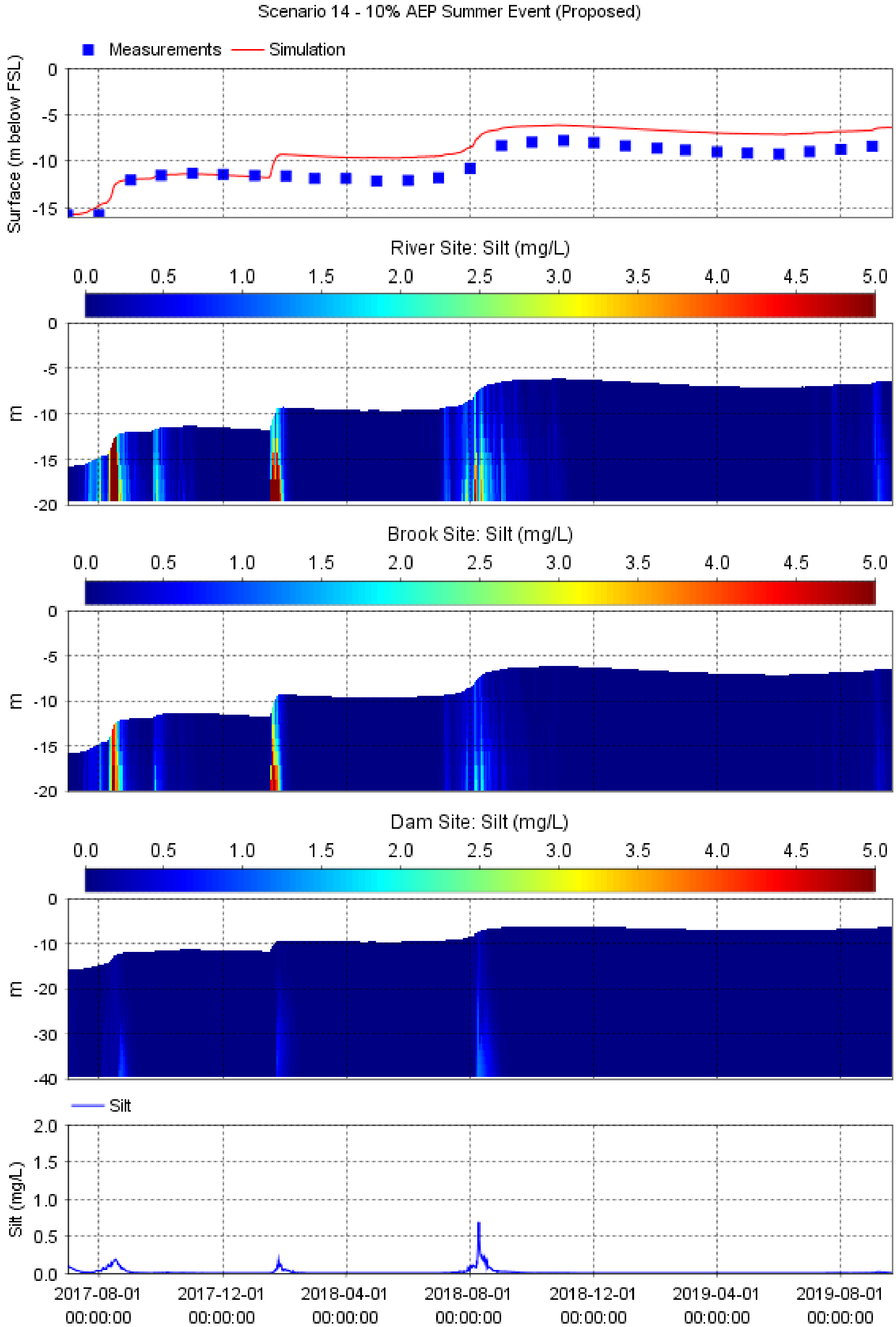

Figure 97 ***SMD simulated levels of silt for scenario 14 (summer proposed case 10% AEP flood event) with moderate drainage failure SS levels.***

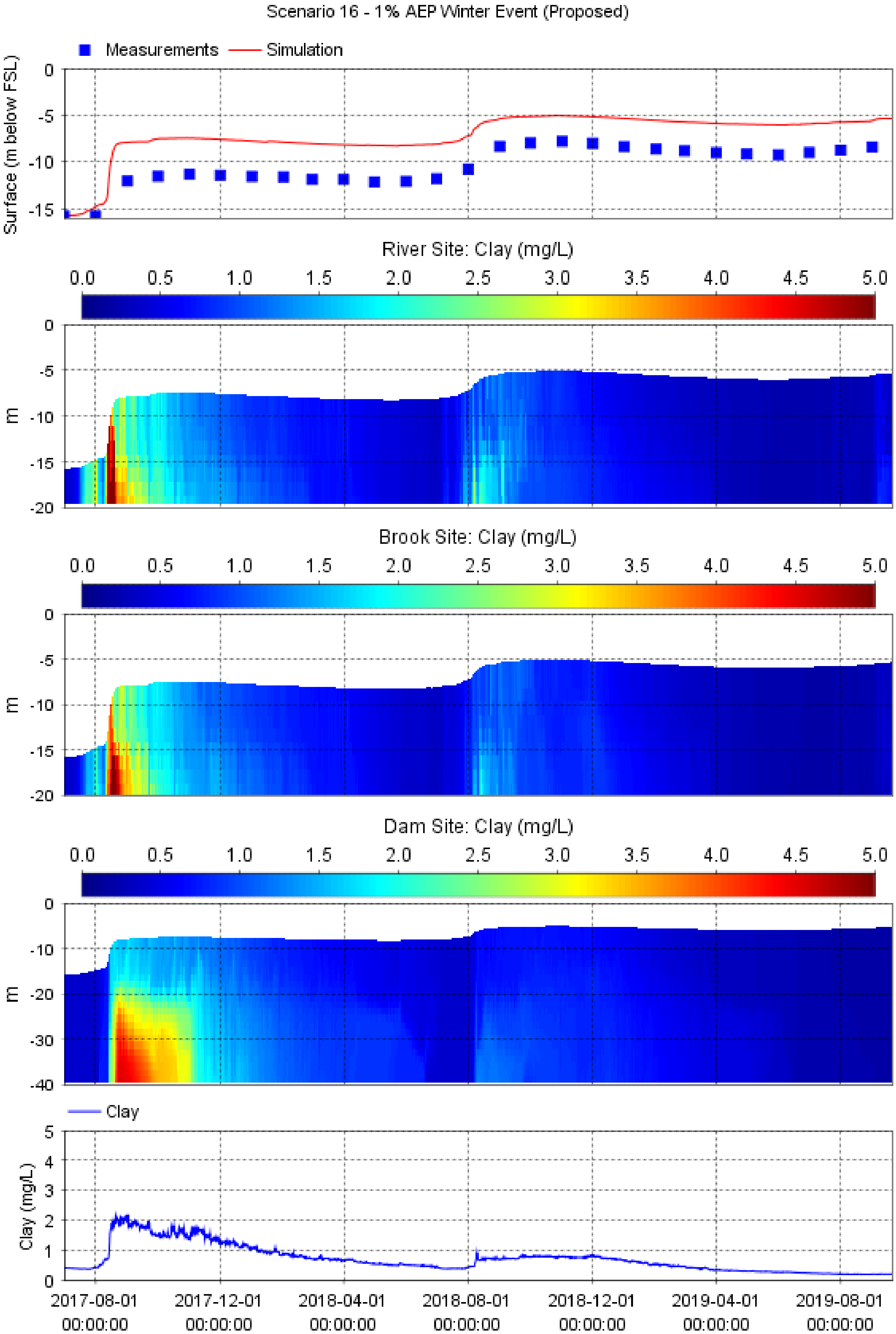

Figure 98 ***SMD simulated levels of clay for scenario 16 (winter proposed case 1% AEP flood event) with moderate drainage failure SS levels.***

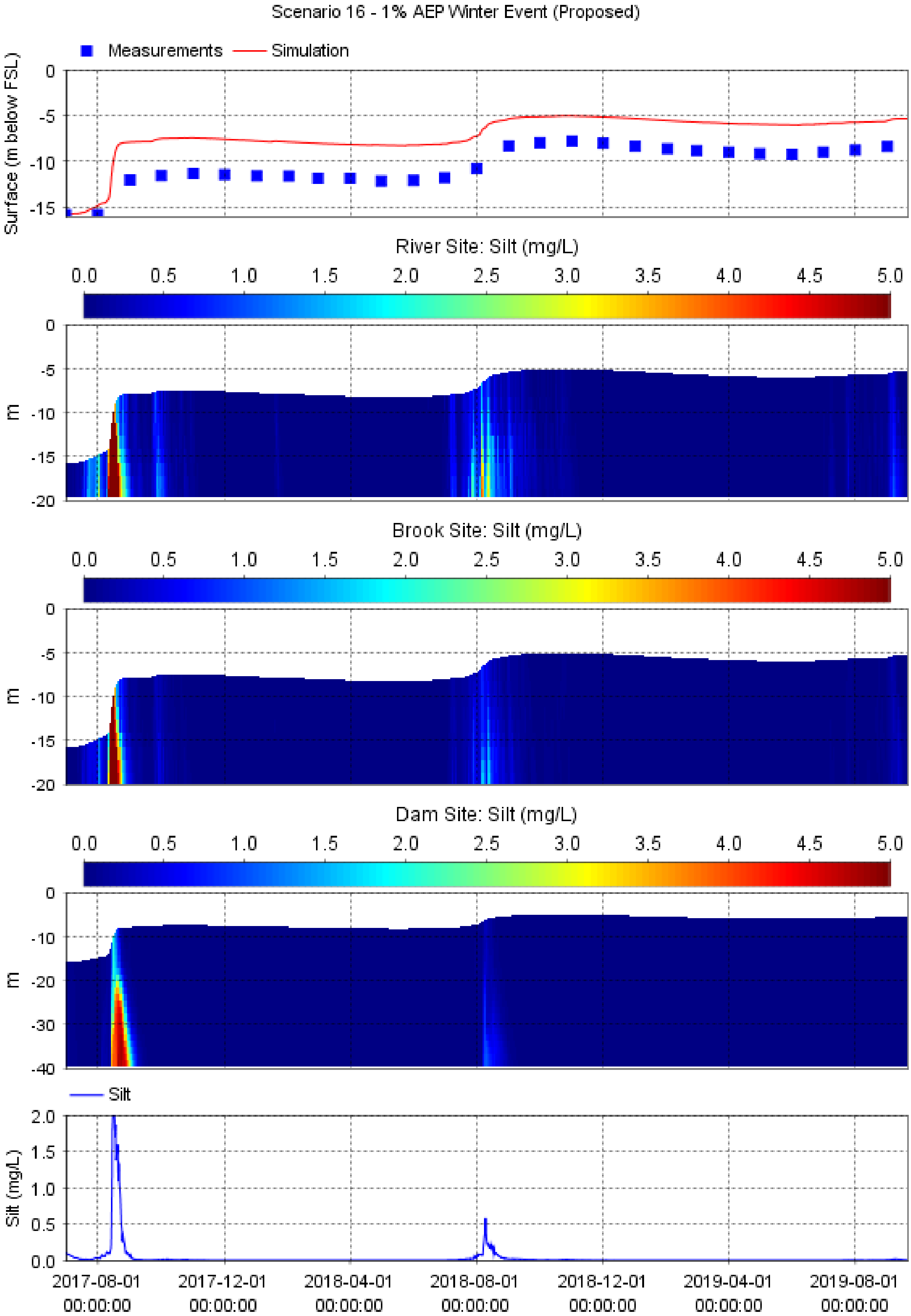

Figure 99 *SMD simulated levels of silt for scenario 16 (winter proposed case 1% AEP flood event) with moderate drainage failure SS levels.*

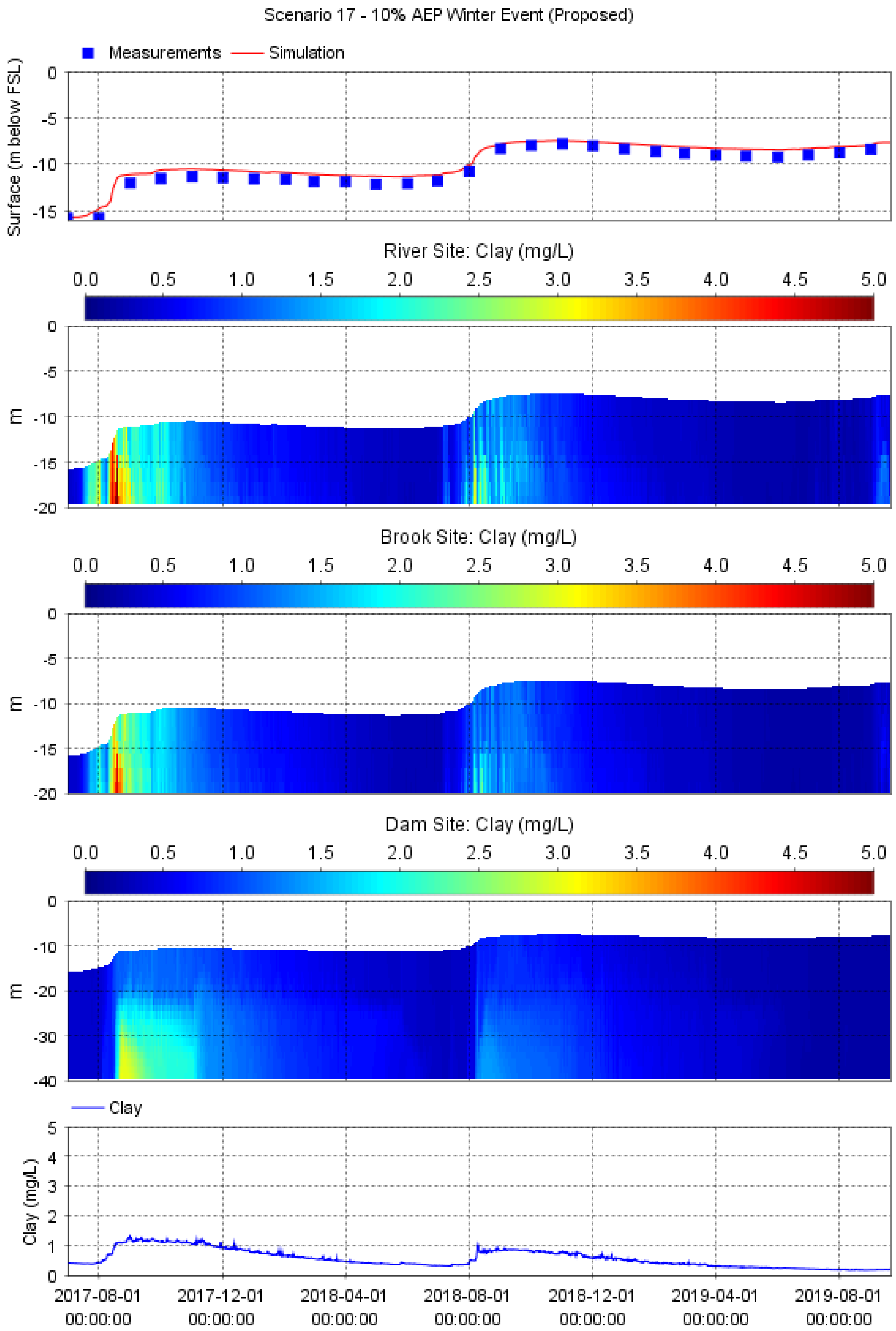

Figure 100 ***SMD simulated levels of clay for scenario 17 (winter proposed case 10% AEP flood event) with moderate drainage failure SS levels.***

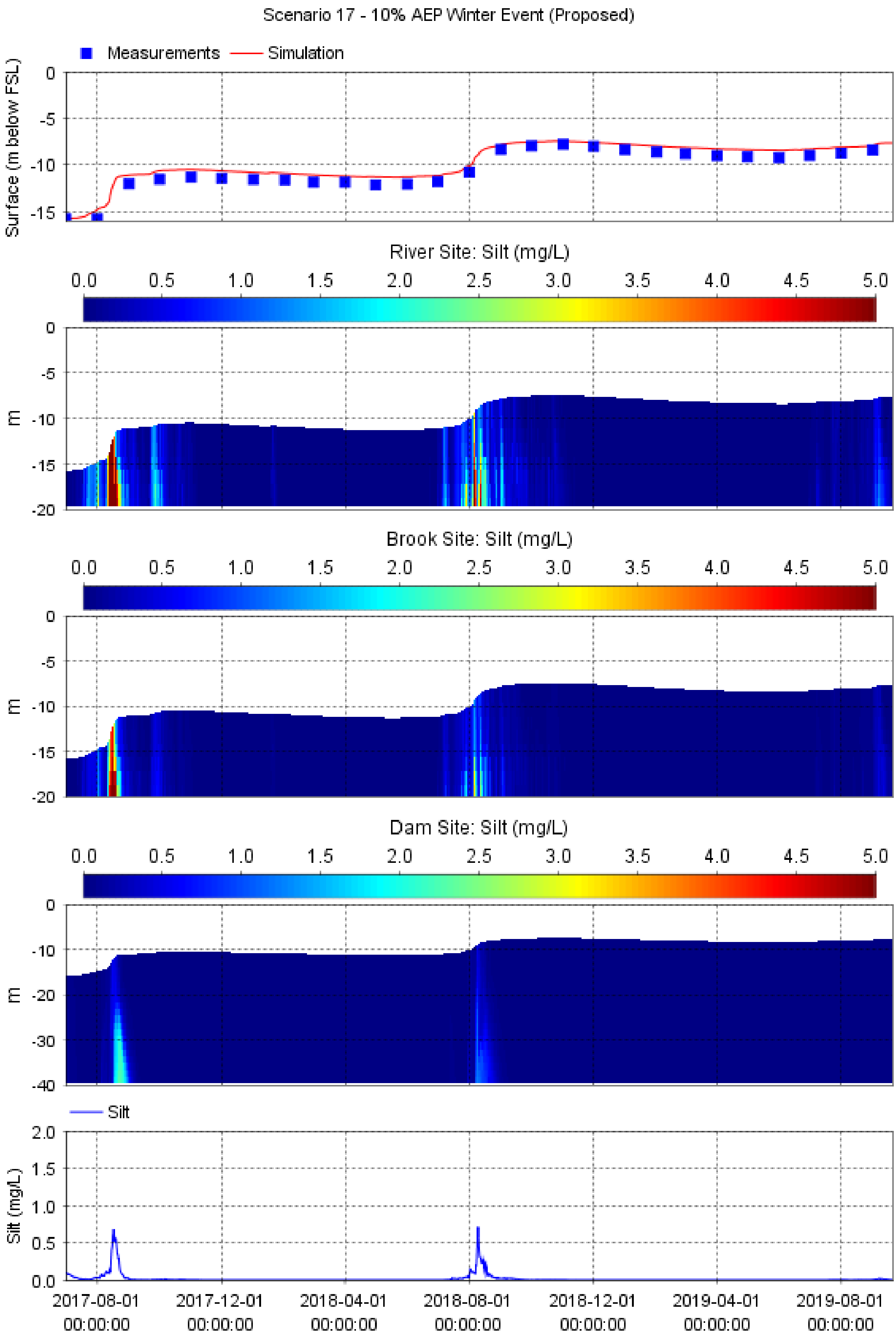

Figure 101 *SMD simulated levels of silt for scenario 17 (winter proposed case 10% AEP flood event) with moderate drainage failure SS levels.*

Appendix C

SMD: 1% and 10% AEP Flood Event Inputs (High Drainage Failure SS Levels)

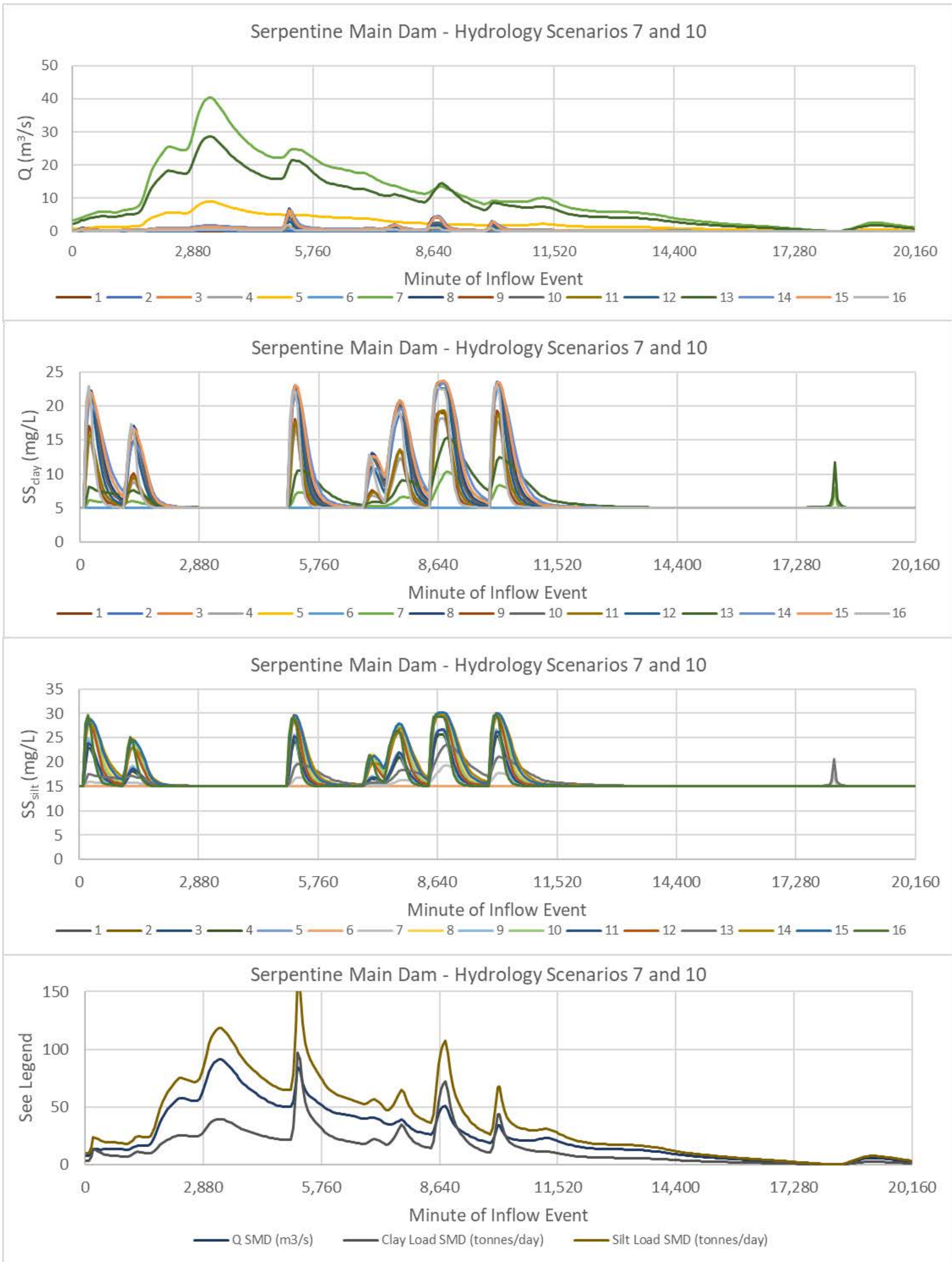

Figure 102 ***SMD hydrology and suspended solids inputs for scenarios 7H and 10H with high drainage failure SS levels.***

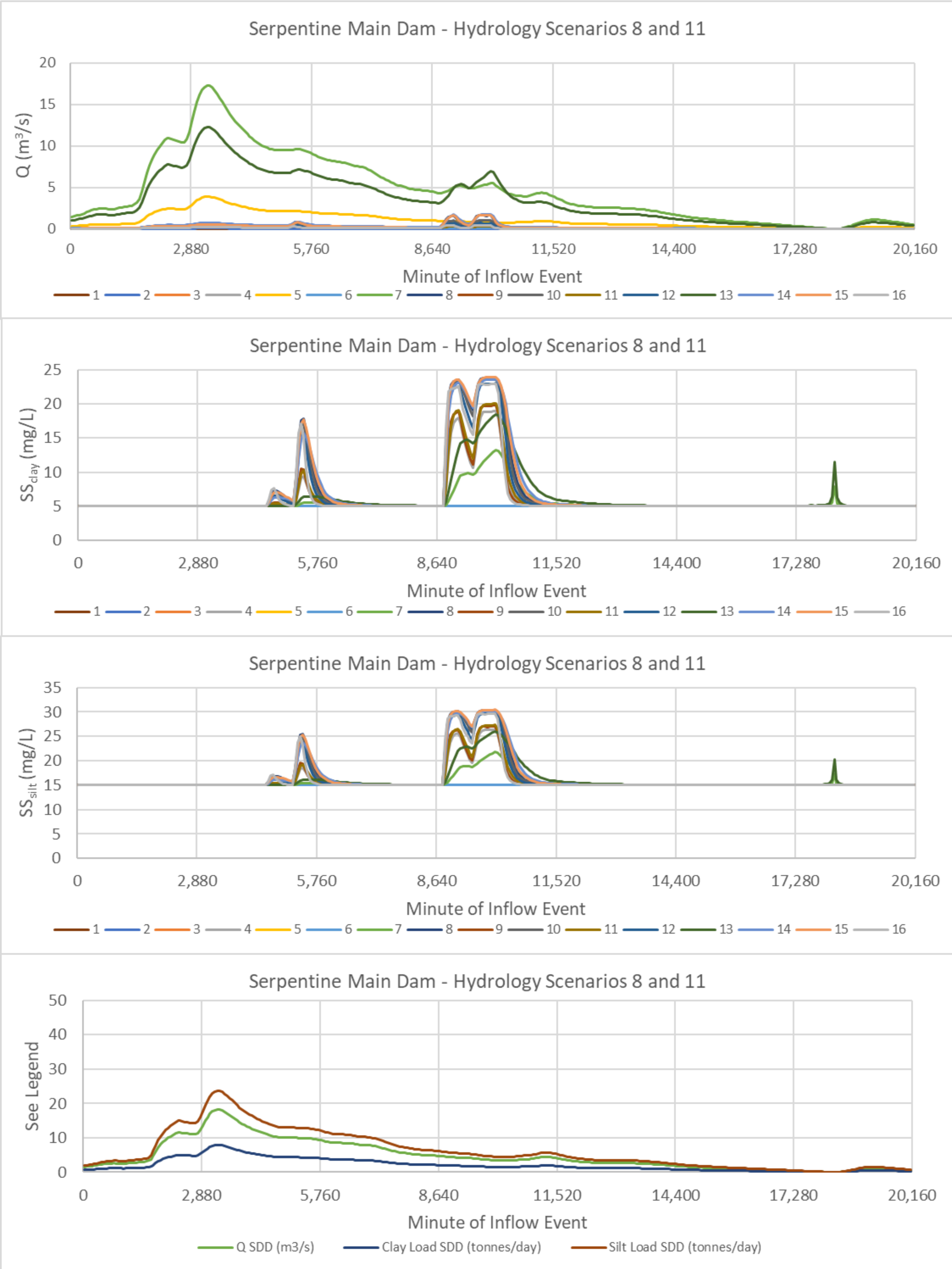

Figure 103 As Figure 102 for scenarios 8H and 11H with high drainage failure SS levels.

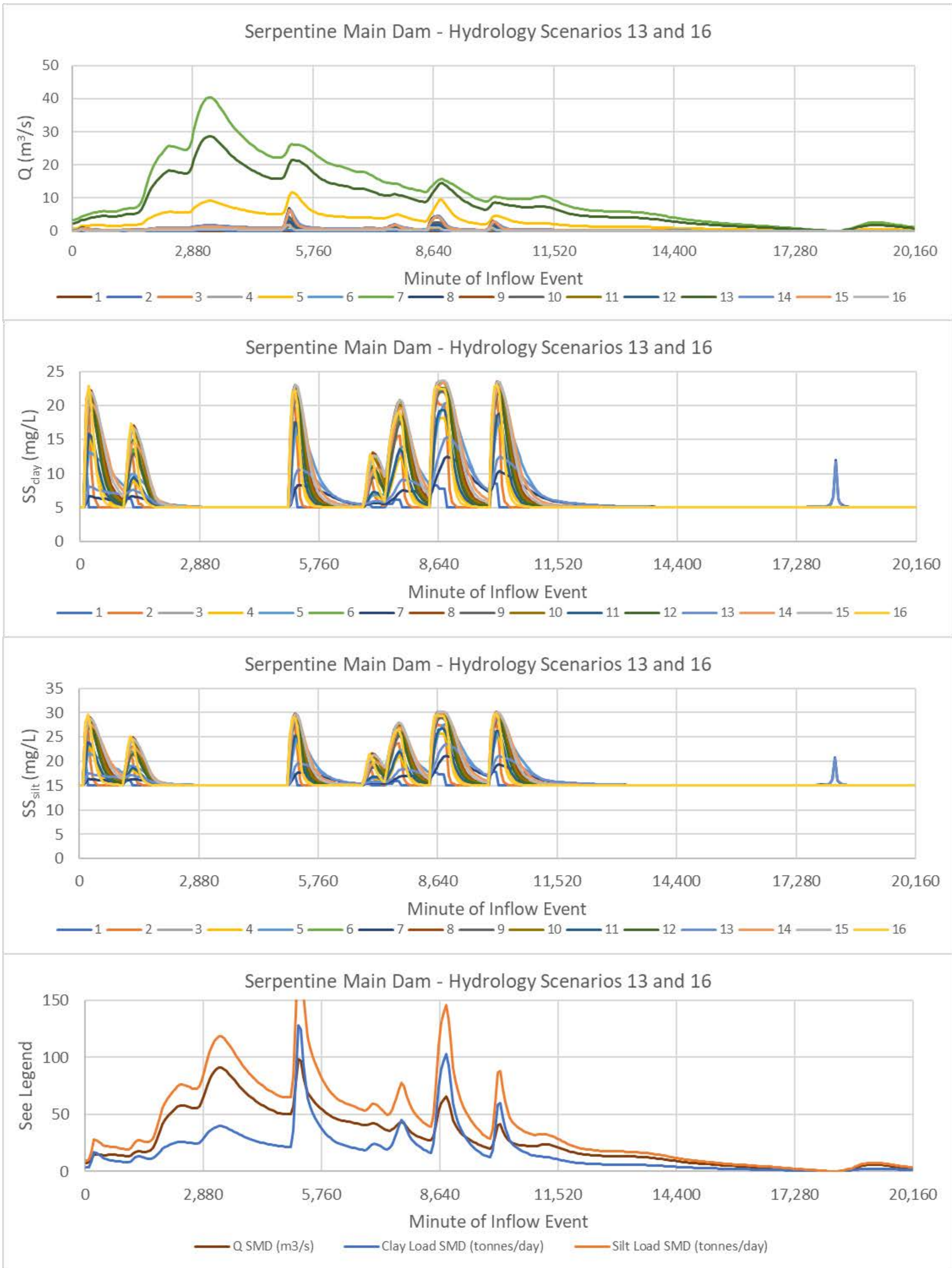

Figure 104 *As Figure 102 for scenarios 13H and 16H with high drainage failure SS levels.*

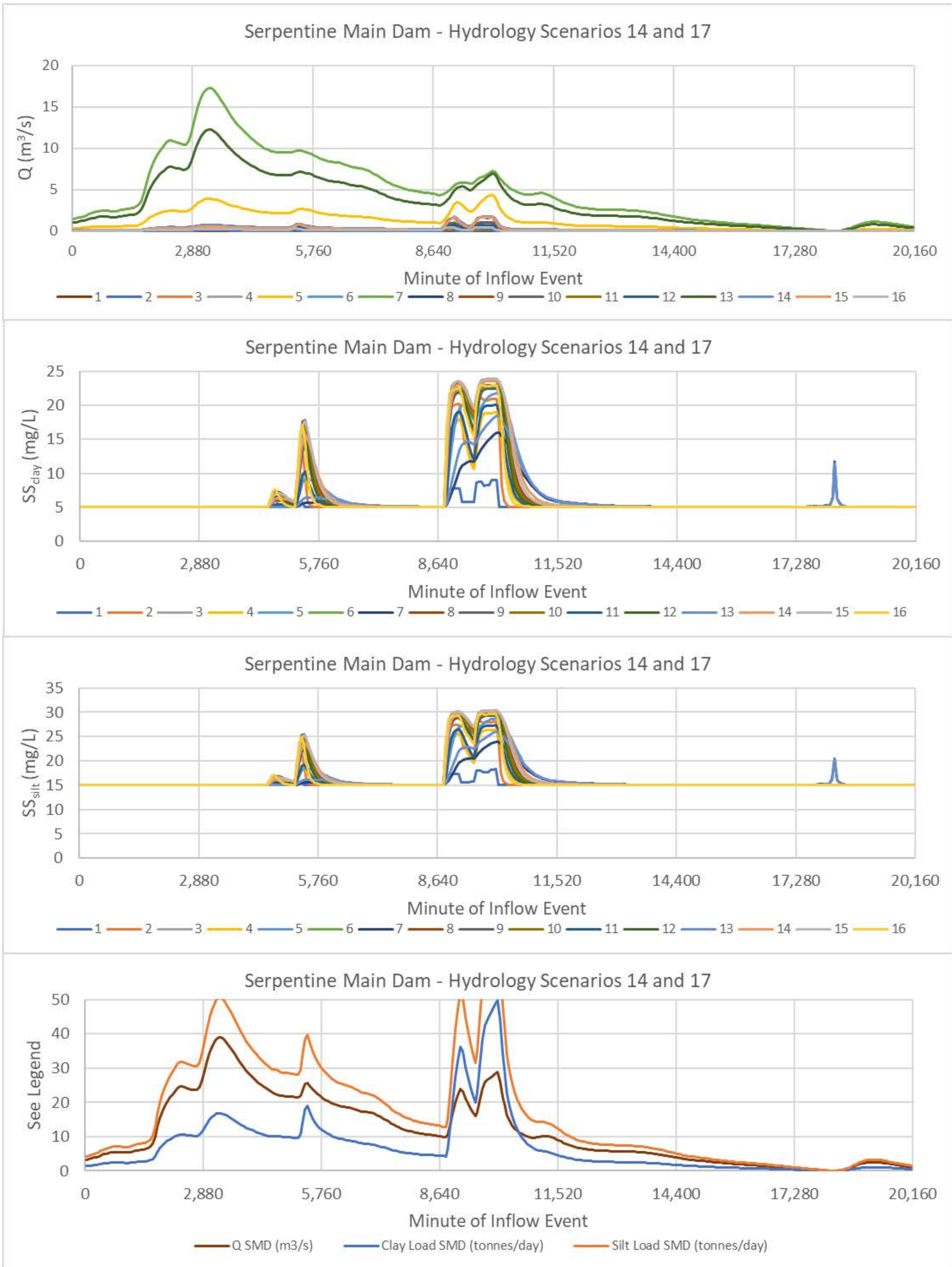

Figure 105 ***As Figure 102 for scenarios 14H and 17H with high drainage failure SS levels.***

Appendix D

SMD: 1% and 10% AEP Flood Event Simulations (High Drainage Failure SS Levels)

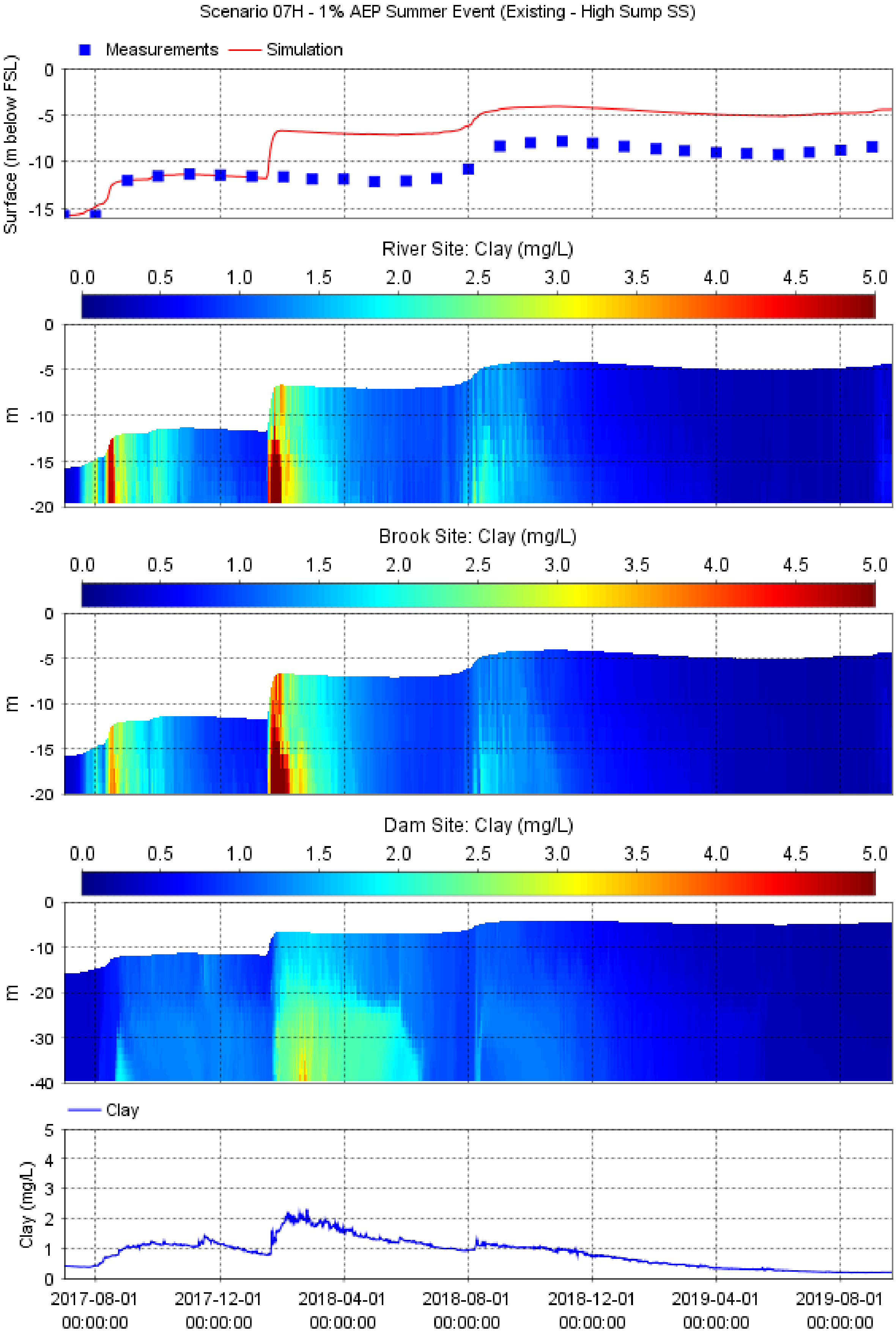

Figure 106 ***SMD simulated levels of clay for scenario 7H (summer existing case 1% AEP flood event) with high drainage failure SS levels.***

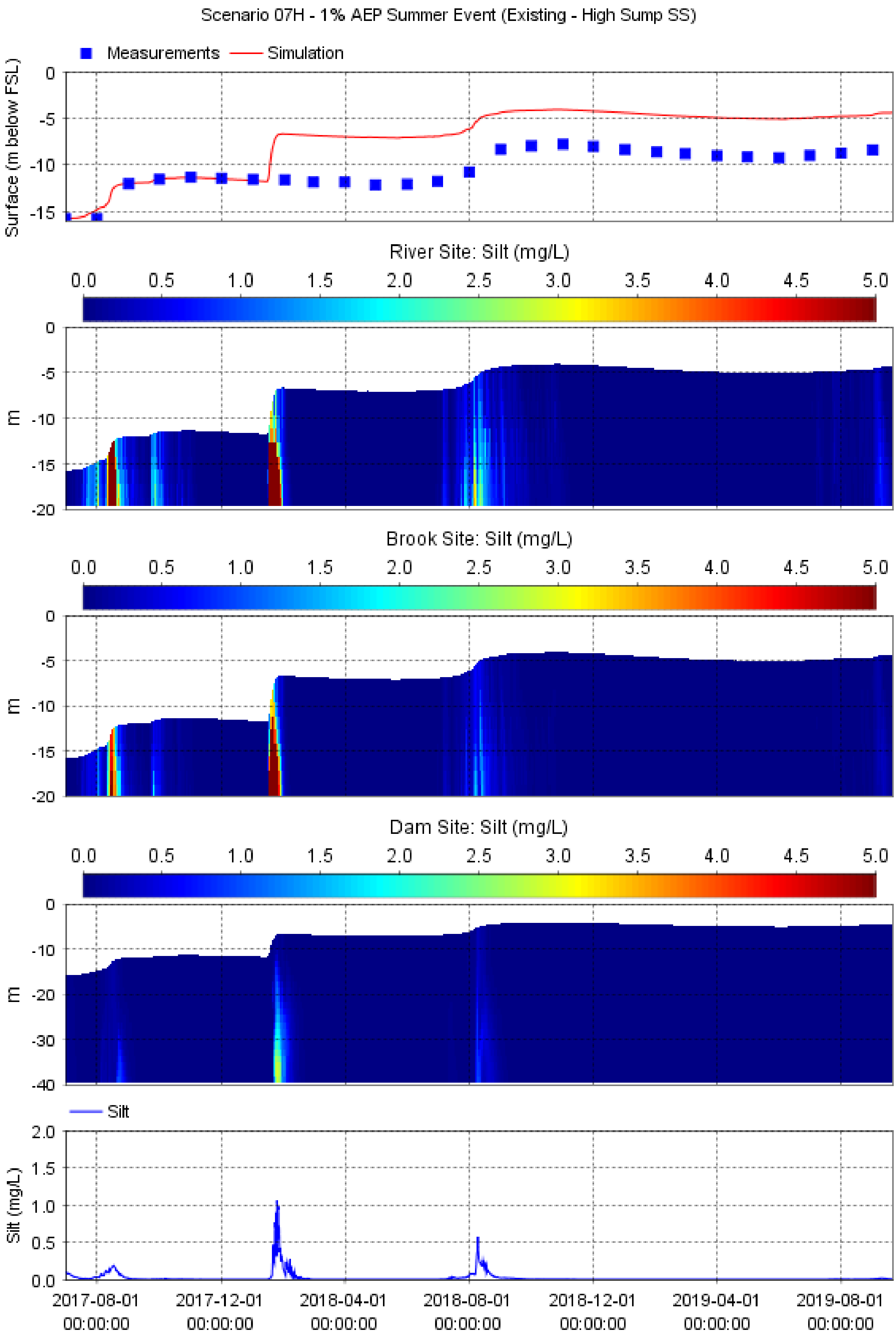

Figure 107 SMD simulated levels of silt for scenario 7H (summer existing case 1% AEP flood event) with high drainage failure SS levels.

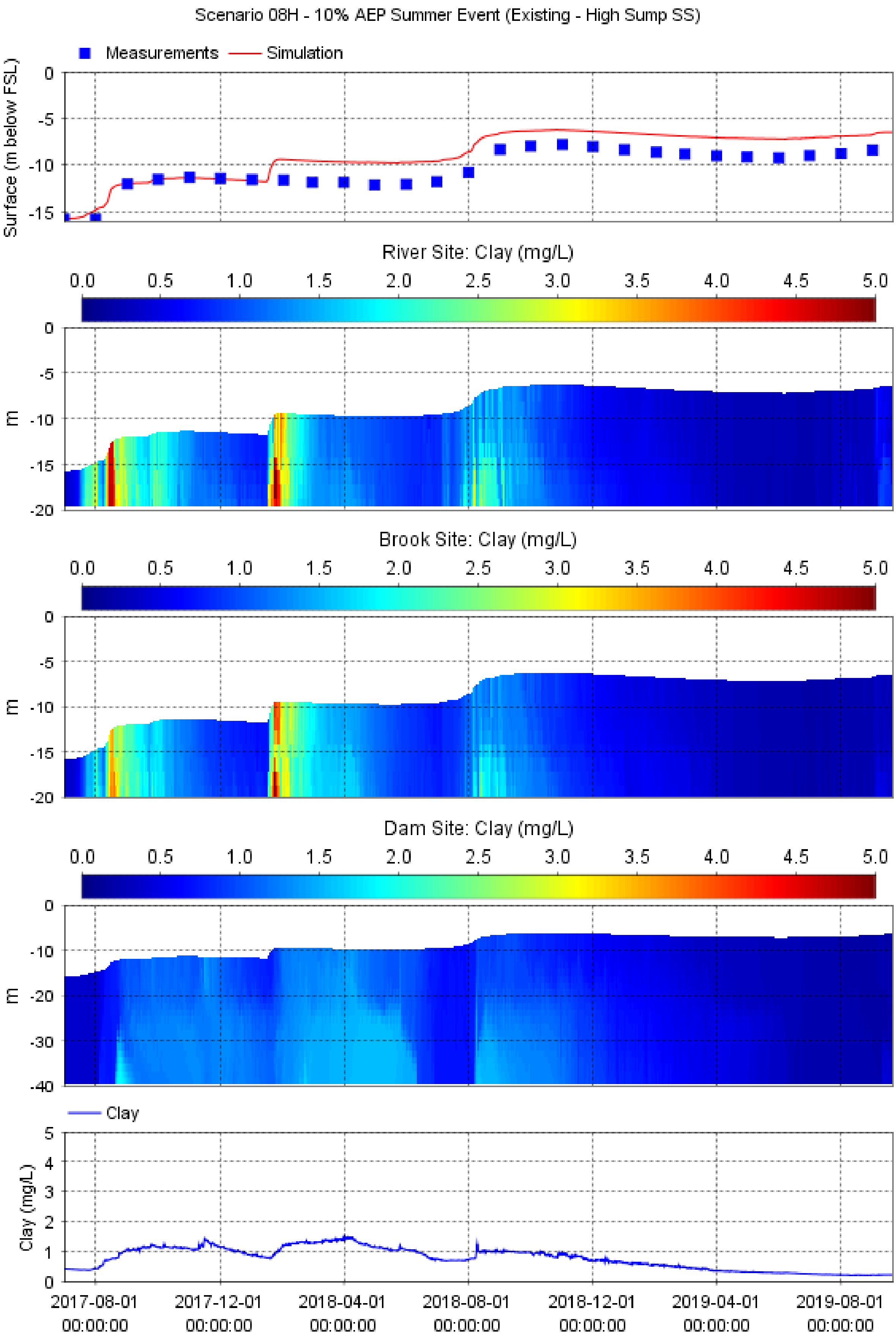

Figure 108 ***SMD simulated levels of clay for scenario 8H (winter existing case 10% AEP flood event) with high drainage failure SS levels.***

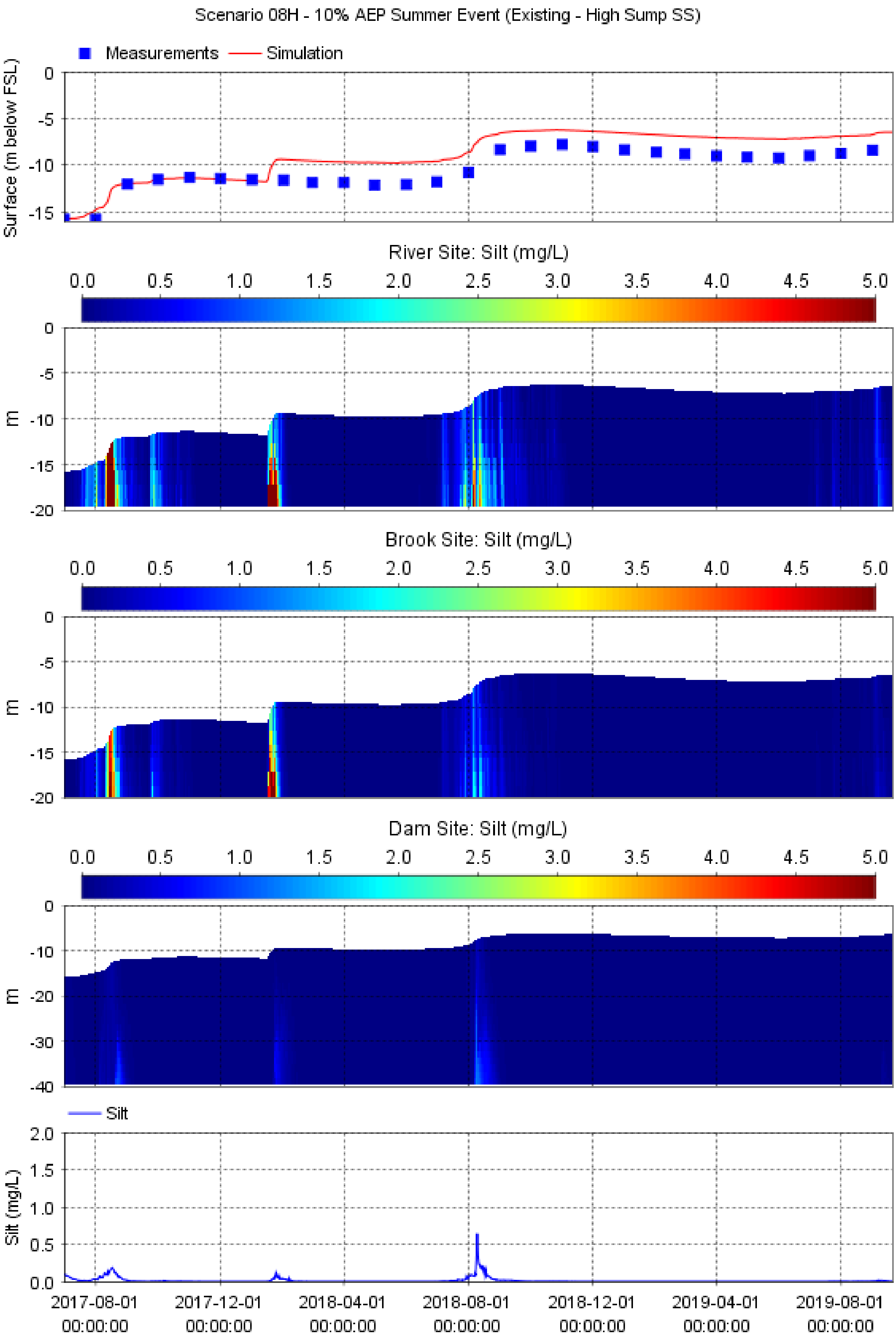

Figure 109 ***SMD simulated levels of silt for scenario 8H (summer existing case 10% AEP flood event) with high drainage failure SS levels.***

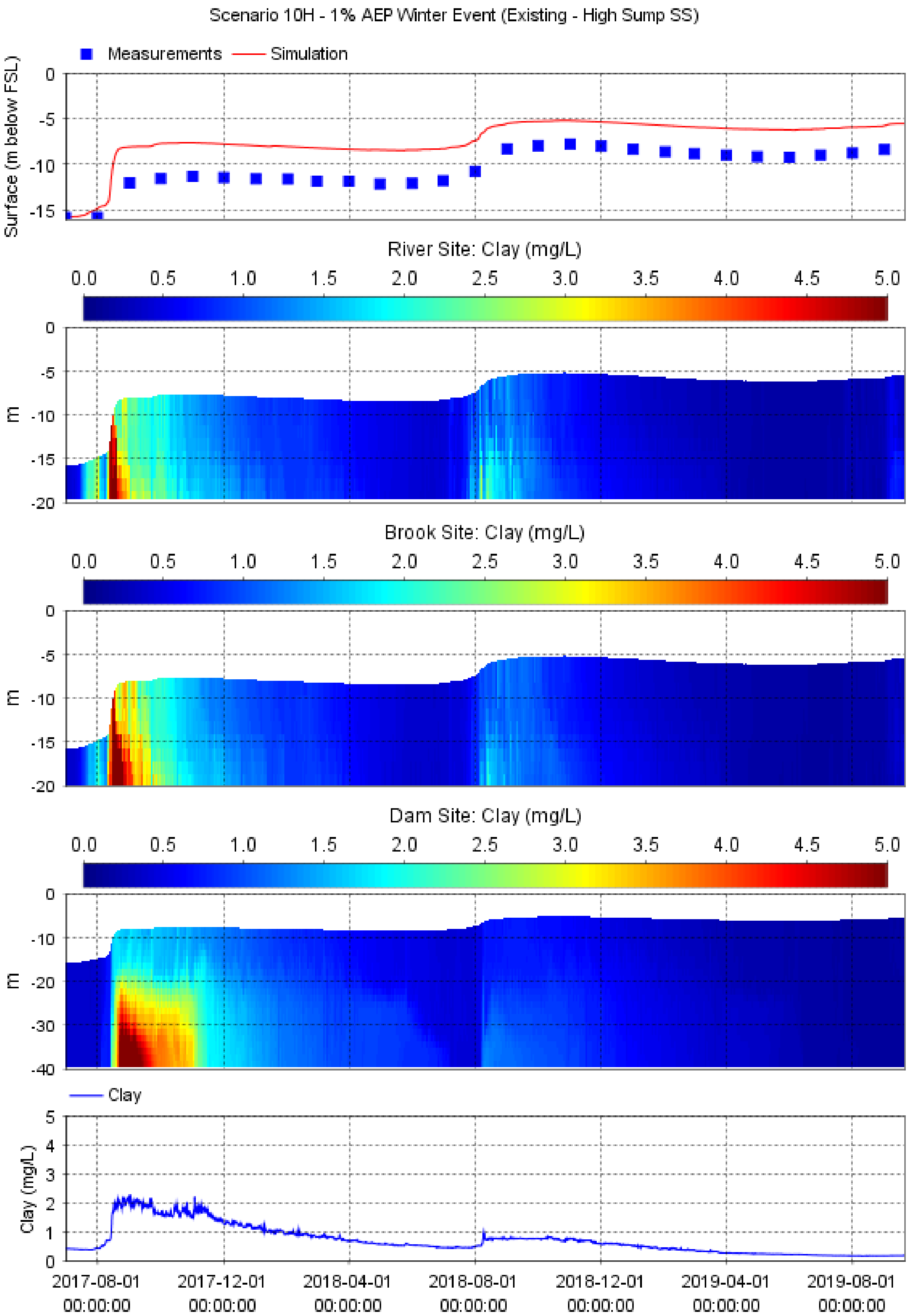

Figure 110 SMD simulated levels of clay for scenario 10H (winter existing case 1% AEP flood event) with high drainage failure SS levels.

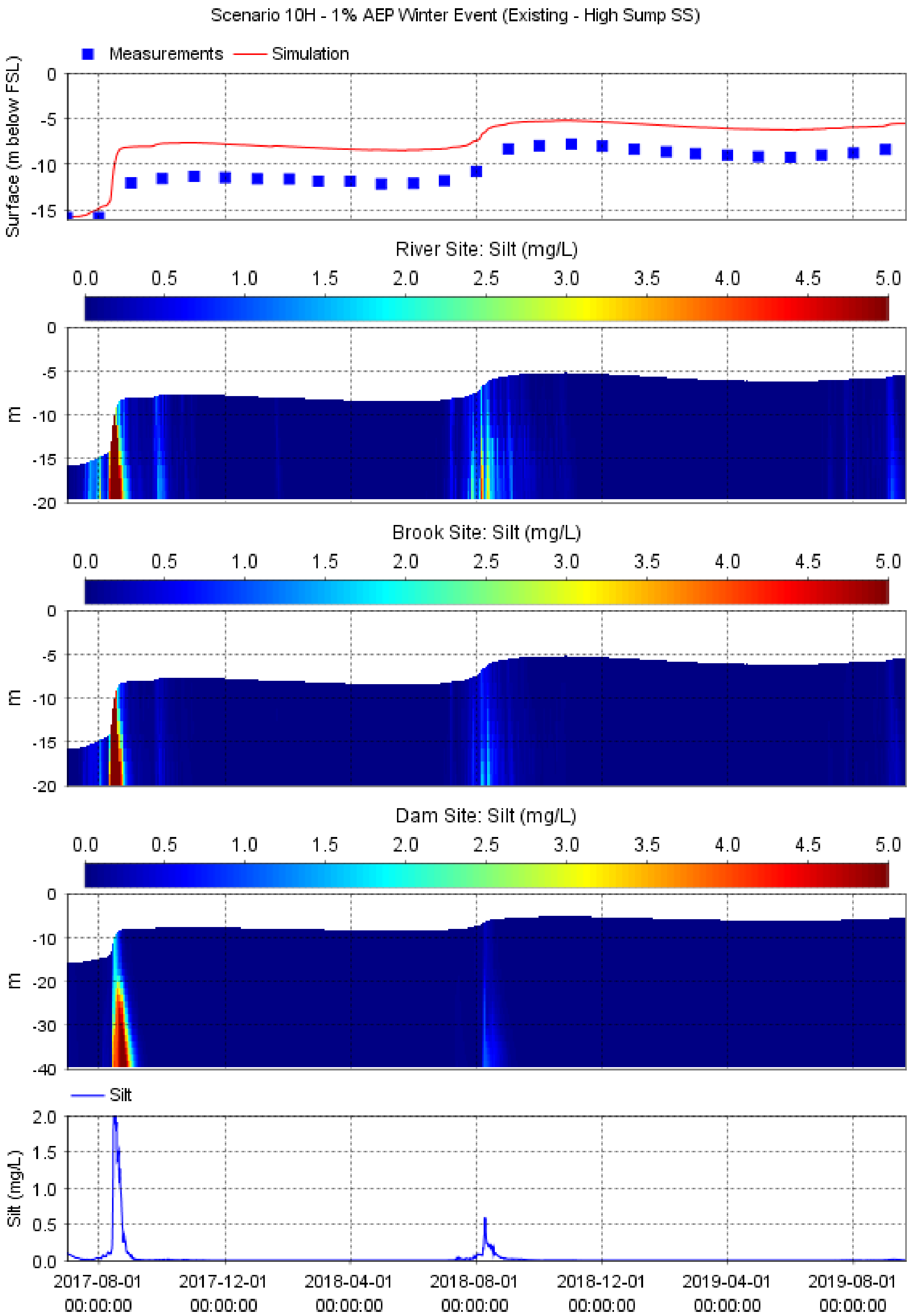

Figure 111 ***SMD simulated levels of silt for scenario 10H (winter existing case 1% AEP flood event) with high drainage failure SS levels.***

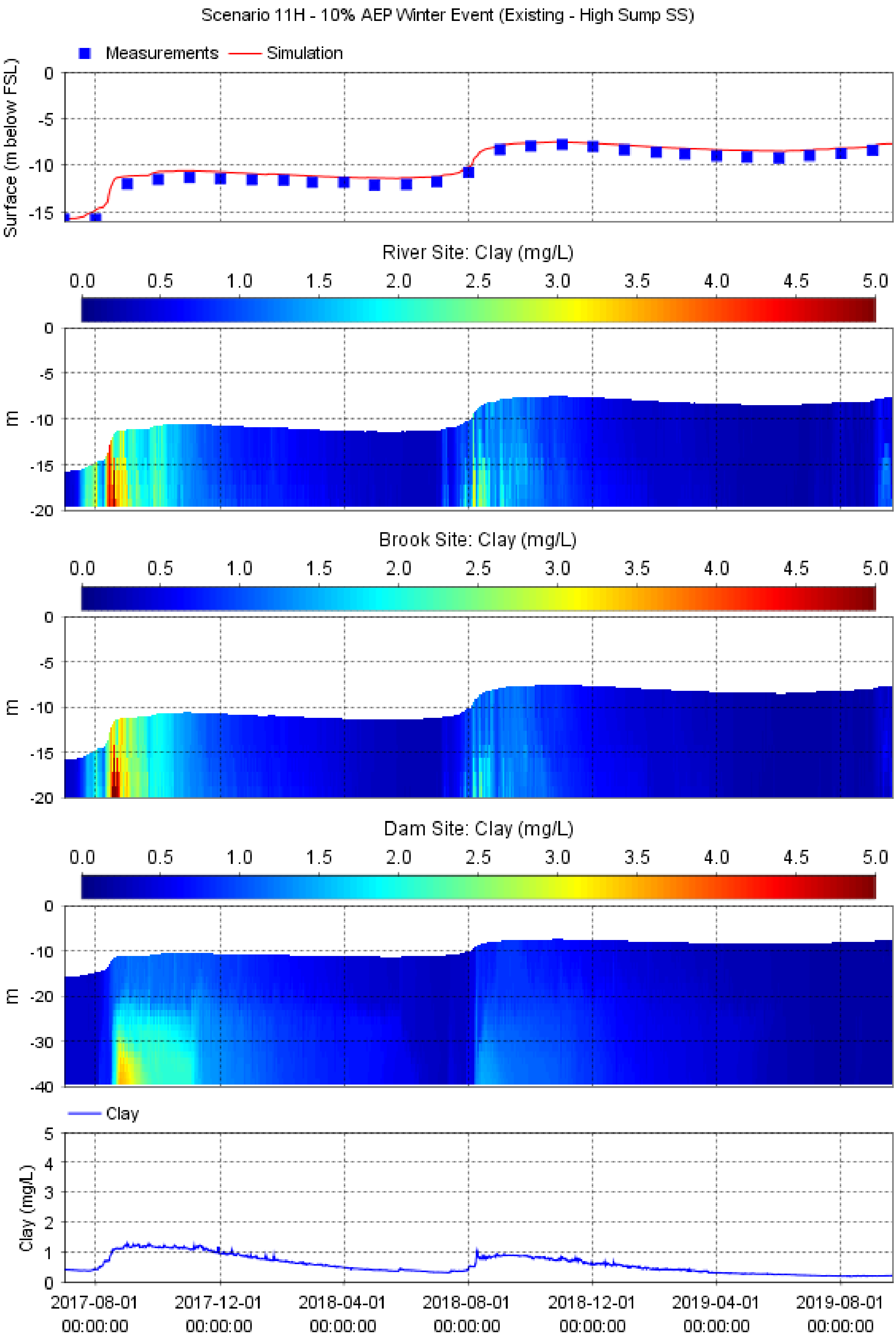

Figure 112 SMD simulated levels of clay for scenario 11H (winter existing case 10% AEP flood event) with high drainage failure SS levels.

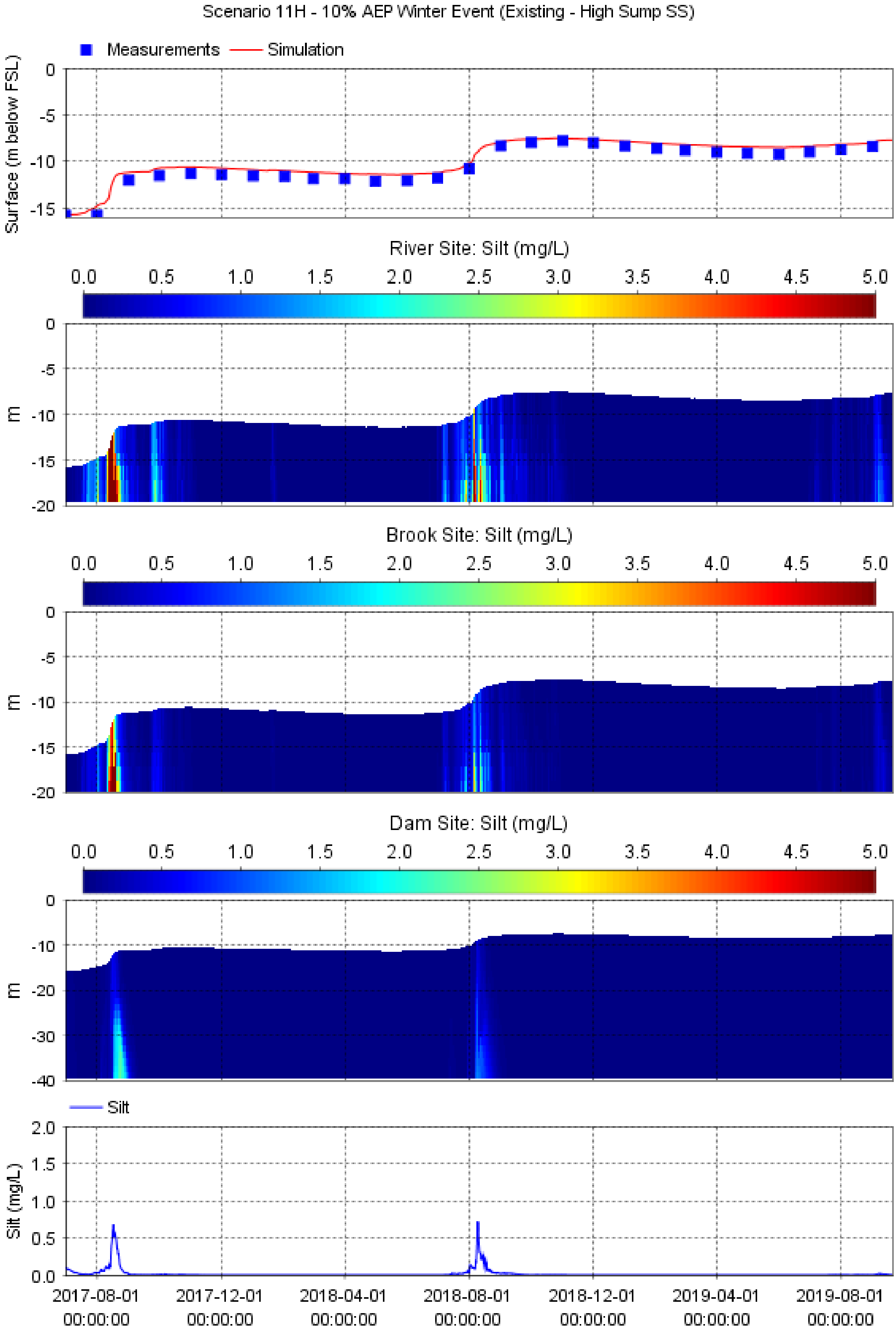

Figure 113 *SMD simulated levels of silt for scenario 11H (winter existing case 10% AEP flood event) with high drainage failure SS levels.*

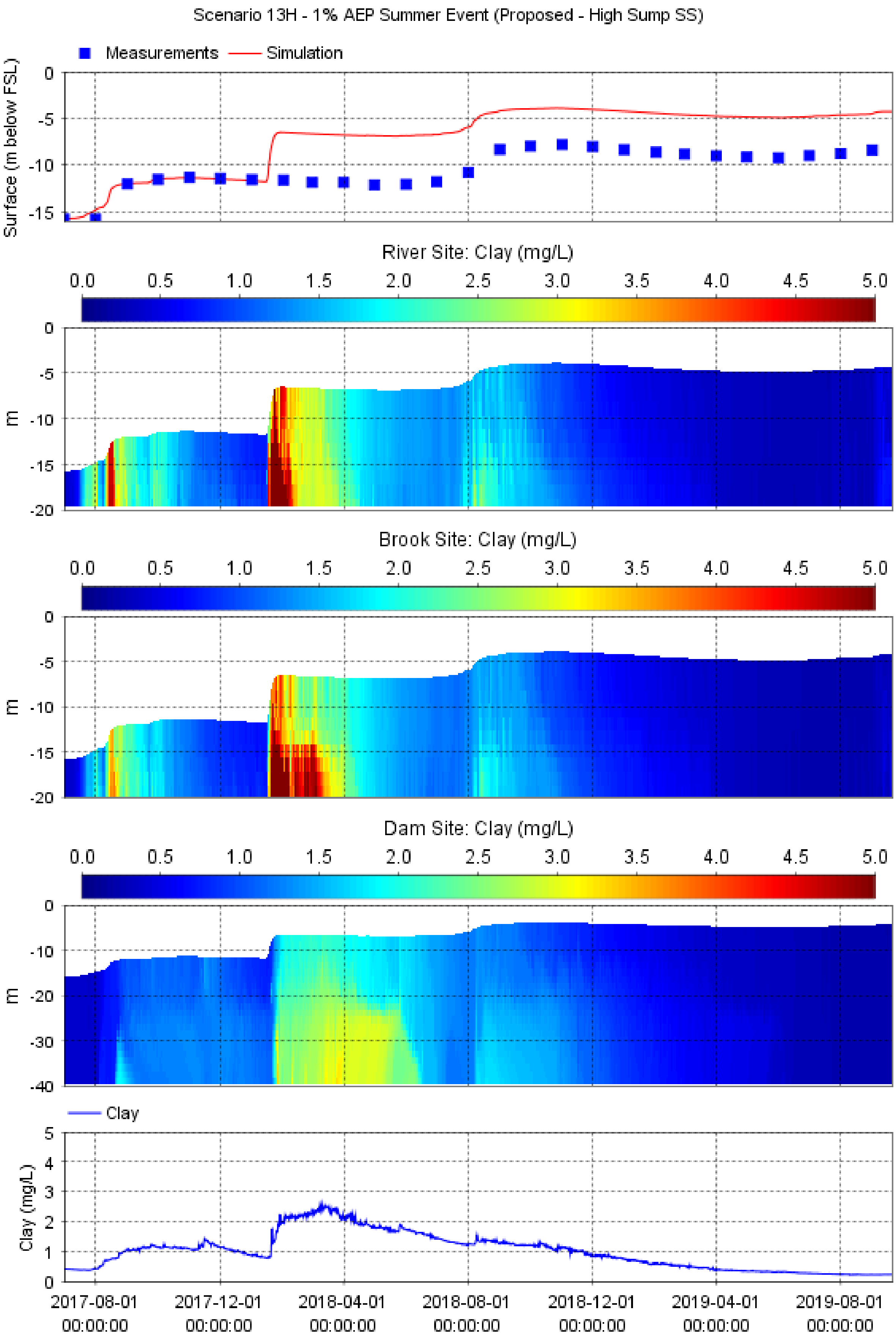

Figure 114 ***SMD simulated levels of clay for scenario 13H (summer proposed case 1% AEP flood event) with high drainage failure SS levels.***

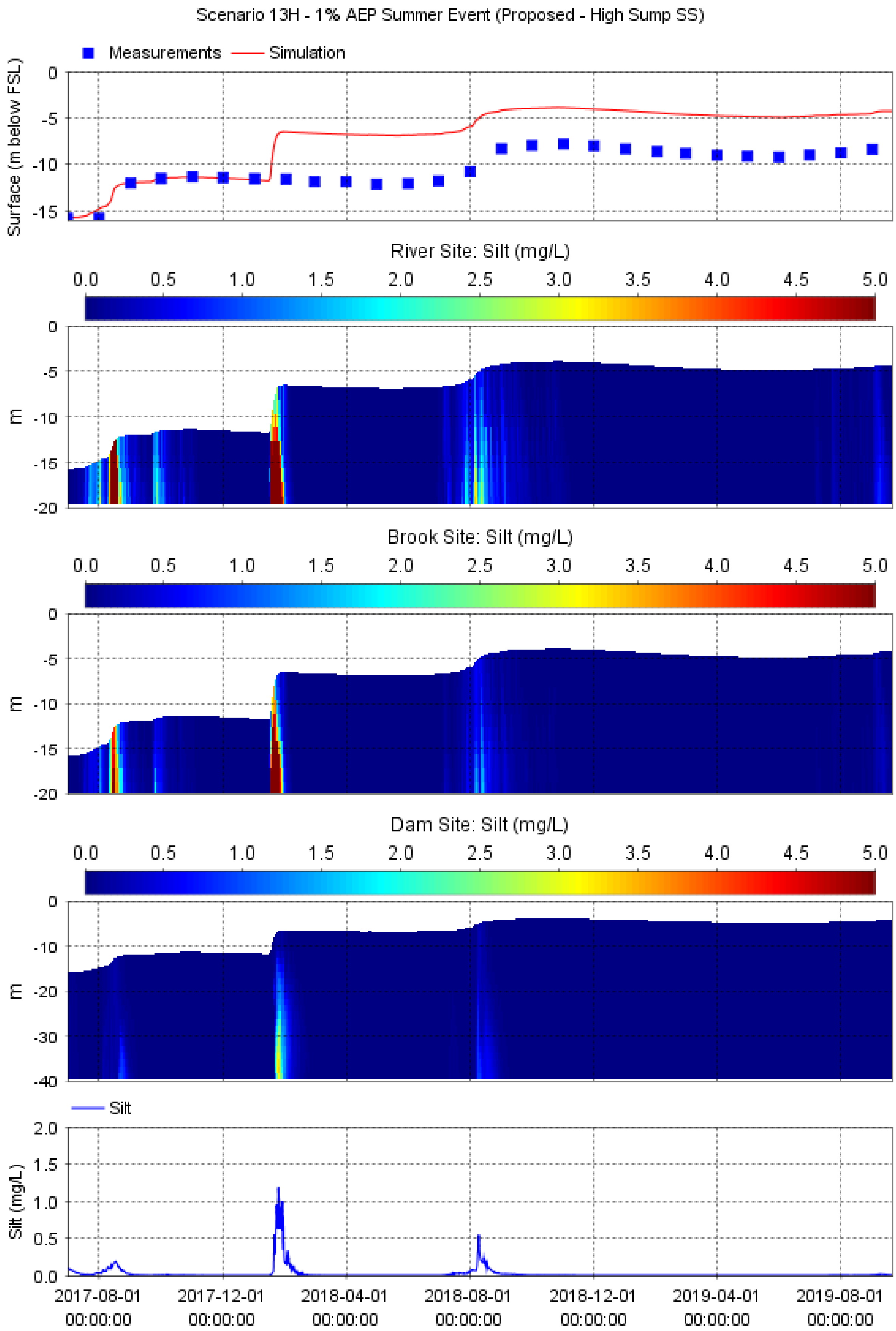

Figure 115 ***SMD simulated levels of silt for scenario 13H (summer proposed case 1% AEP flood event) with high drainage failure SS levels.***

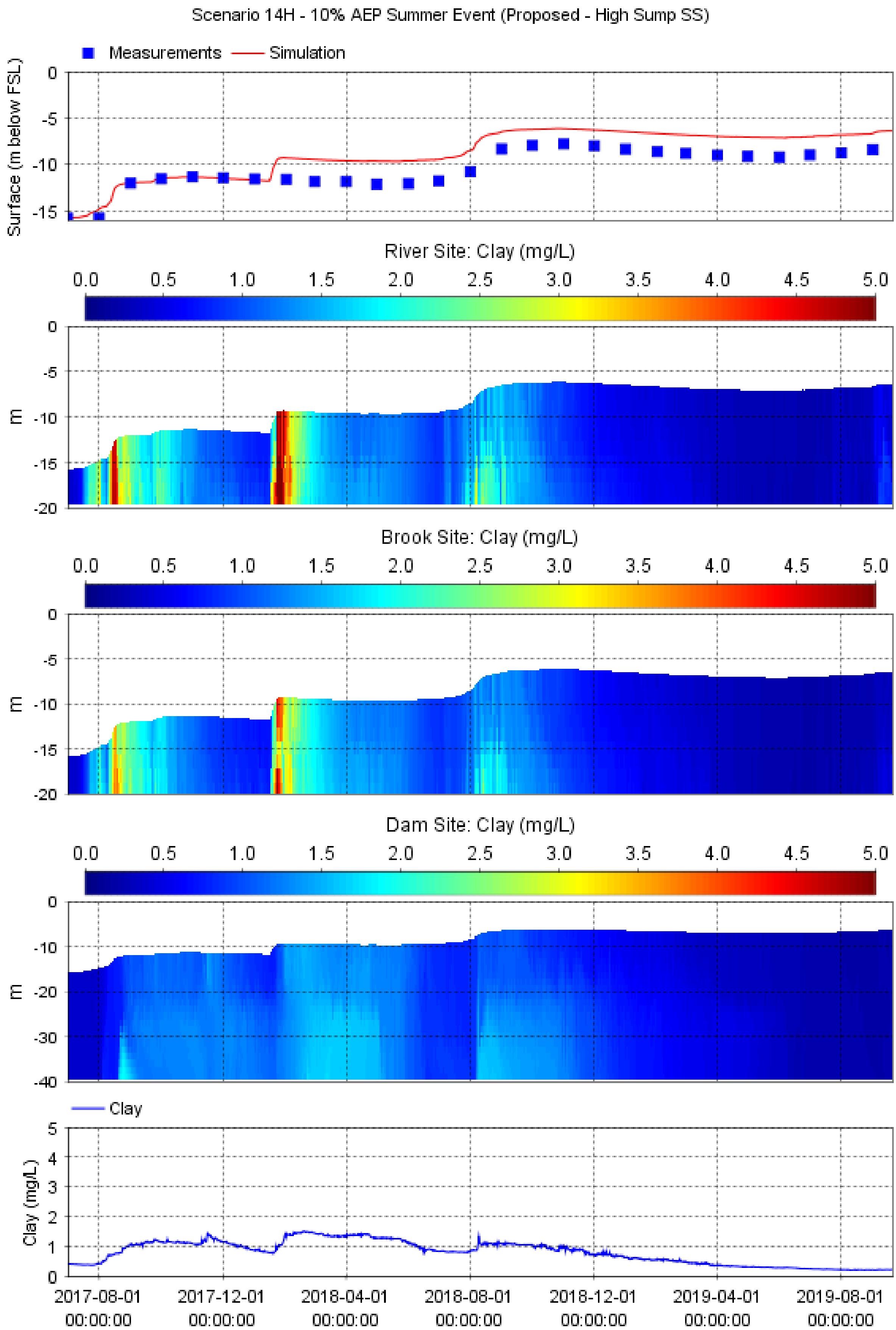

Figure 116 ***SMD simulated levels of clay for scenario 14H (summer proposed case 10% AEP flood event) with high drainage failure SS levels.***

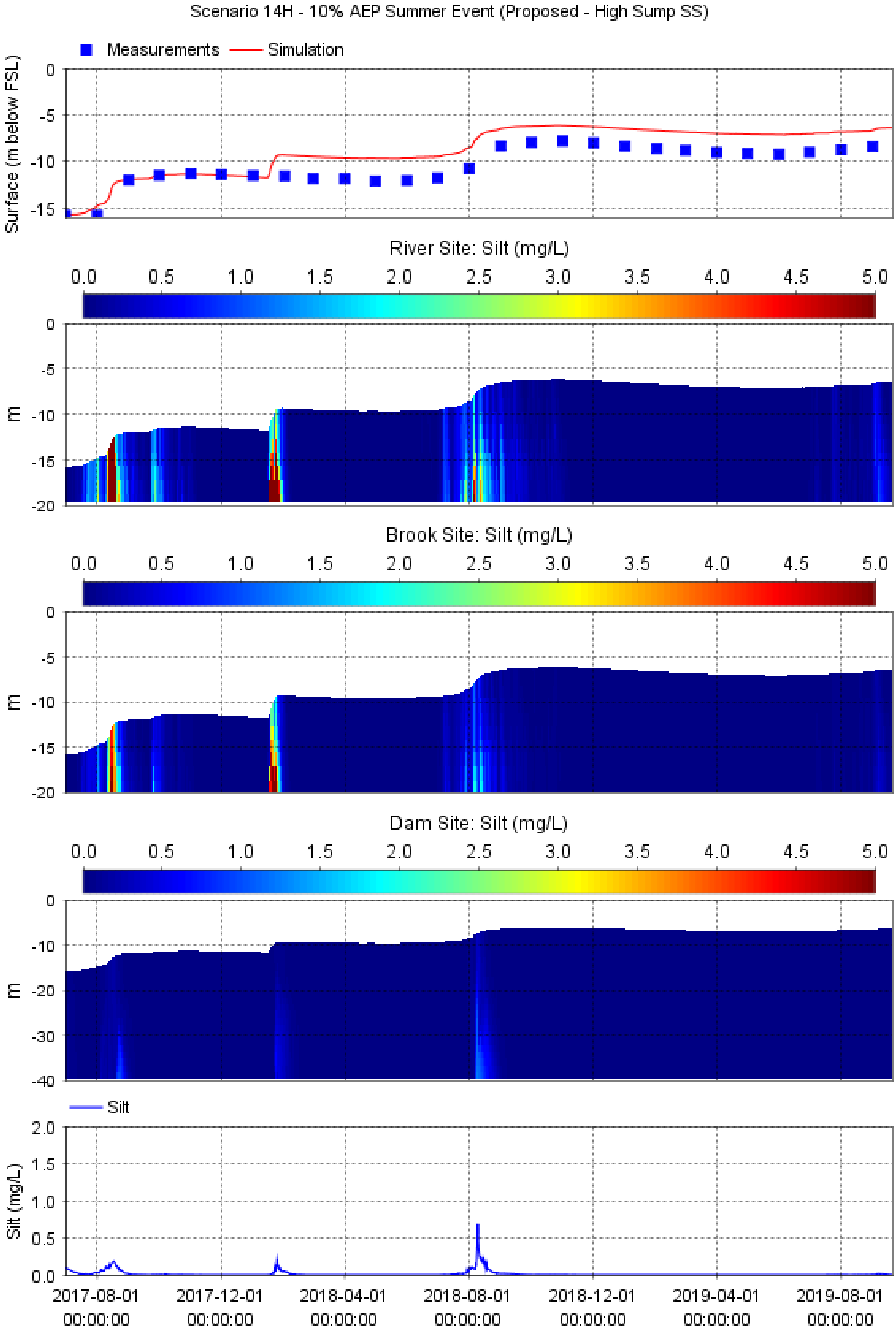

Figure 117 ***SMD simulated levels of silt for scenario 14H (summer proposed case 10% AEP flood event) with high drainage failure SS levels.***

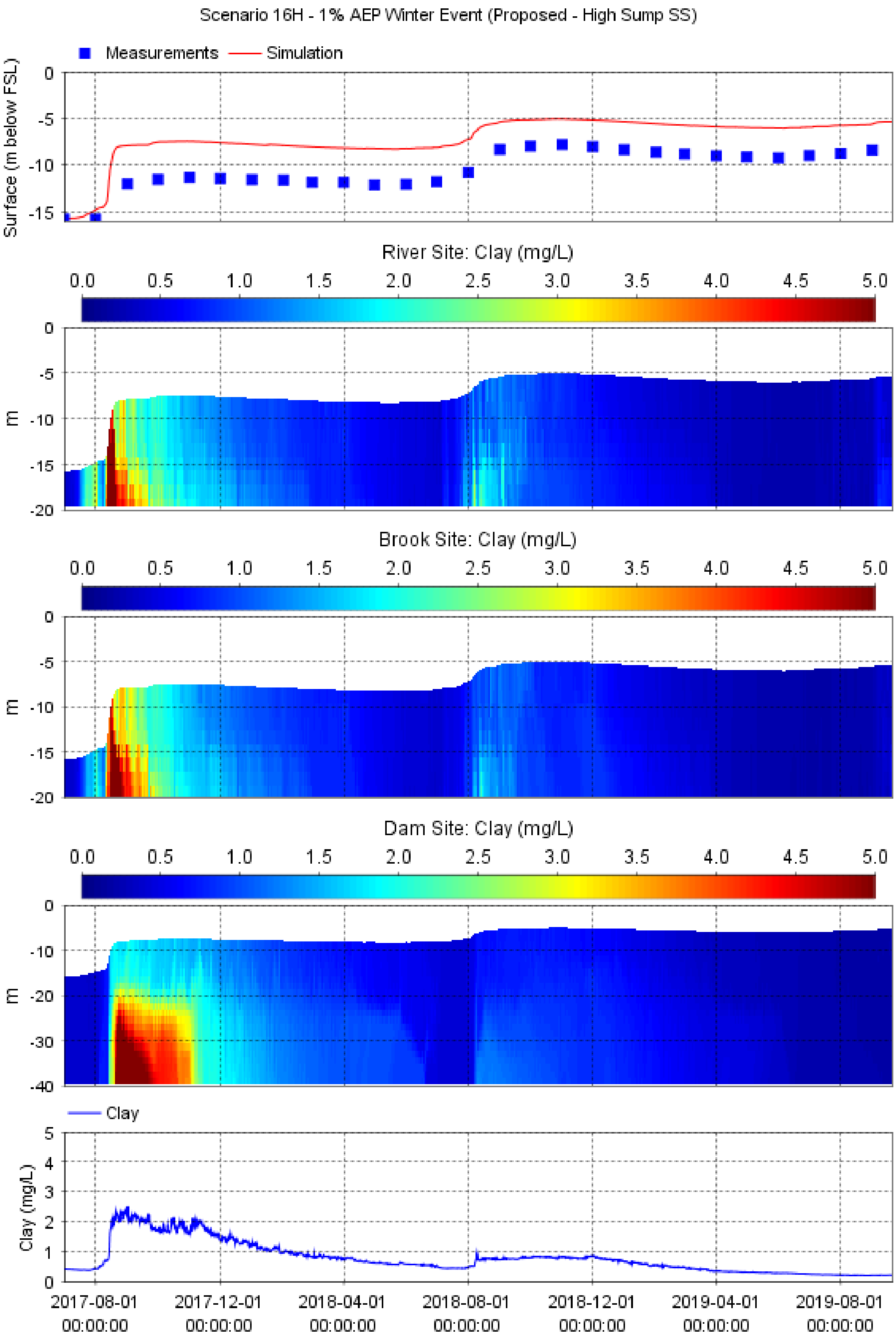

Figure 118 ***SMD simulated levels of clay for scenario 16H (winter proposed case 1% AEP flood event) with high drainage failure SS levels.***

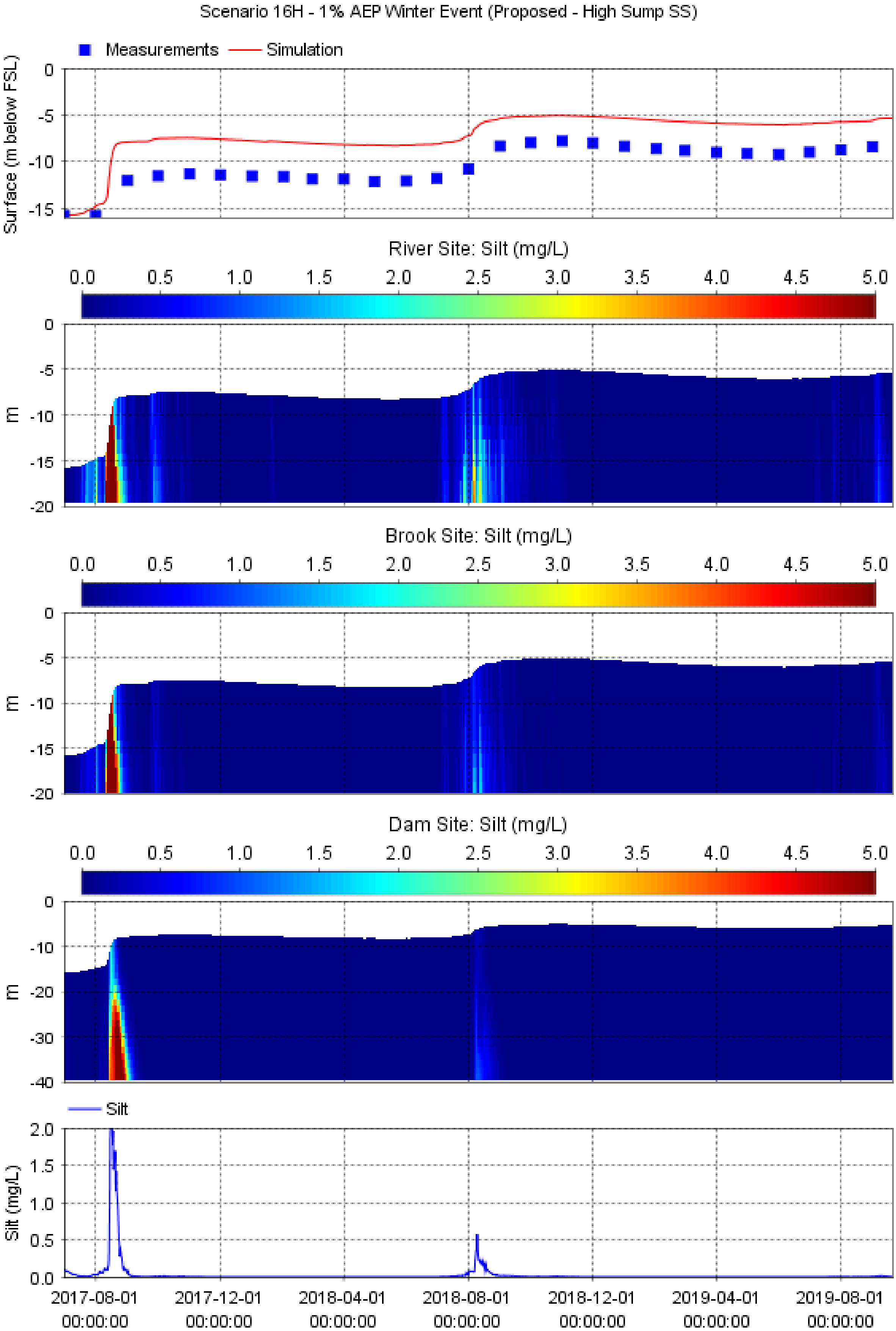

Figure 119 ***SMD simulated levels of silt for scenario 16H (winter proposed case 1% AEP flood event) with high drainage failure SS levels.***

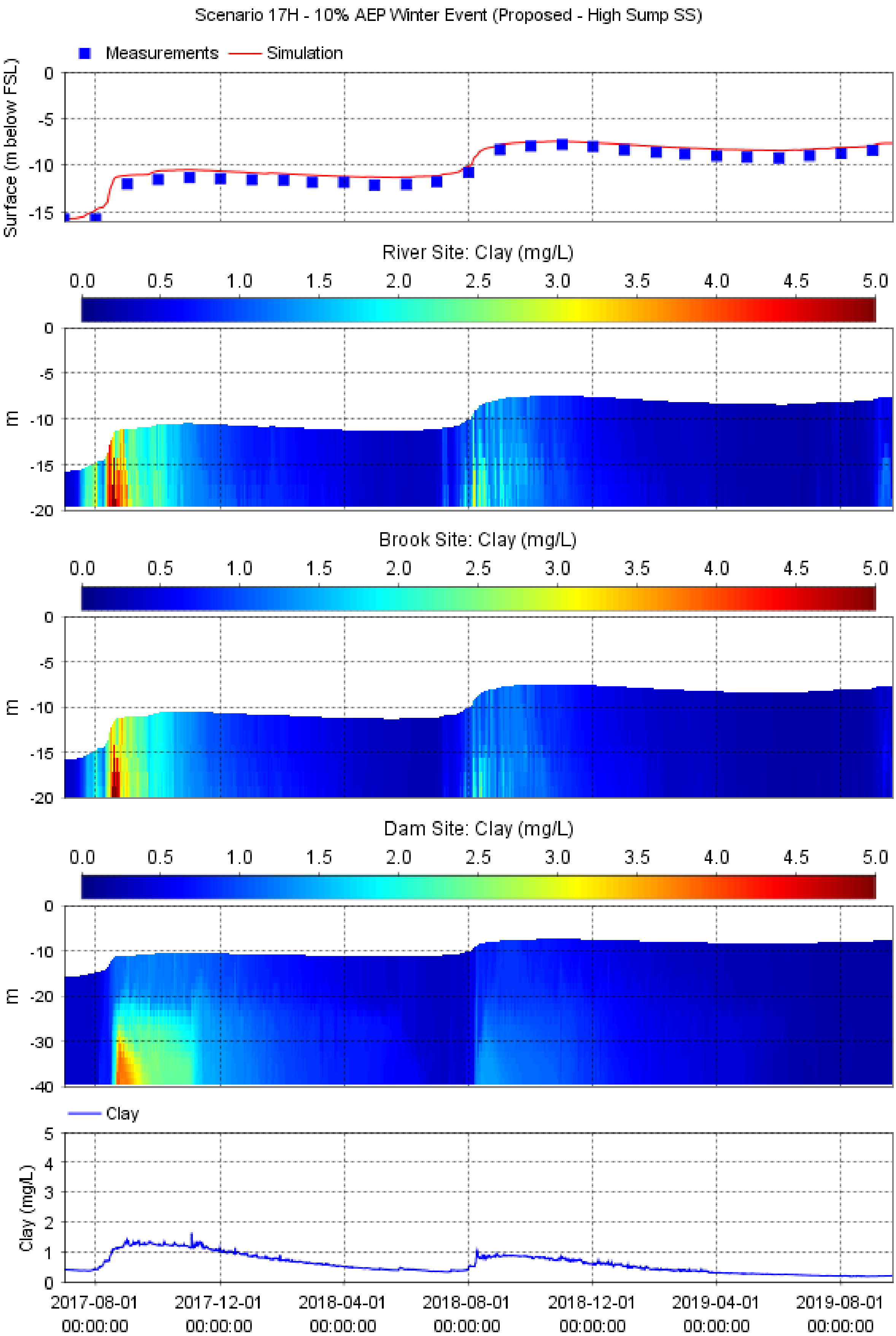

Figure 120 ***SMD simulated levels of clay for scenario 17H (winter proposed case 10% AEP flood event) with high drainage failure SS levels.***

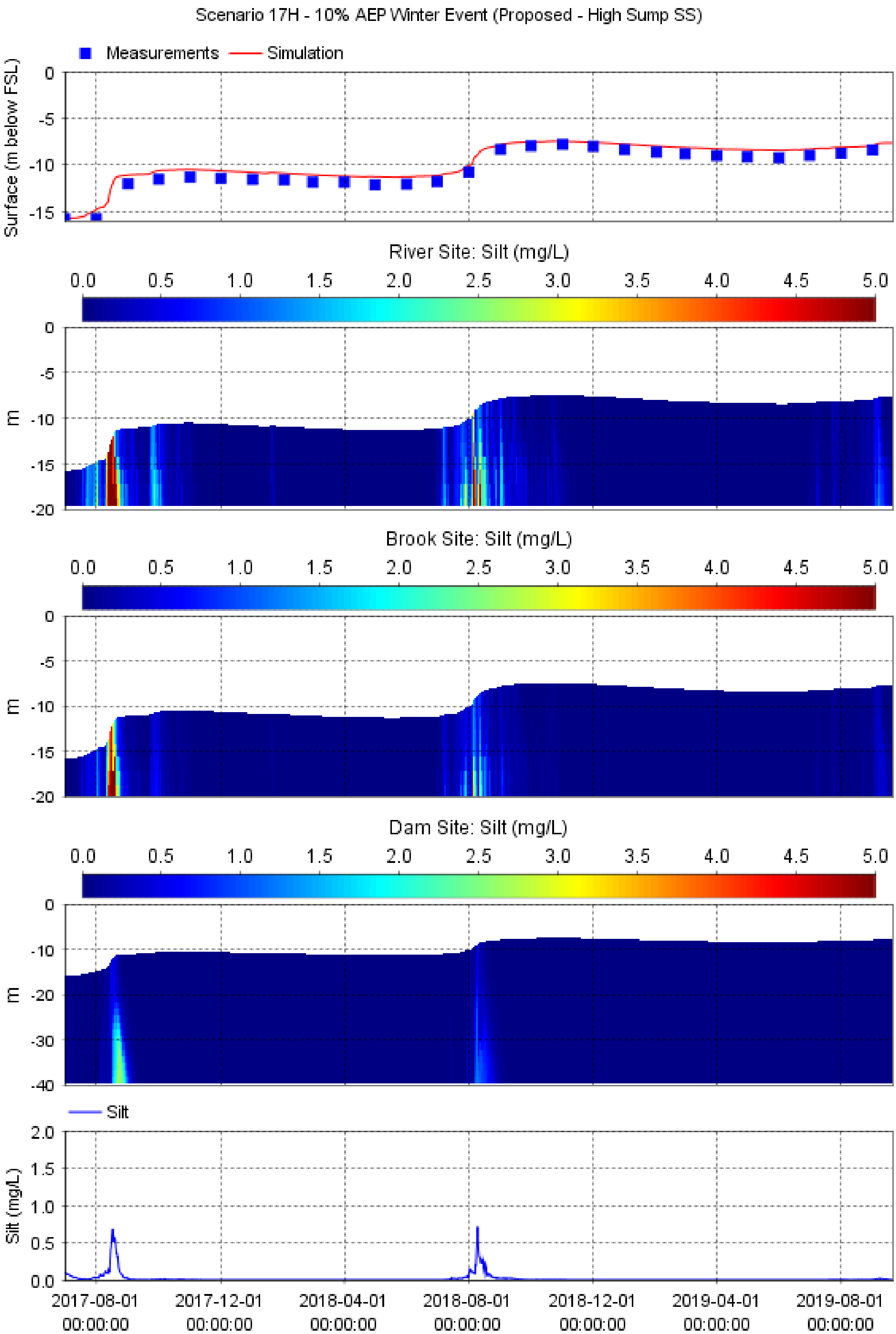

Figure 121 *SMD simulated levels of silt for scenario 17H (winter proposed case 10% AEP flood event) with high drainage failure SS levels.*

Appendix E

SDD: 1% and 10% AEP Flood Event Inputs (Moderate Drainage Failure SS Levels)

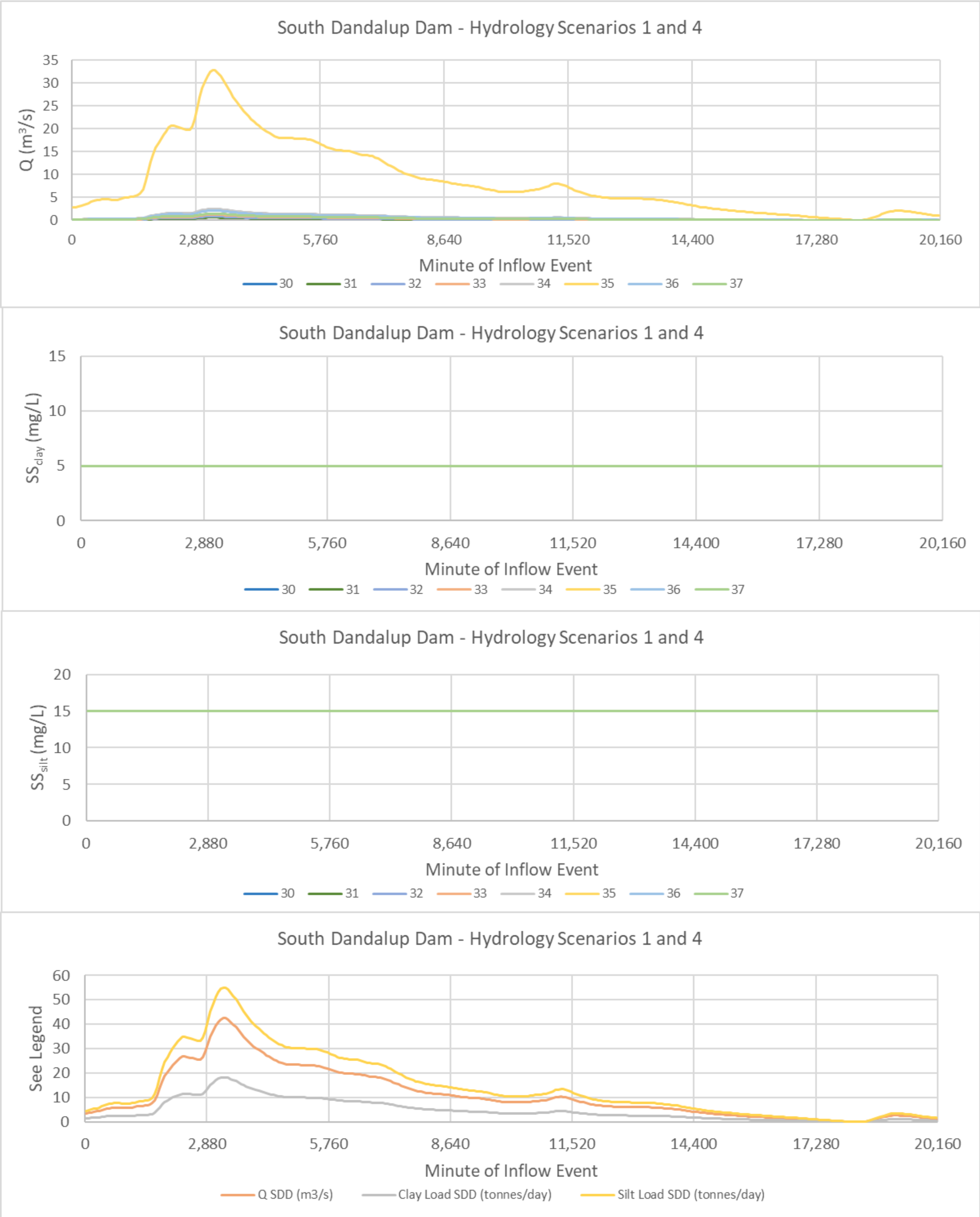

Figure 122 ***SDD hydrology and suspended solids inputs for scenarios 1 and 4.***

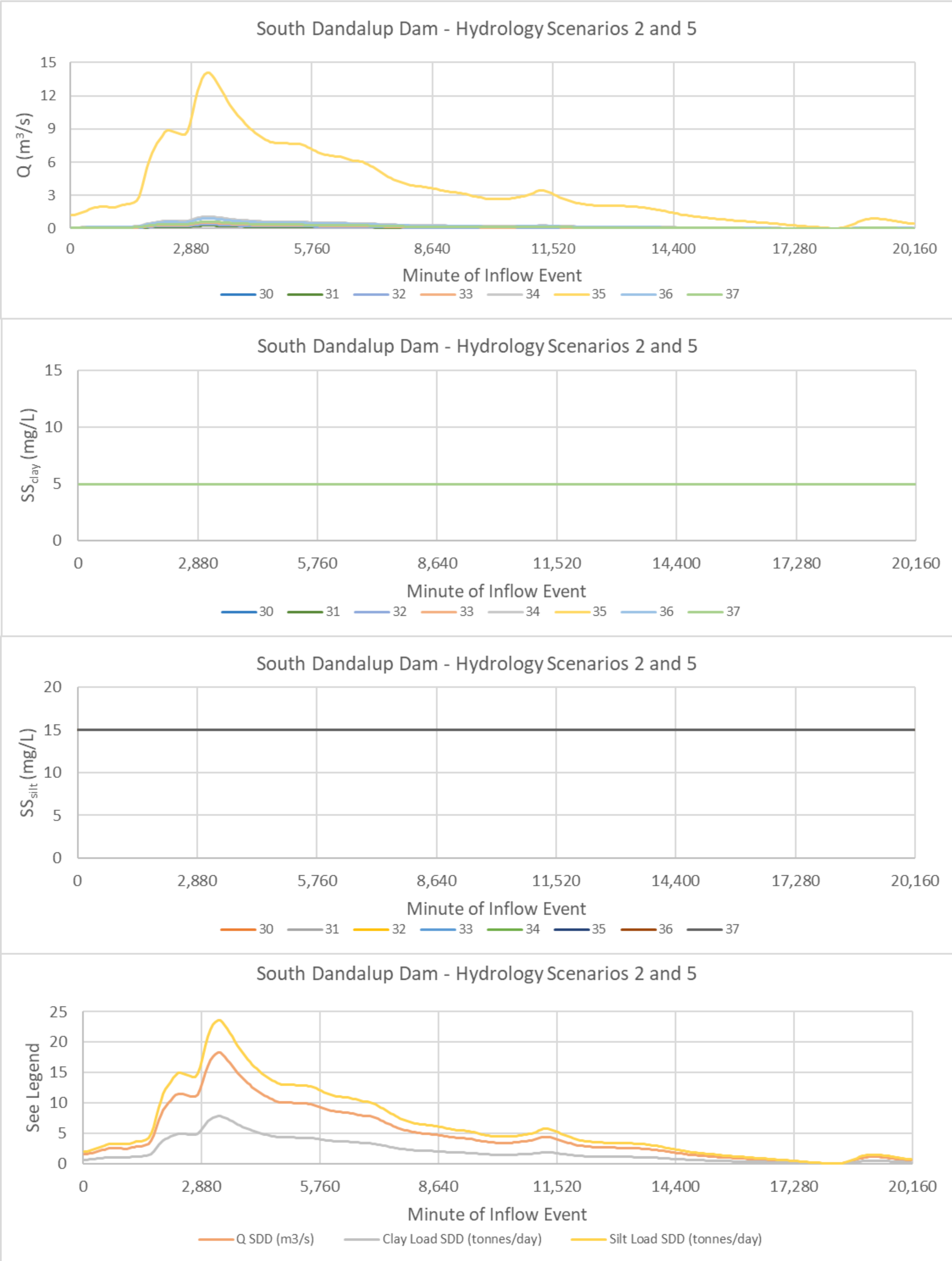

Figure 123 As Figure 122 for scenarios 2 and 5.

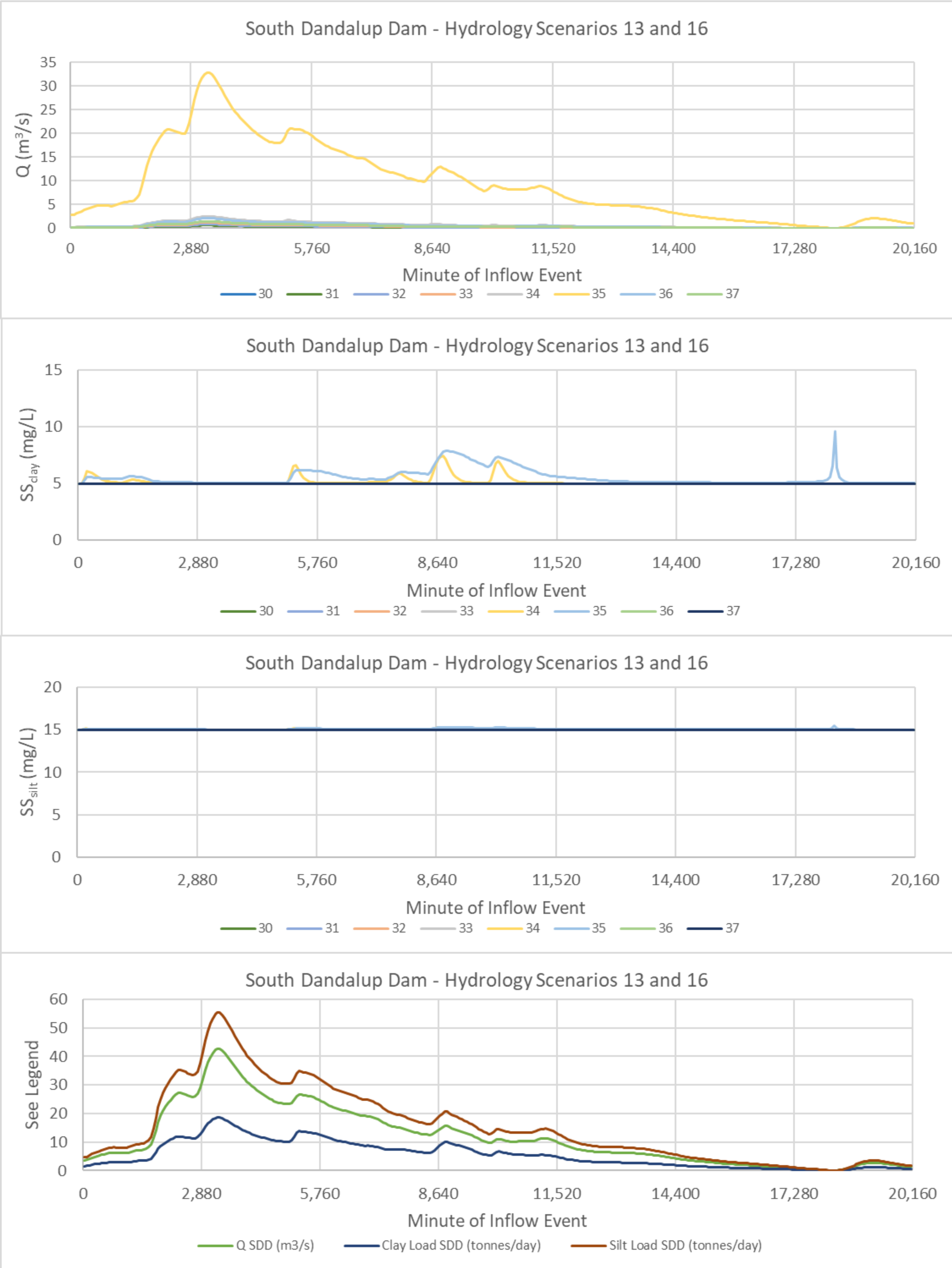

Figure 124 ***As Figure 122 for scenarios 13 and 16 with moderate drainage failure SS levels.***

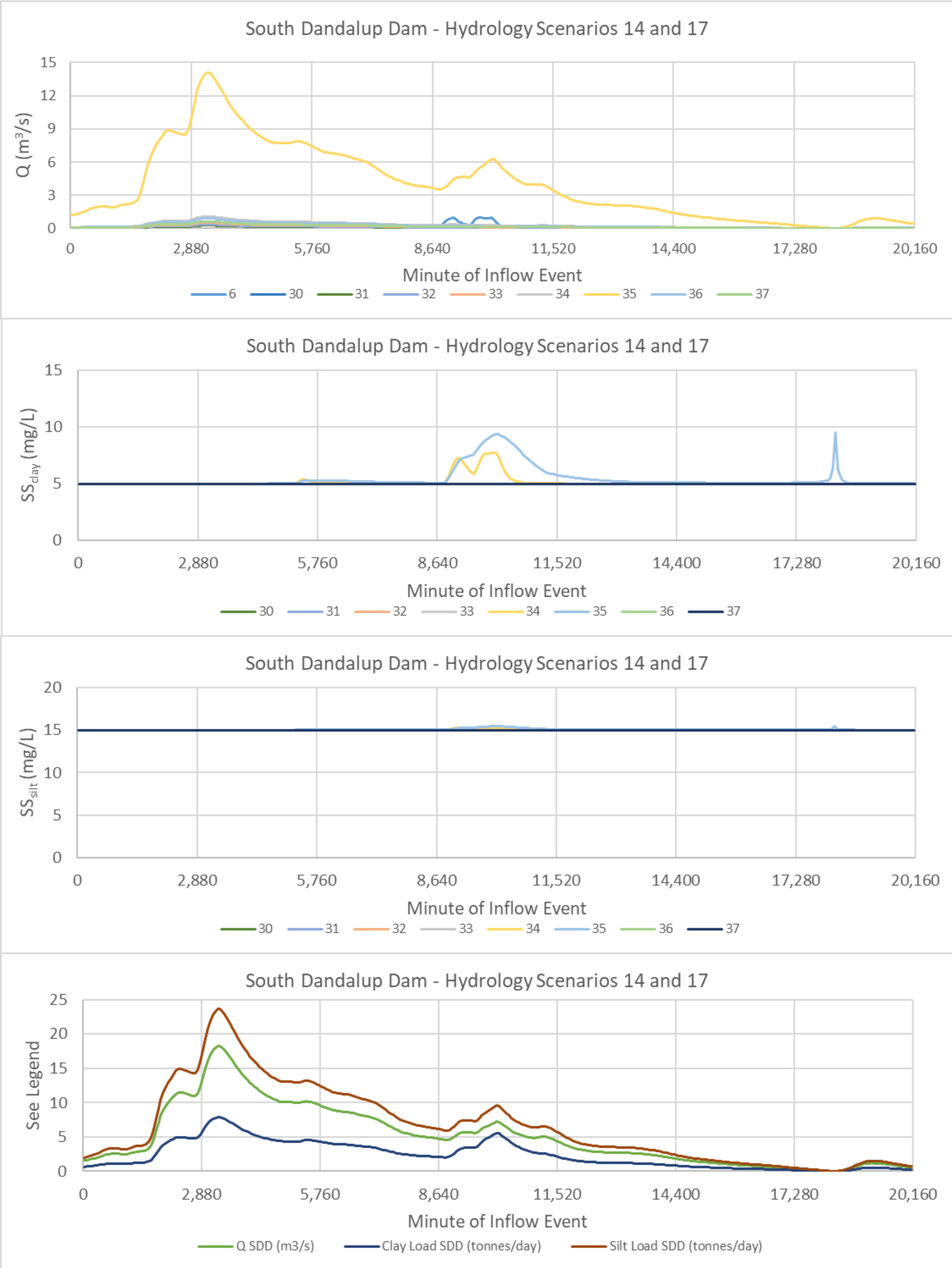

Figure 125 ***As Figure 122 for scenarios 14 and 17 with moderate drainage failure SS levels.***

Appendix F

SDD: 1% and 10% AEP Flood Event Simulations (Moderate Drainage Failure SS Levels)

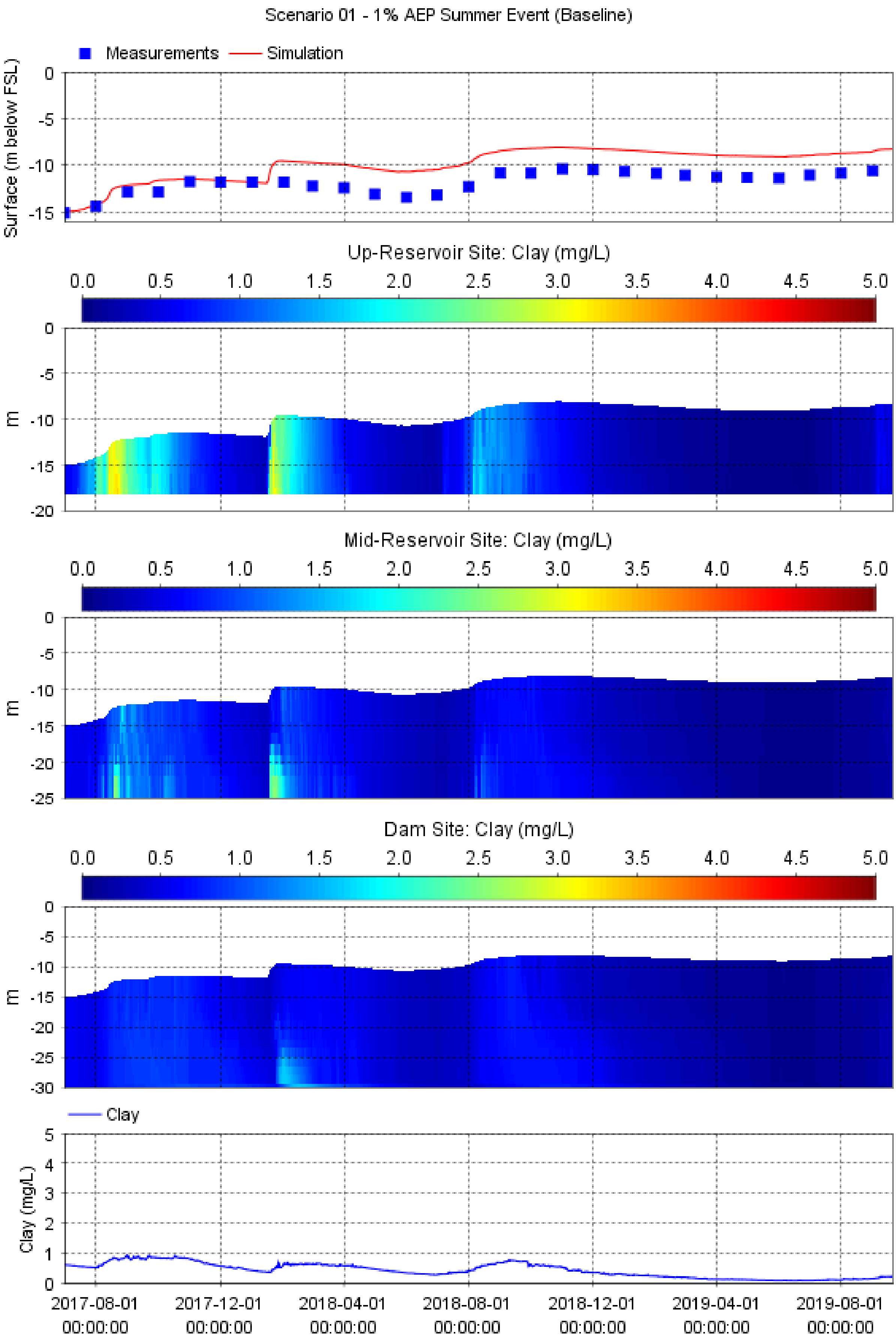

Figure 126 SDD simulated levels of clay for scenario 1 (summer baseline case 1% AEP flood event).

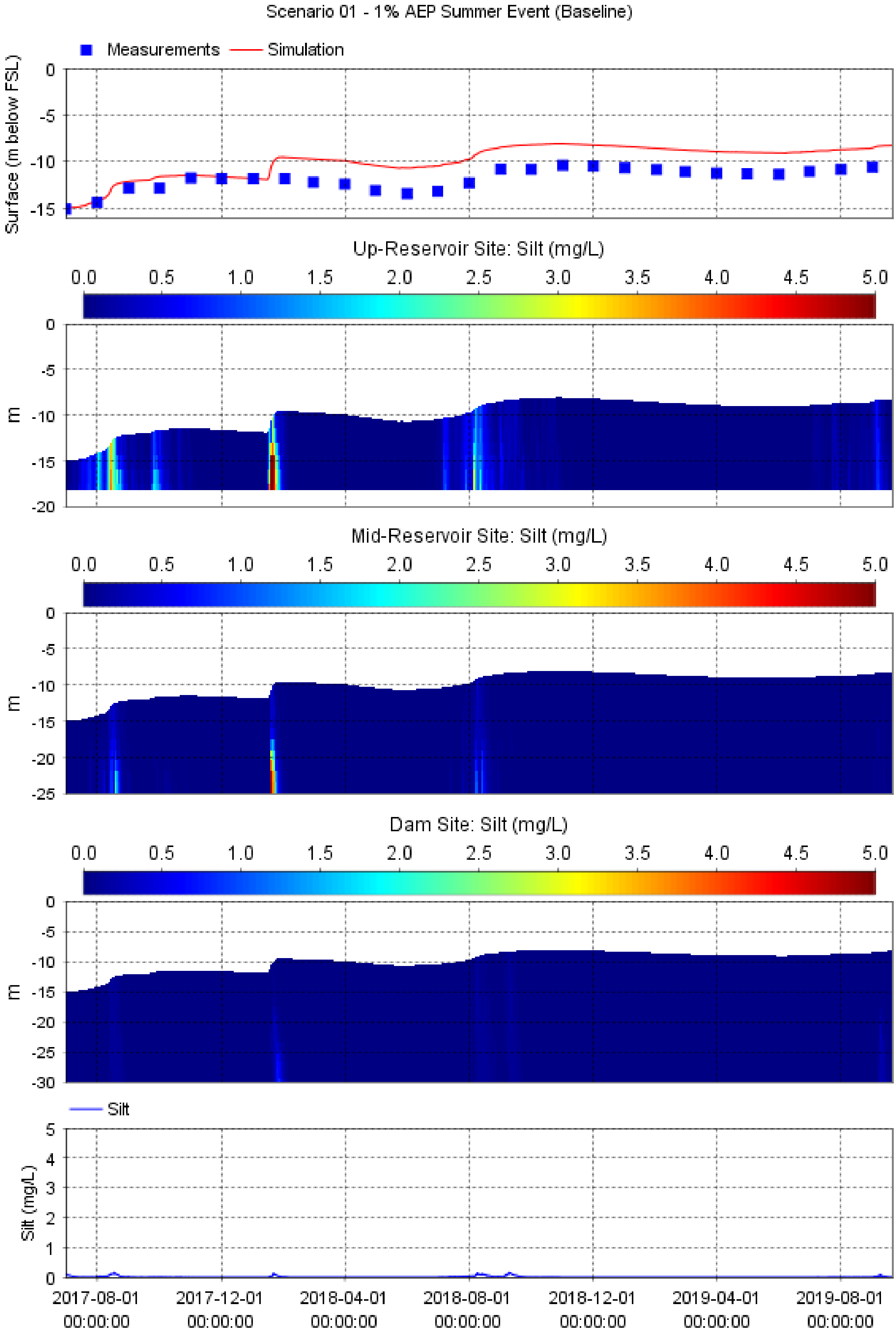

Figure 127 SDD simulated levels of silt for scenario 1 (summer baseline case 1% AEP flood event).

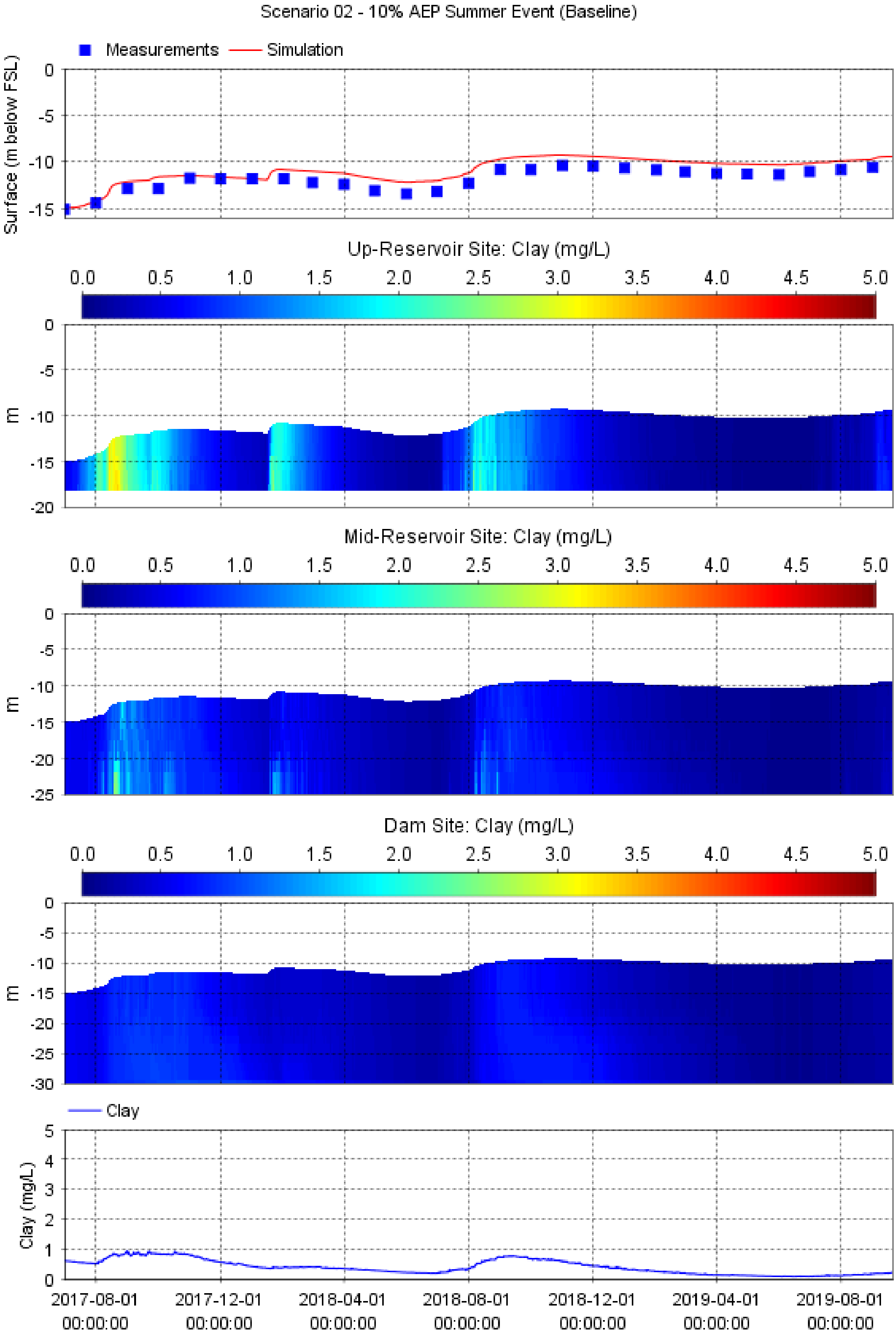

Figure 128 SDD simulated levels of clay for scenario 2 (summer baseline case 10% AEP flood event).

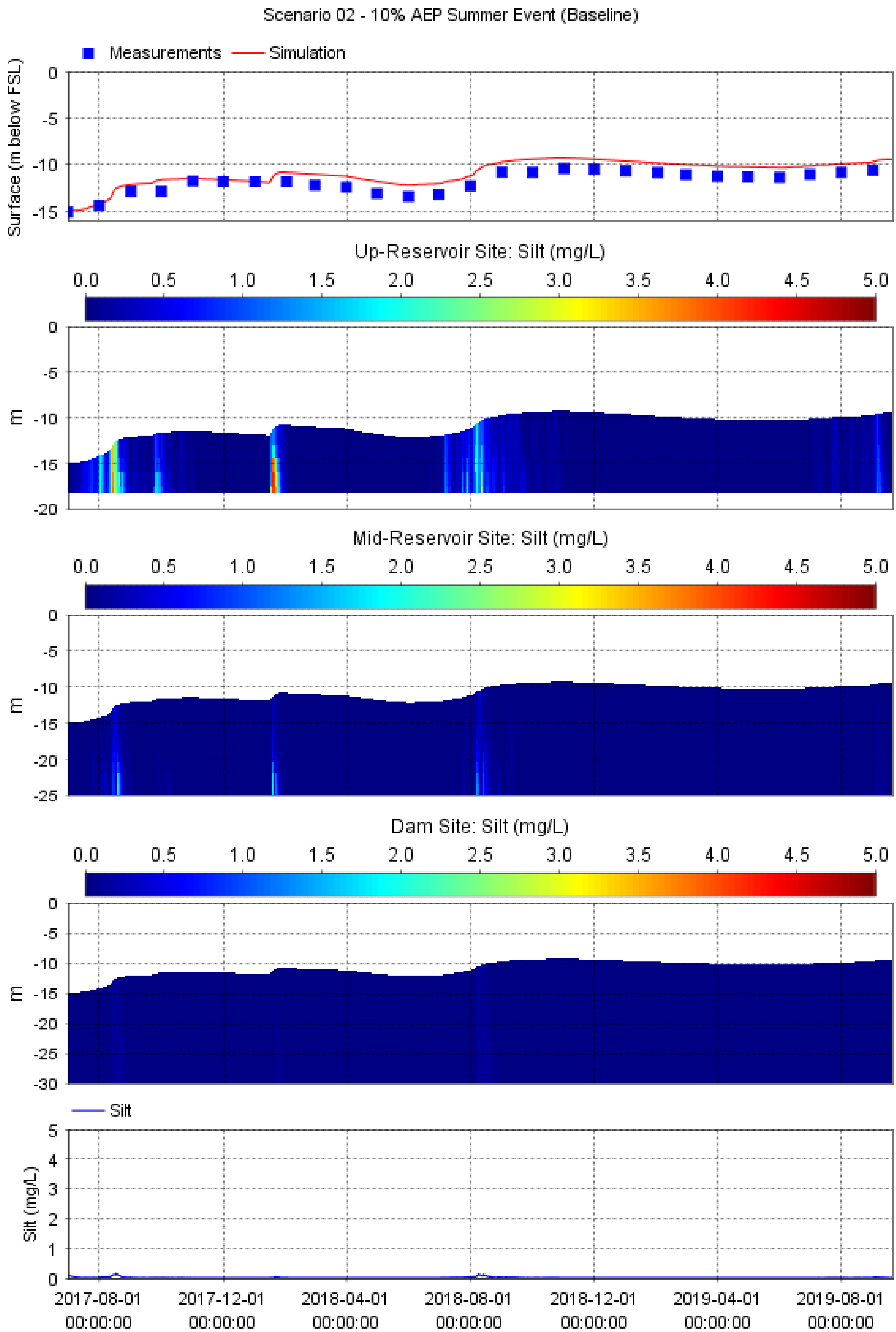

Figure 129 SDD simulated levels of silt for scenario 2 (summer baseline case 10% AEP flood event).

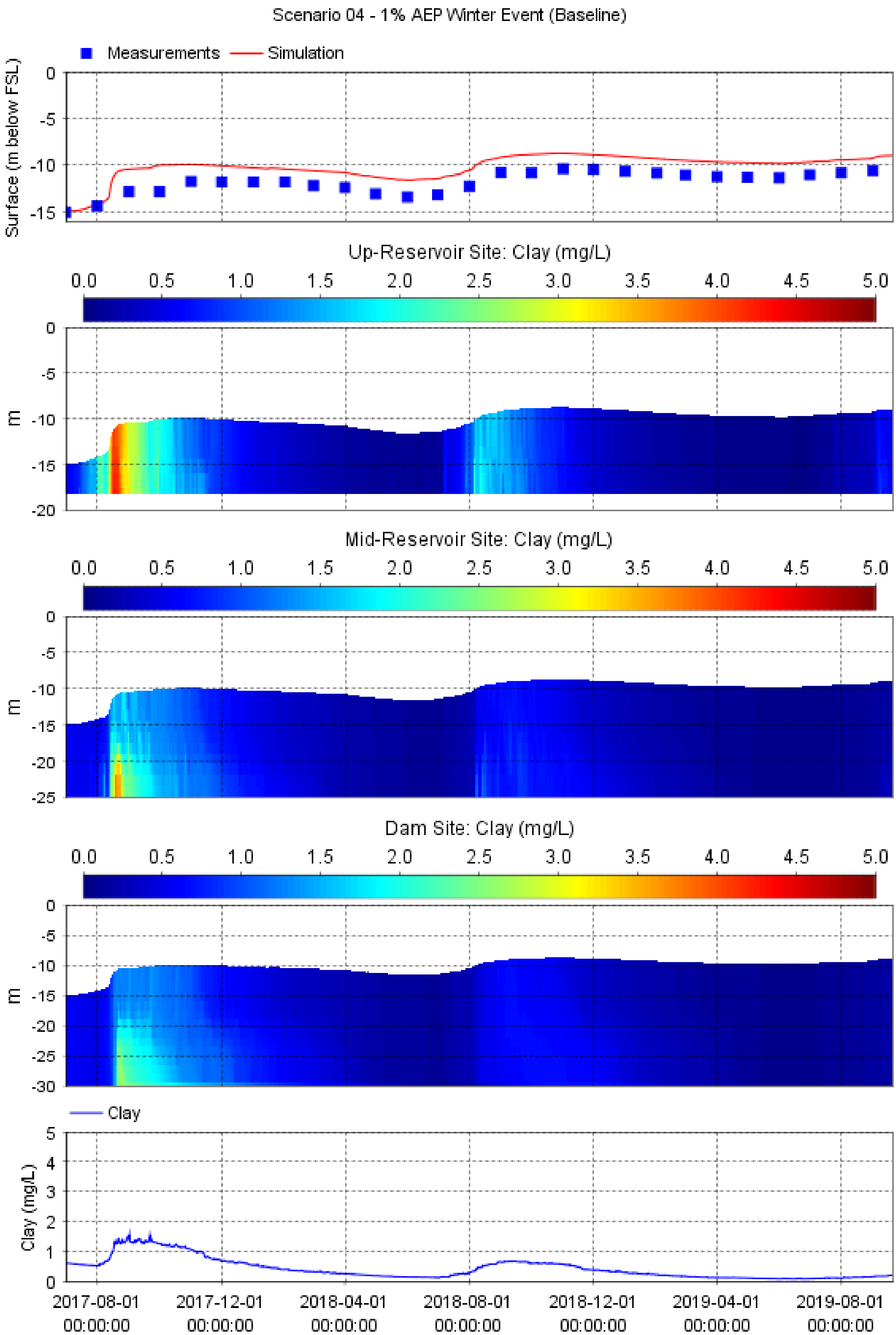

Figure 130 SDD simulated levels of clay for scenario 4 (winter baseline case 1% AEP flood event).

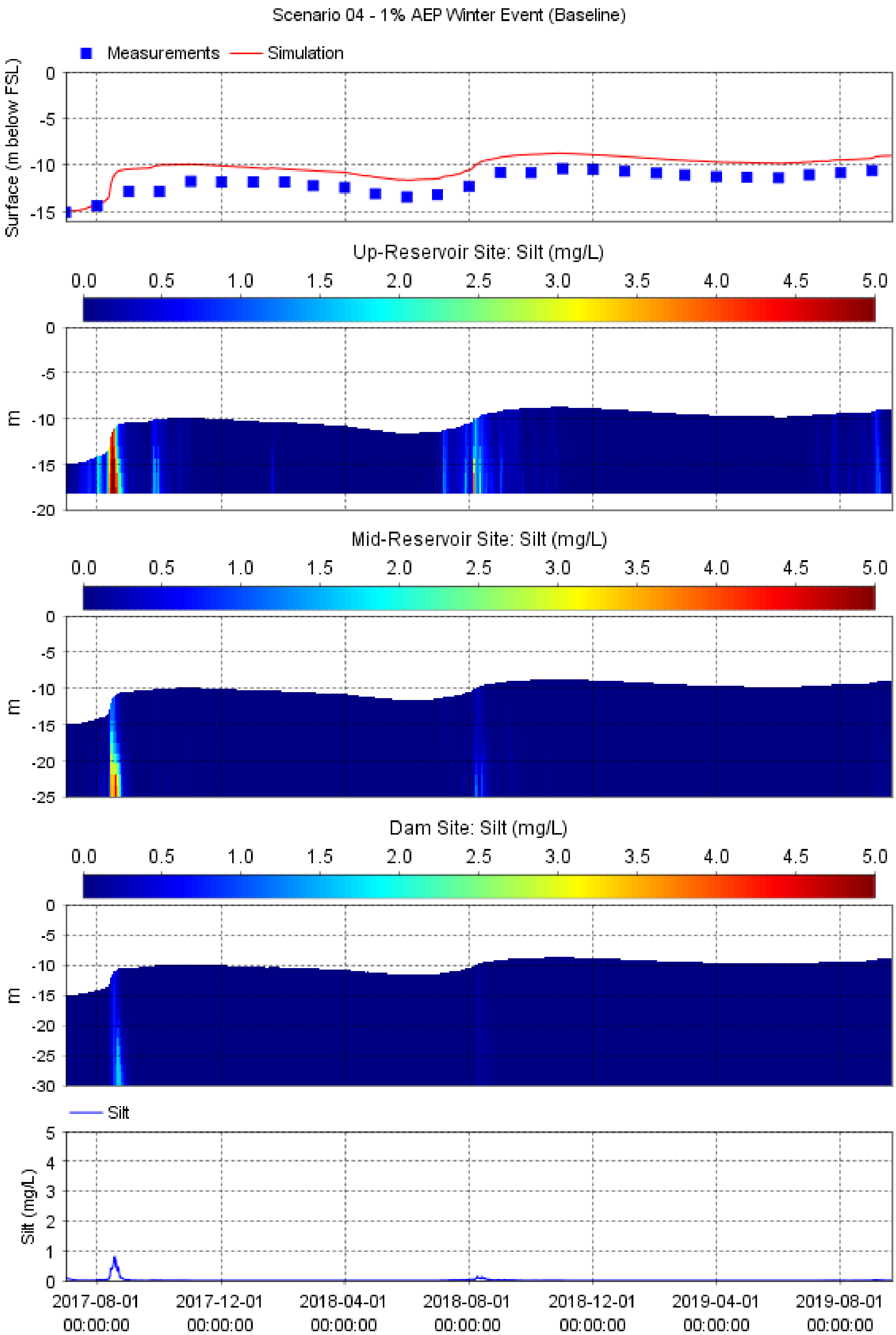

Figure 131 SDD simulated levels of silt for scenario 4 (winter baseline case 1% AEP flood event).

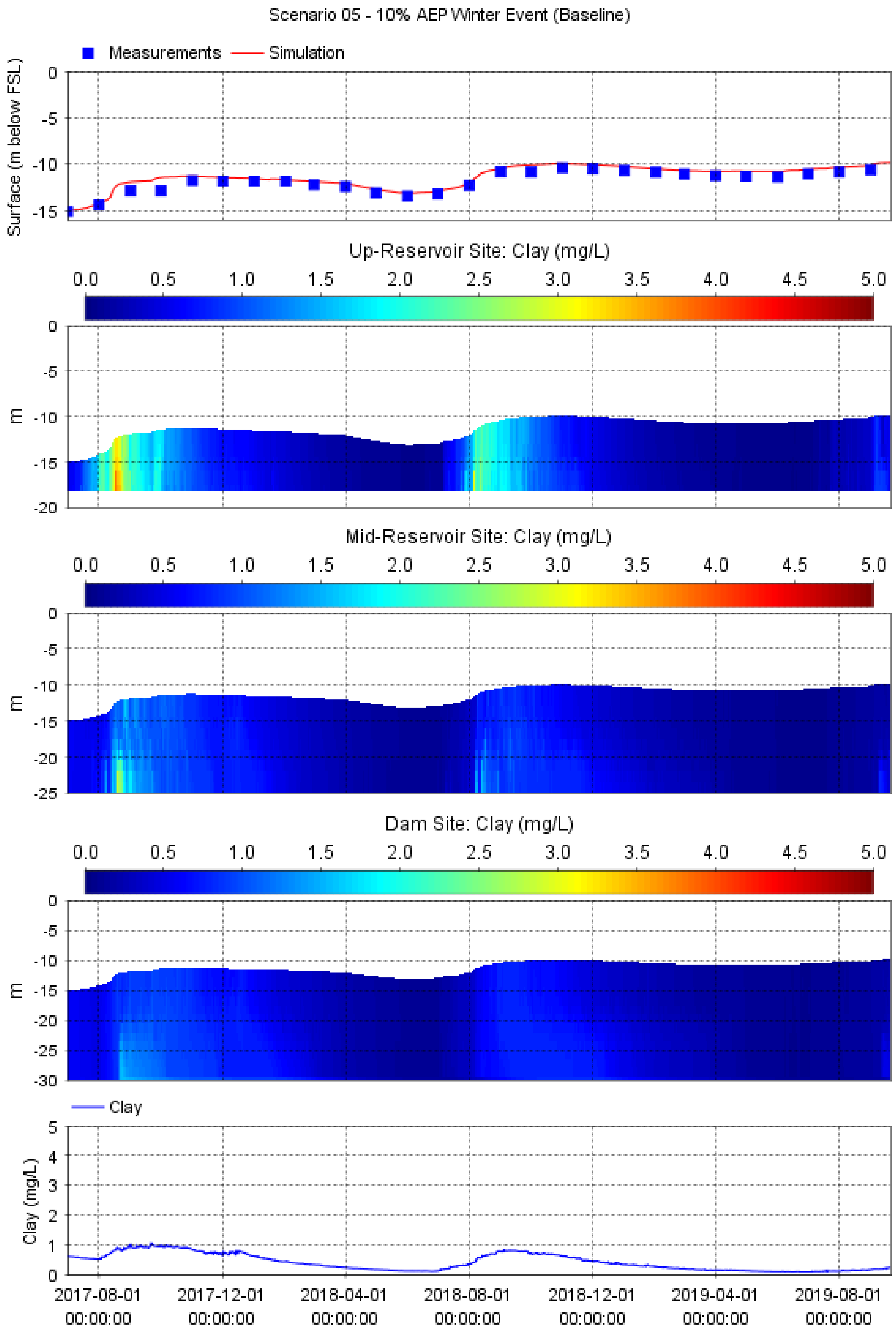

Figure 132 SDD simulated levels of clay for scenario 5 (winter baseline case 10% AEP flood event).

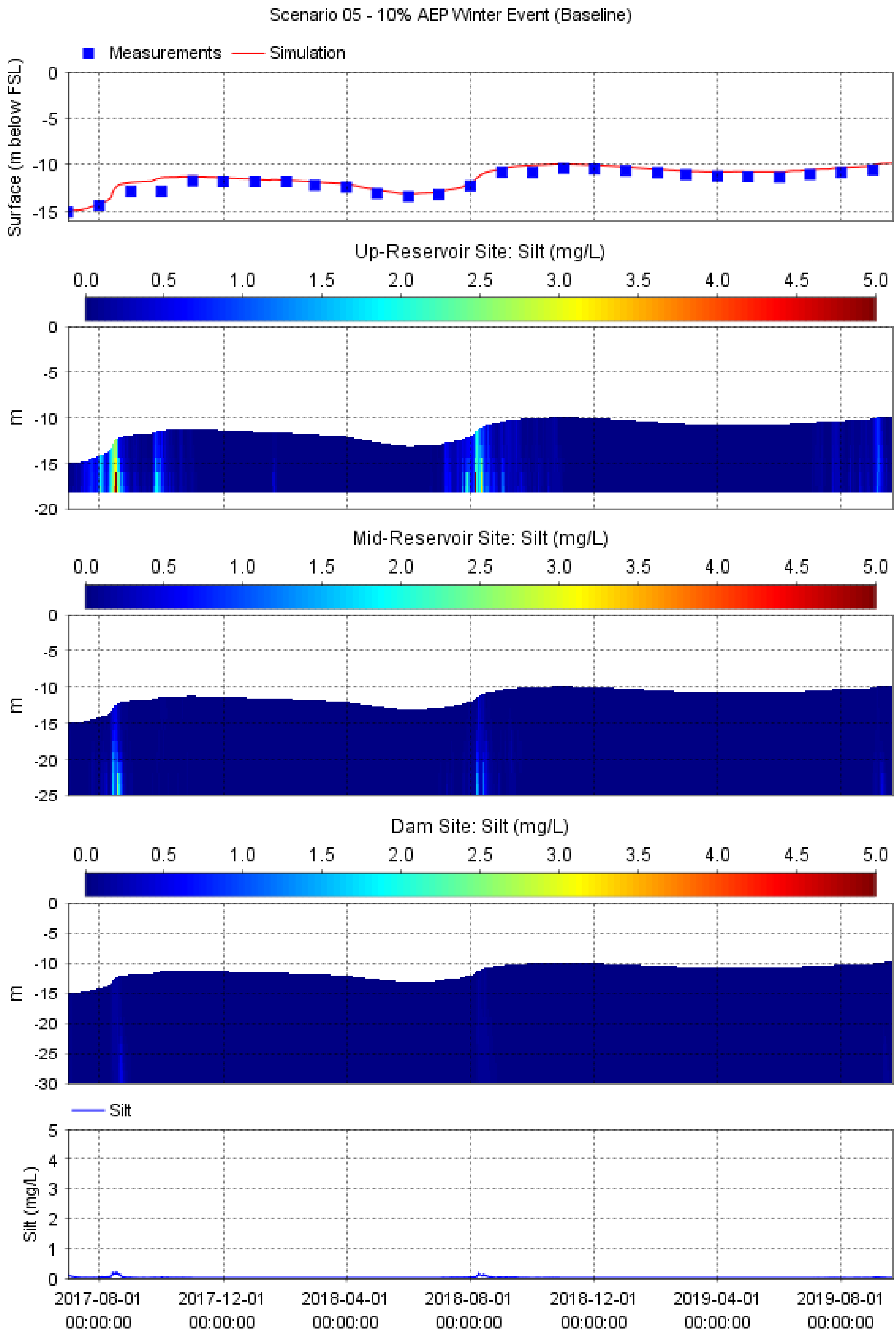

Figure 133 SDD simulated levels of silt for scenario 5 (winter baseline case 10% AEP flood event).

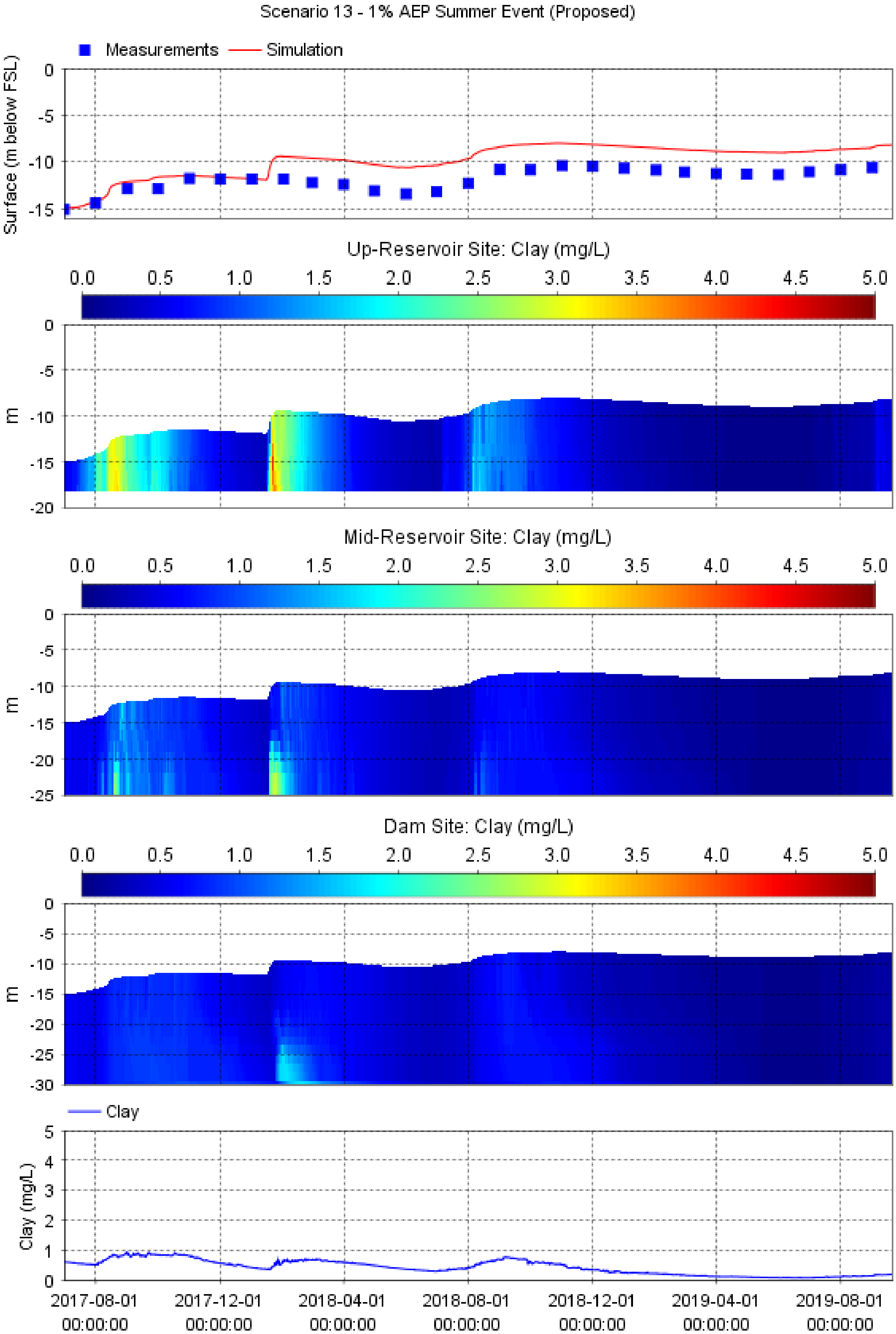

Figure 134 SDD simulated levels of clay for scenario 13 (summer proposed case 1% AEP flood event) with moderate drainage failure SS levels.

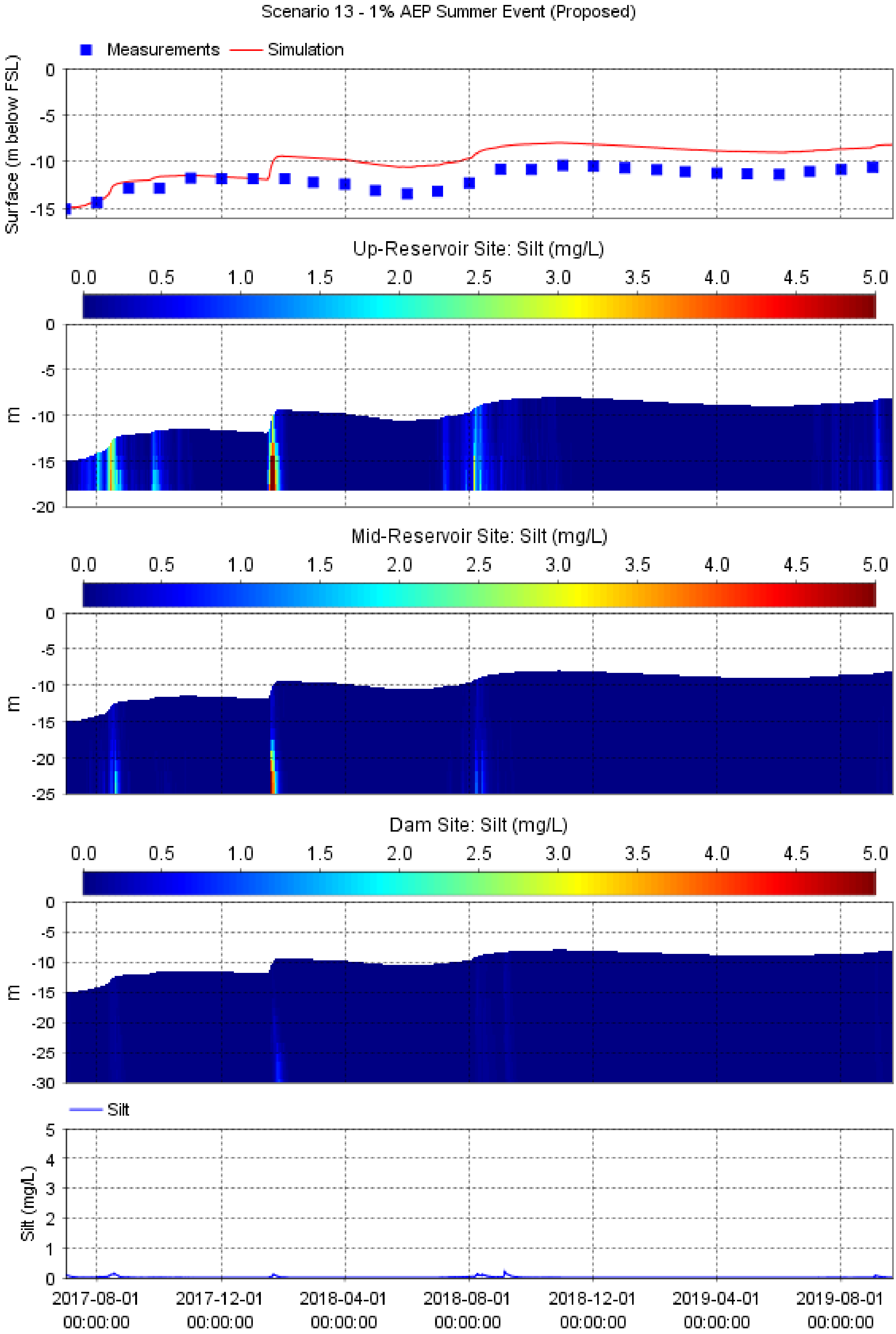

Figure 135 ***SDD simulated levels of silt for scenario 13 (summer proposed case 1% AEP flood event) with moderate drainage failure SS levels.***

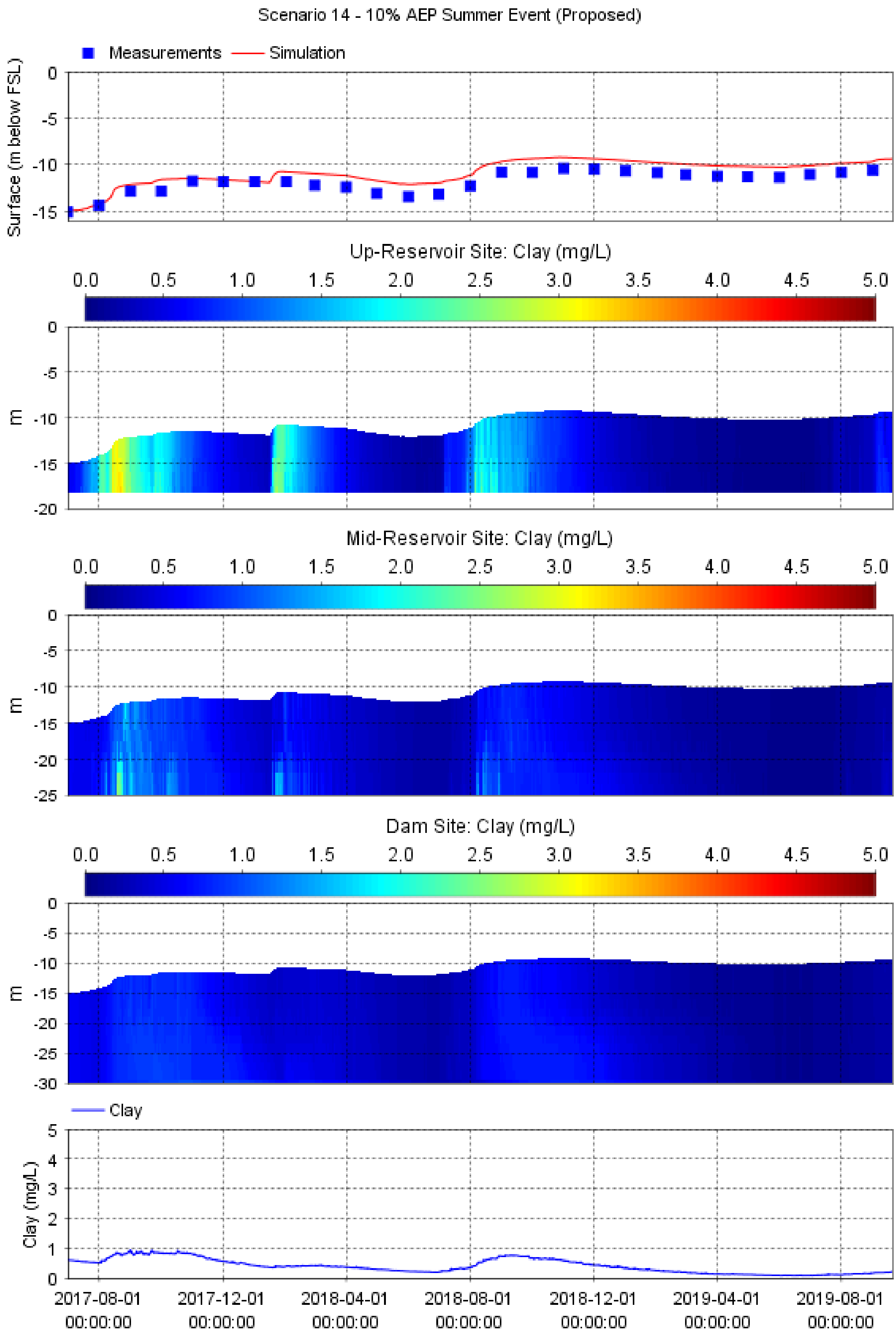

Figure 136 *SDD simulated levels of clay for scenario 14 (summer proposed case 10% AEP flood event) with moderate drainage failure SS levels.*

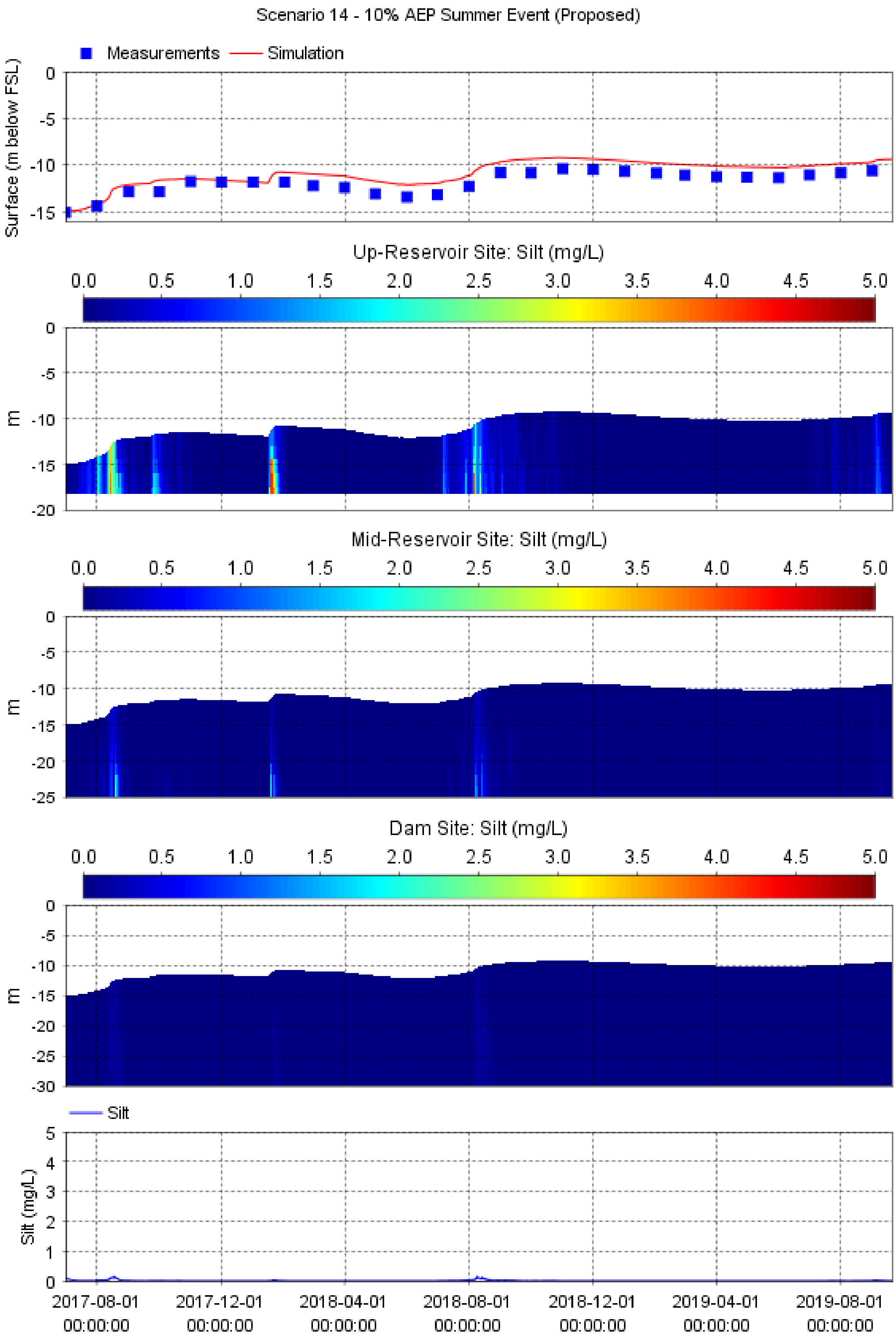

Figure 137 *SDD simulated levels of silt for scenario 14 (summer proposed case 10% AEP flood event) with moderate drainage failure SS levels.*

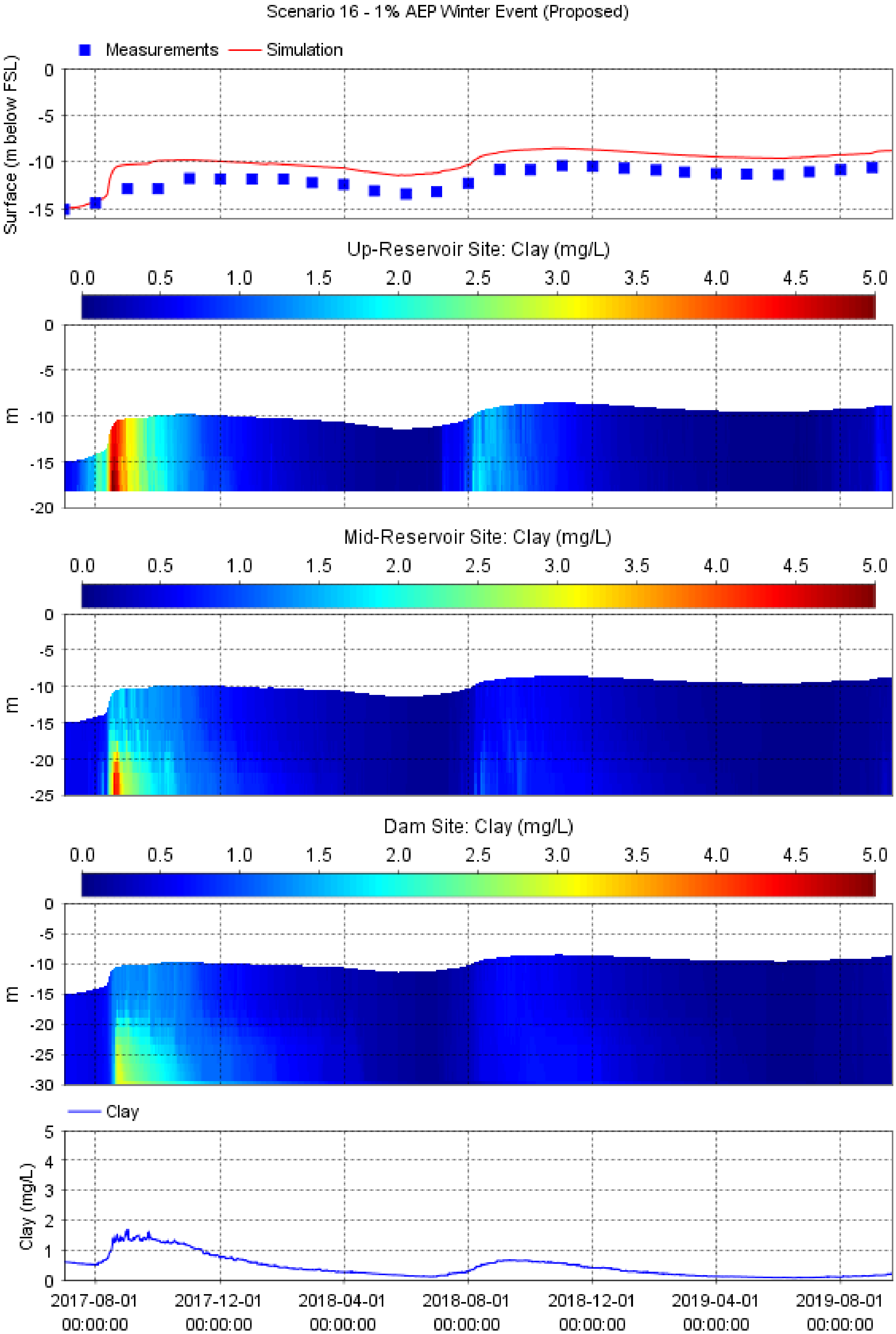

Figure 138 *SDD simulated levels of clay for scenario 16 (winter proposed case 1% AEP flood event) with moderate drainage failure SS levels.*

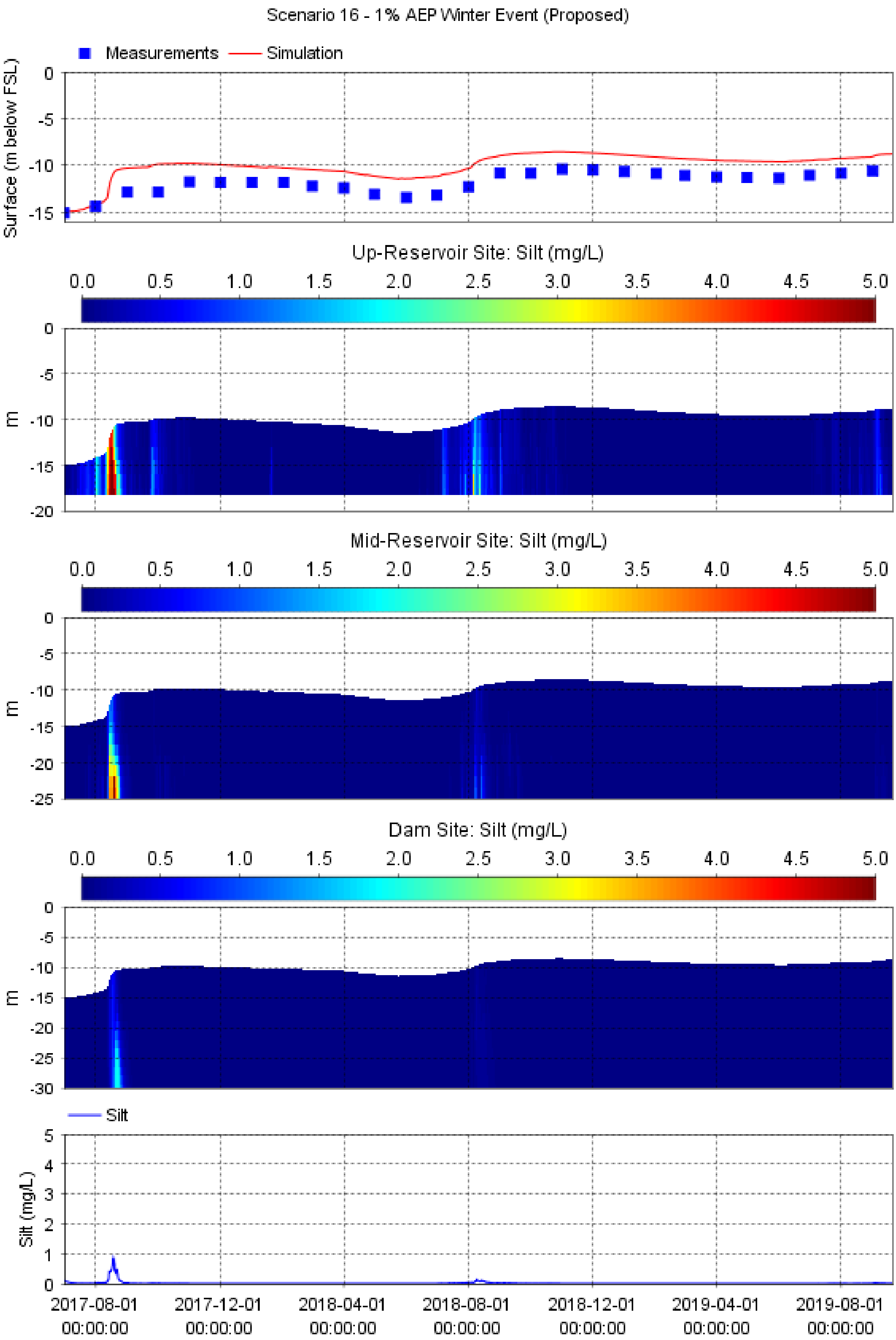

Figure 139 *SDD simulated levels of silt for scenario 16 (winter proposed case 1% AEP flood event) with moderate drainage failure SS levels.*

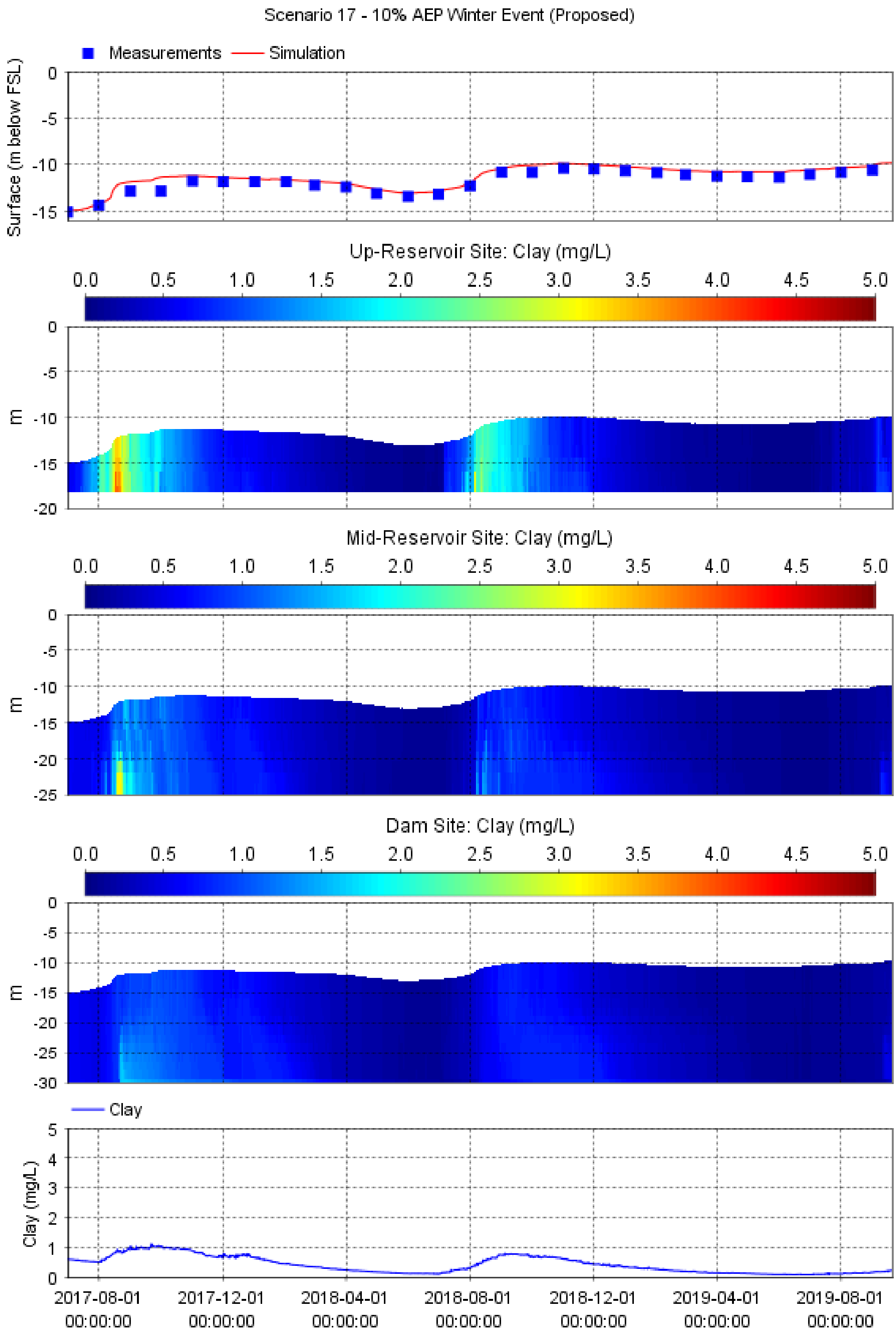

Figure 140 *SDD simulated levels of clay for scenario 17 (winter proposed case 10% AEP flood event) with moderate drainage failure SS levels.*

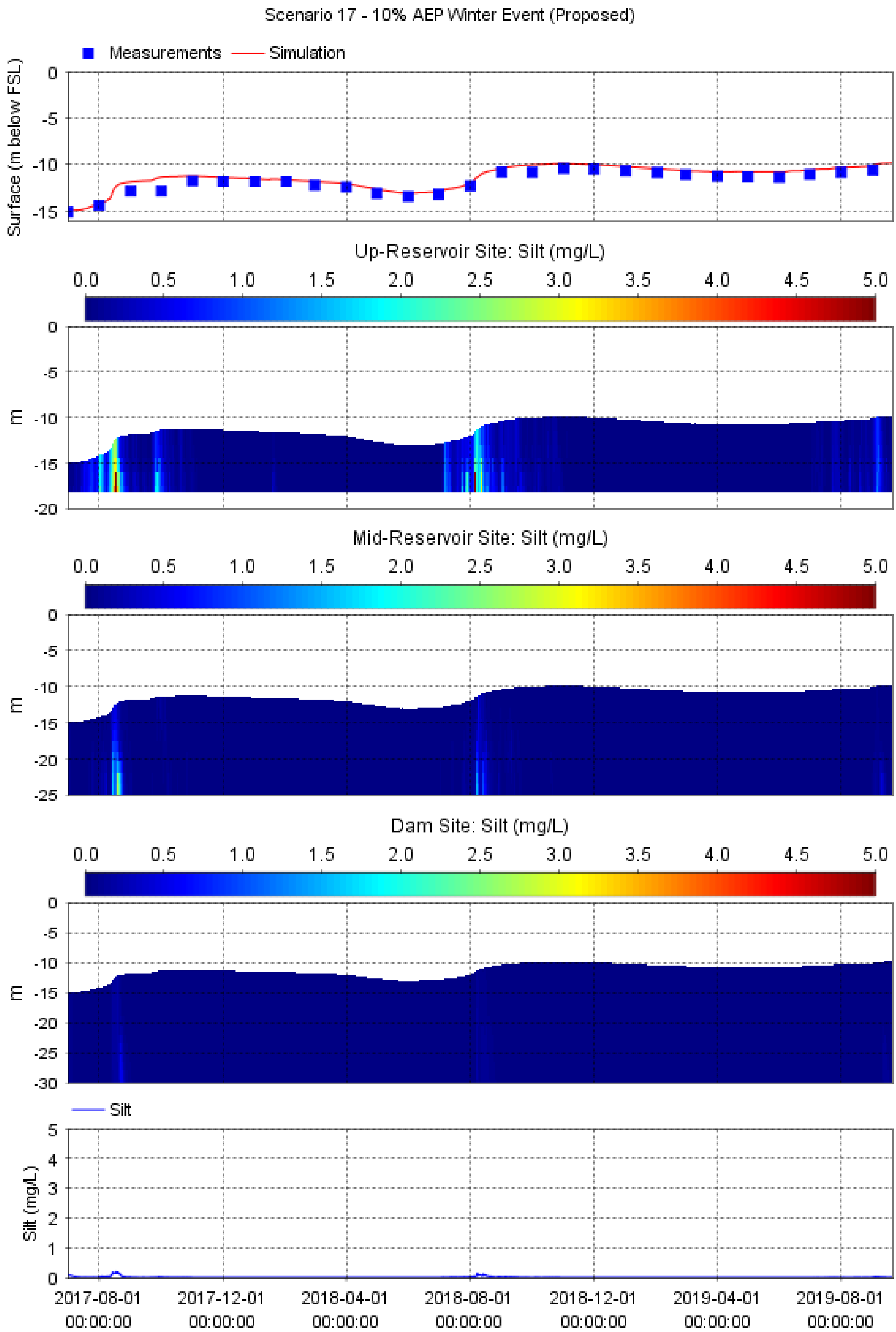

Figure 141 SDD simulated levels of silt for scenario 17 (winter proposed case 10% AEP flood event) with moderate drainage failure SS levels.

Appendix G

SDD: 1% and 10% AEP Flood Event Inputs (High Drainage Failure SS Levels)

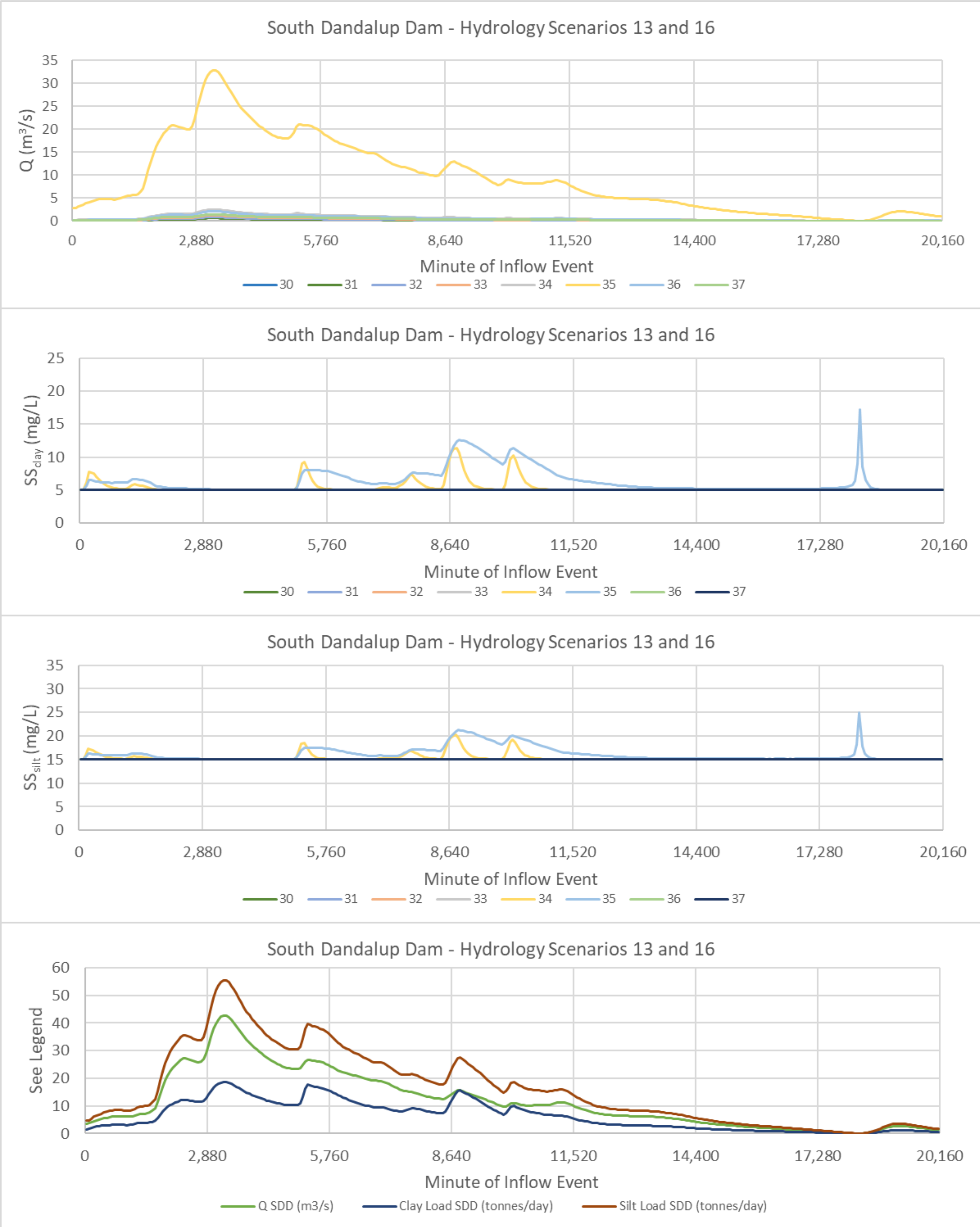

Figure 142 ***SDD hydrology and suspended solids inputs for scenarios 13H and 16H with high drainage failure SS levels.***

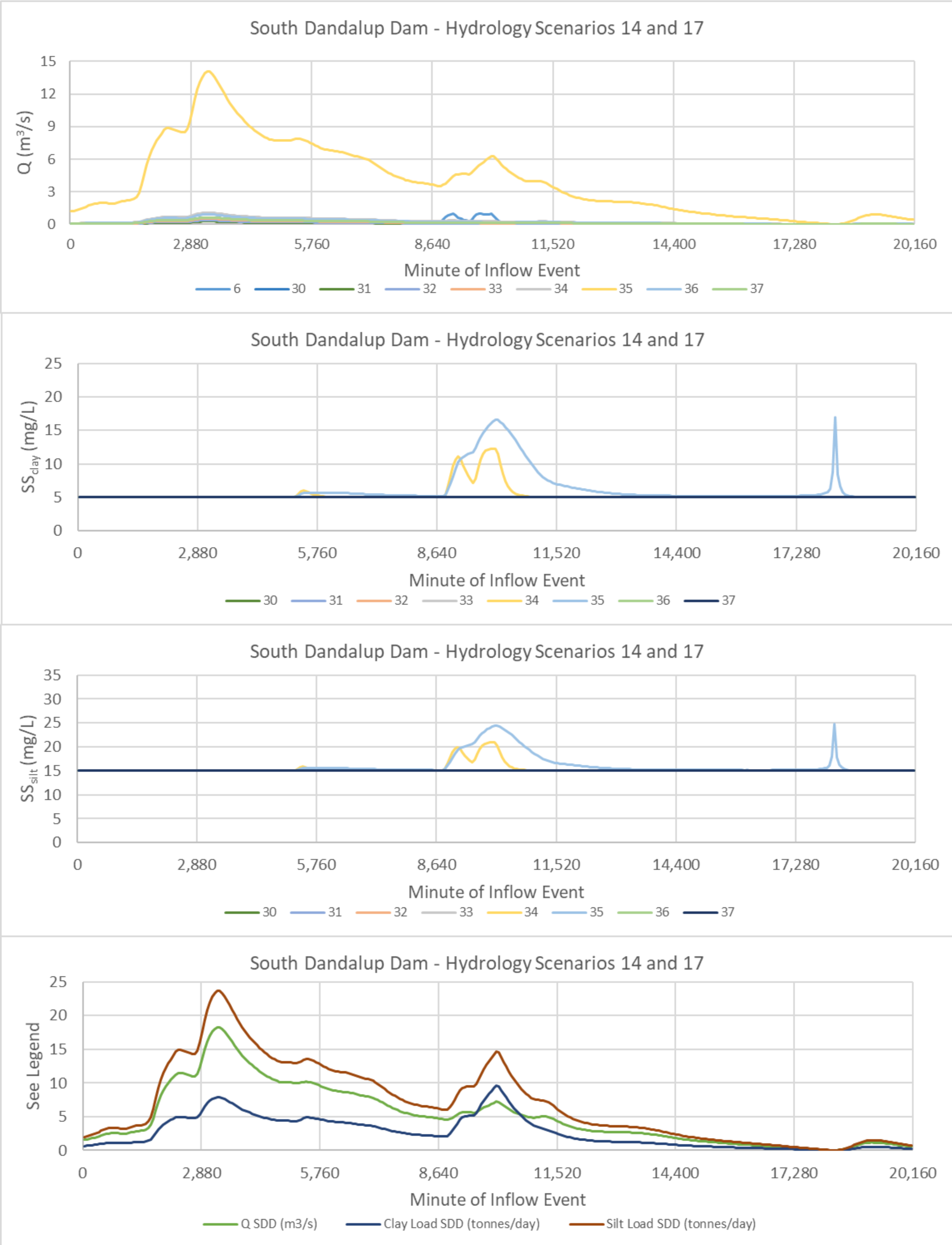

Figure 143 ***As Figure 122 for scenarios 14H and 17H with high drainage failure SS levels.***

Appendix H

SDD: 1% and 10% AEP Flood Event Simulations (High Drainage Failure SS Levels)

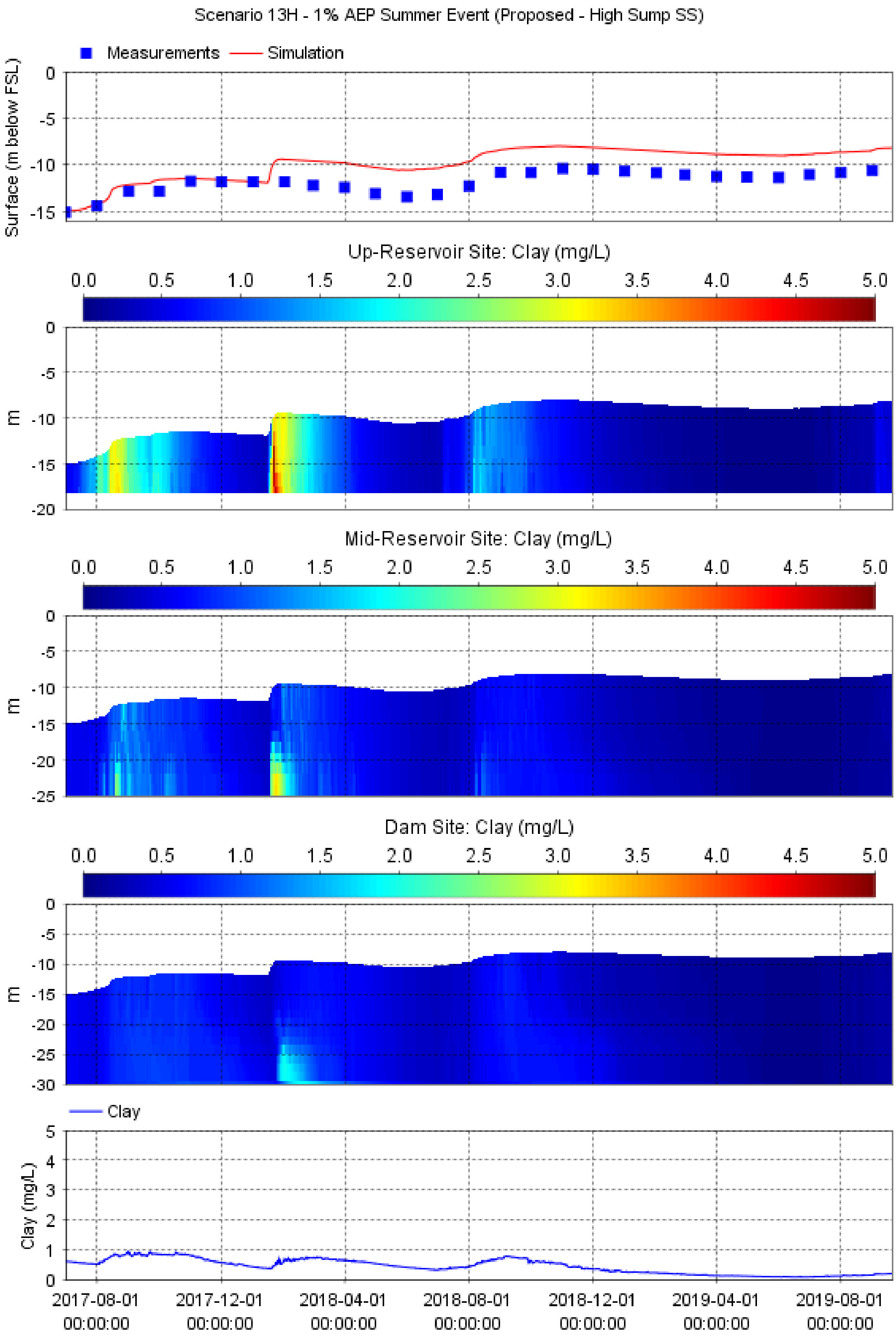

Figure 144 *SDD simulated levels of clay for scenario 13H (summer proposed case 1% AEP flood event) with high drainage failure SS levels.*

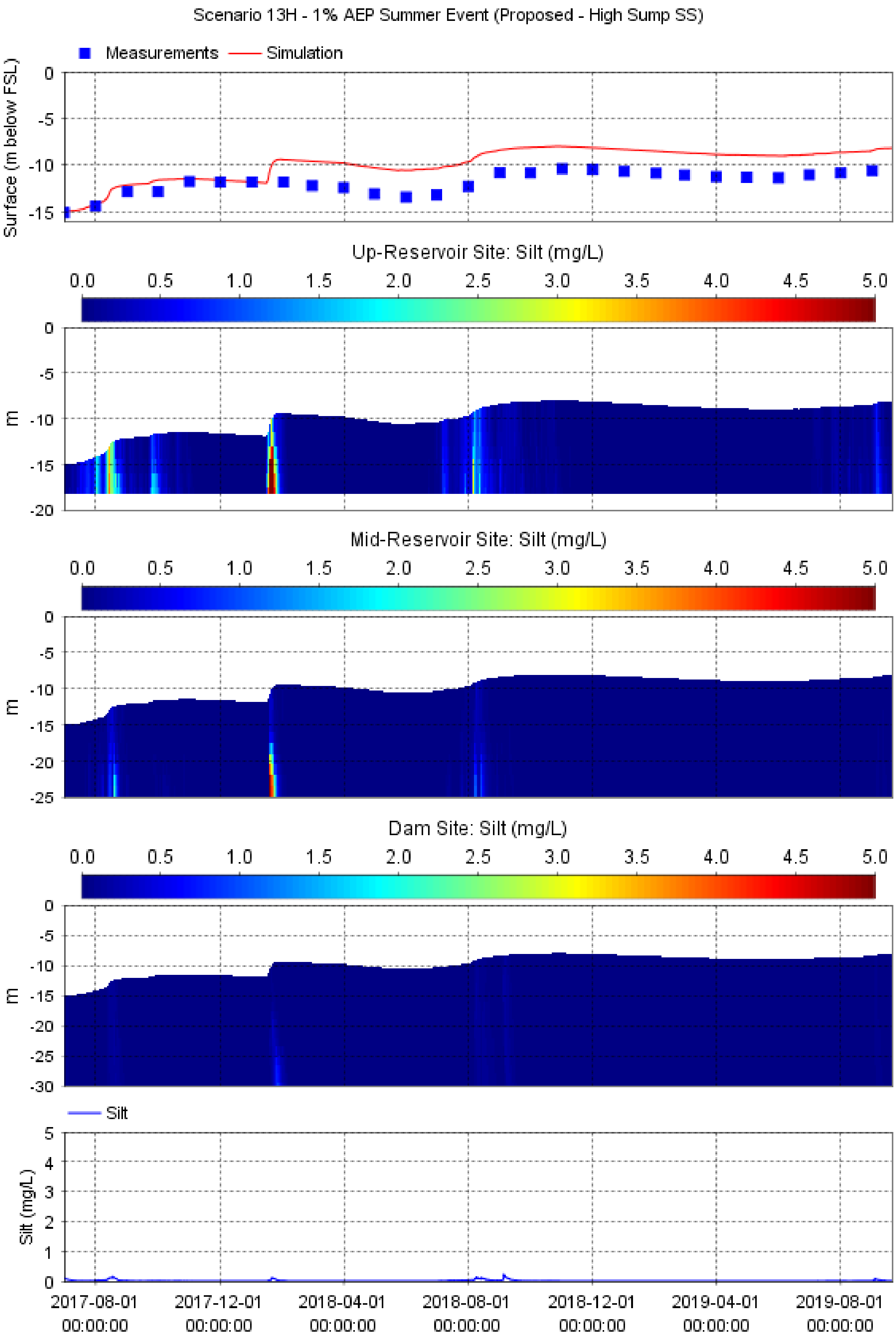

Figure 145 SDD simulated levels of silt for scenario 13H (summer proposed case 1% AEP flood event) with high drainage failure SS levels.

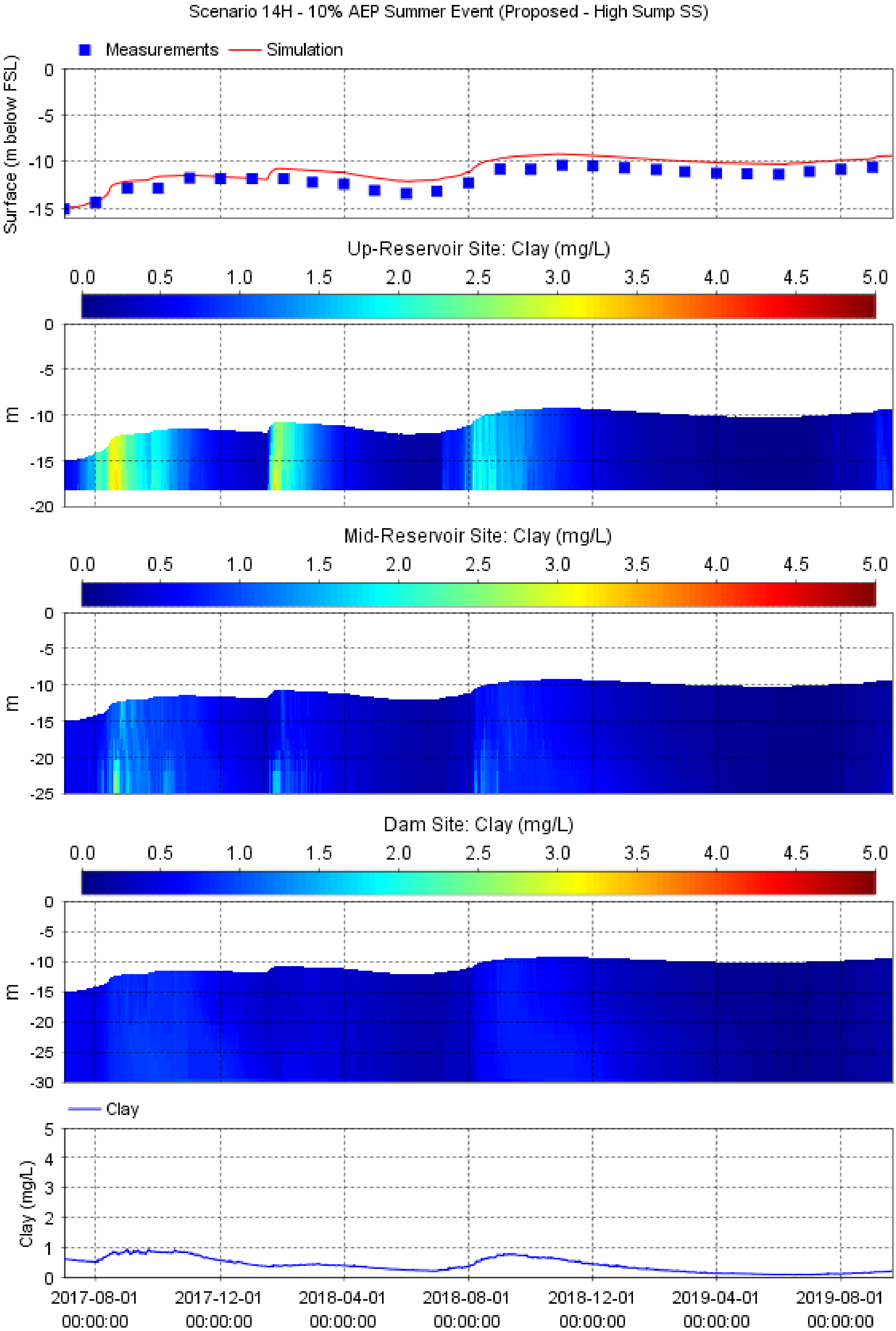

Figure 146 ***SDD simulated levels of clay for scenario 14H (summer proposed case 10% AEP flood event) with high drainage failure SS levels.***

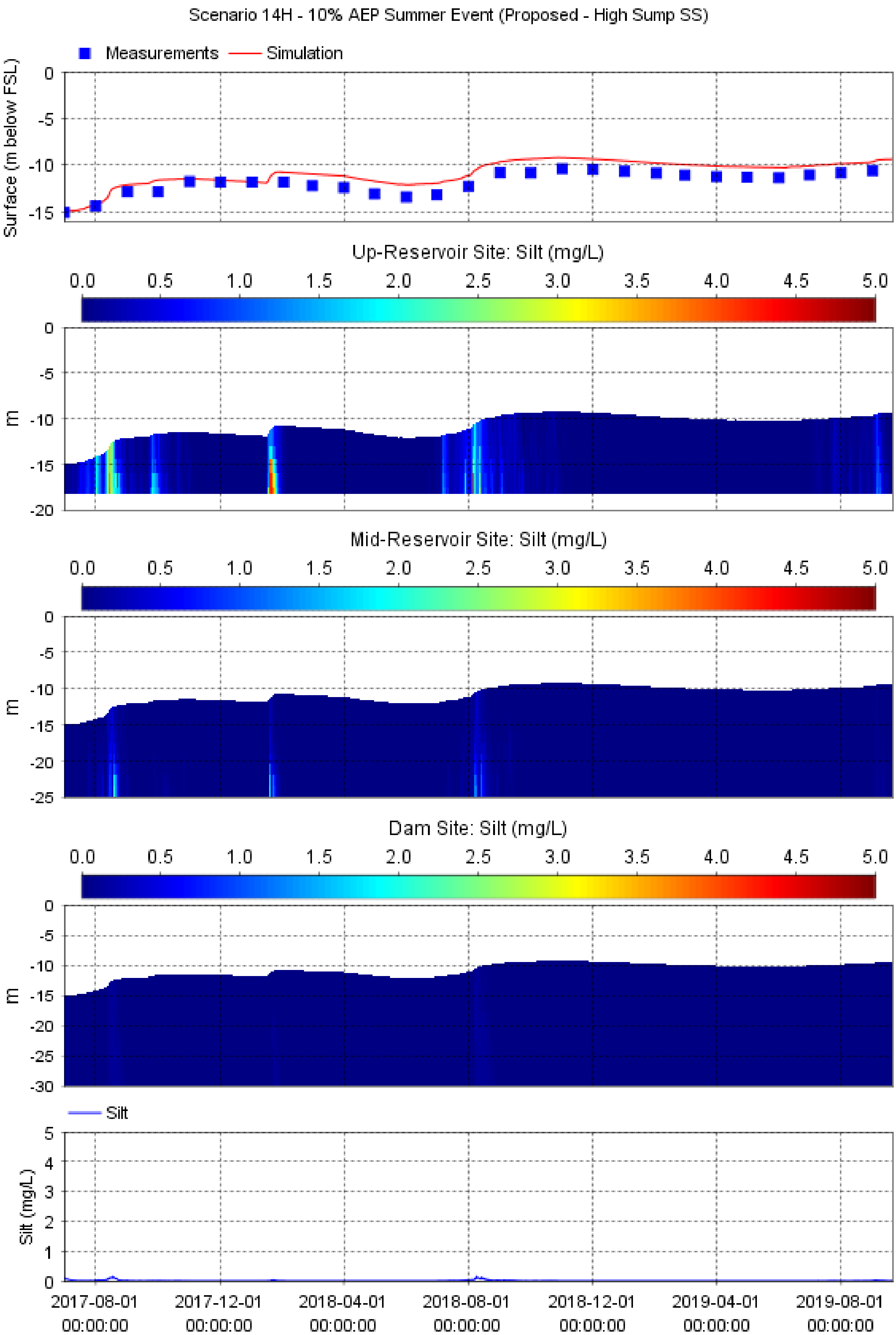

Figure 147 ***SDD simulated levels of silt for scenario 14H (summer proposed case 10% AEP flood event) with high drainage failure SS levels.***

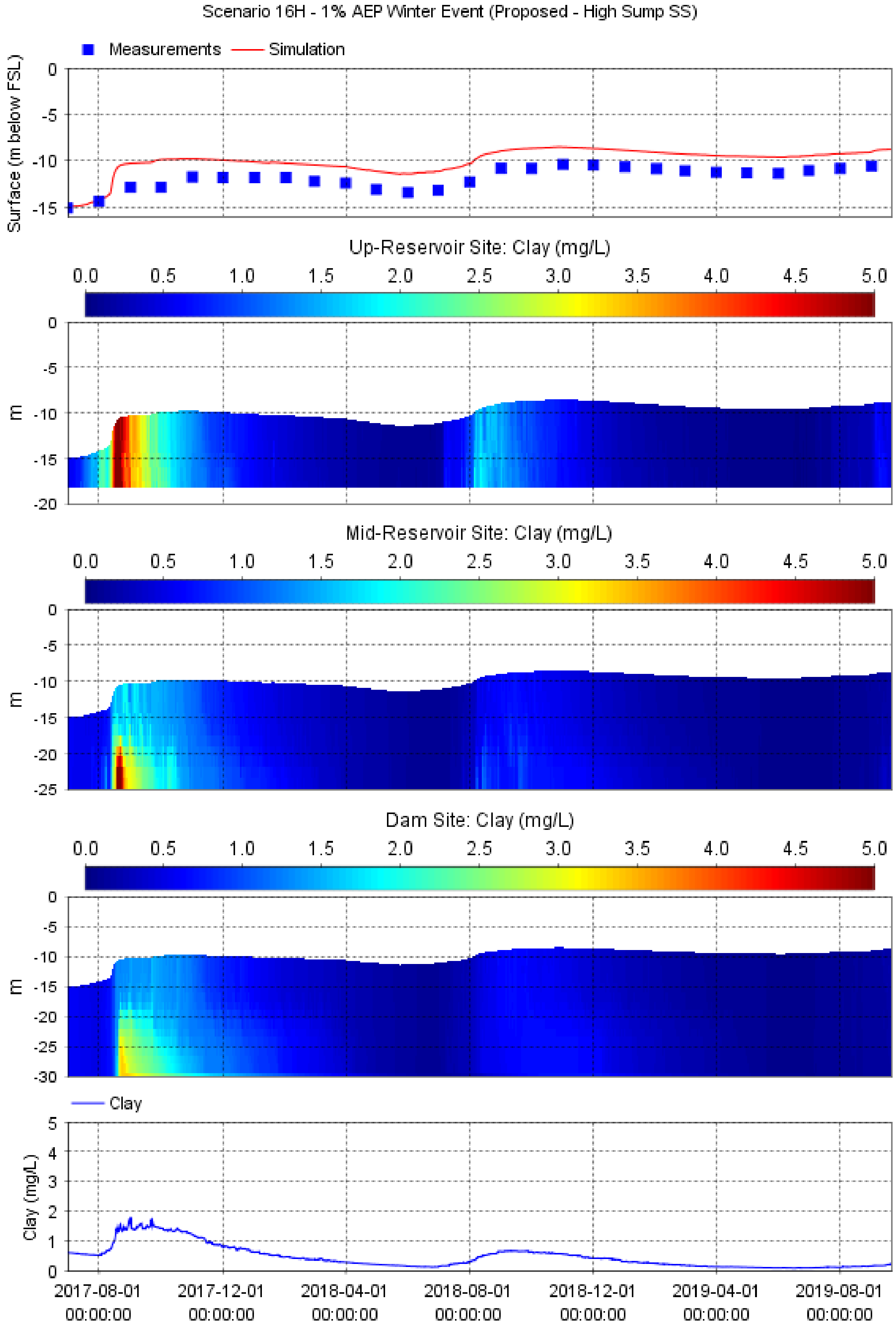

Figure 148 SDD simulated levels of clay for scenario 16H (winter proposed case 1% AEP flood event) with high drainage failure SS levels.

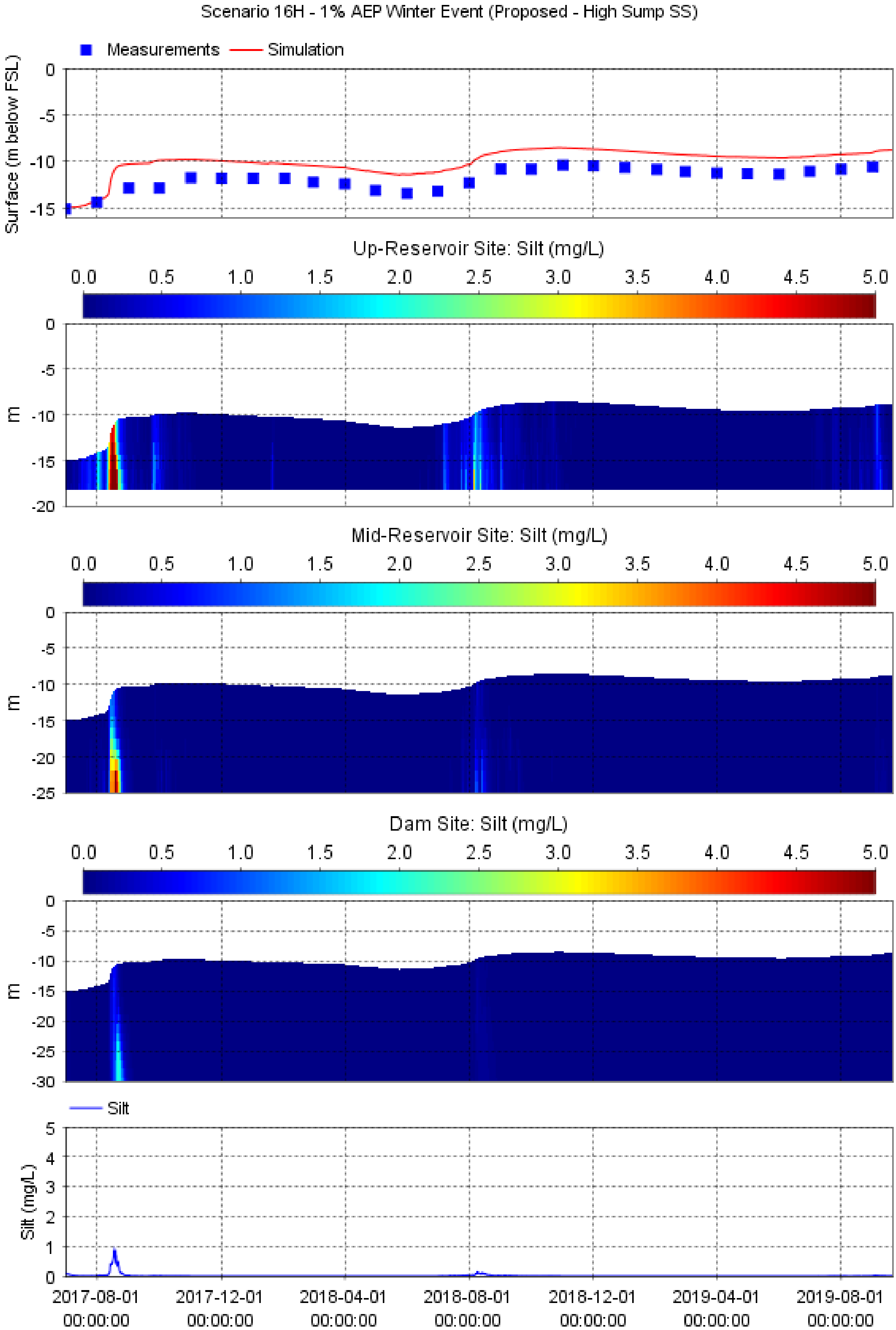

Figure 149 *SDD simulated levels of silt for scenario 16H (winter proposed case 1% AEP flood event) with high drainage failure SS levels.*

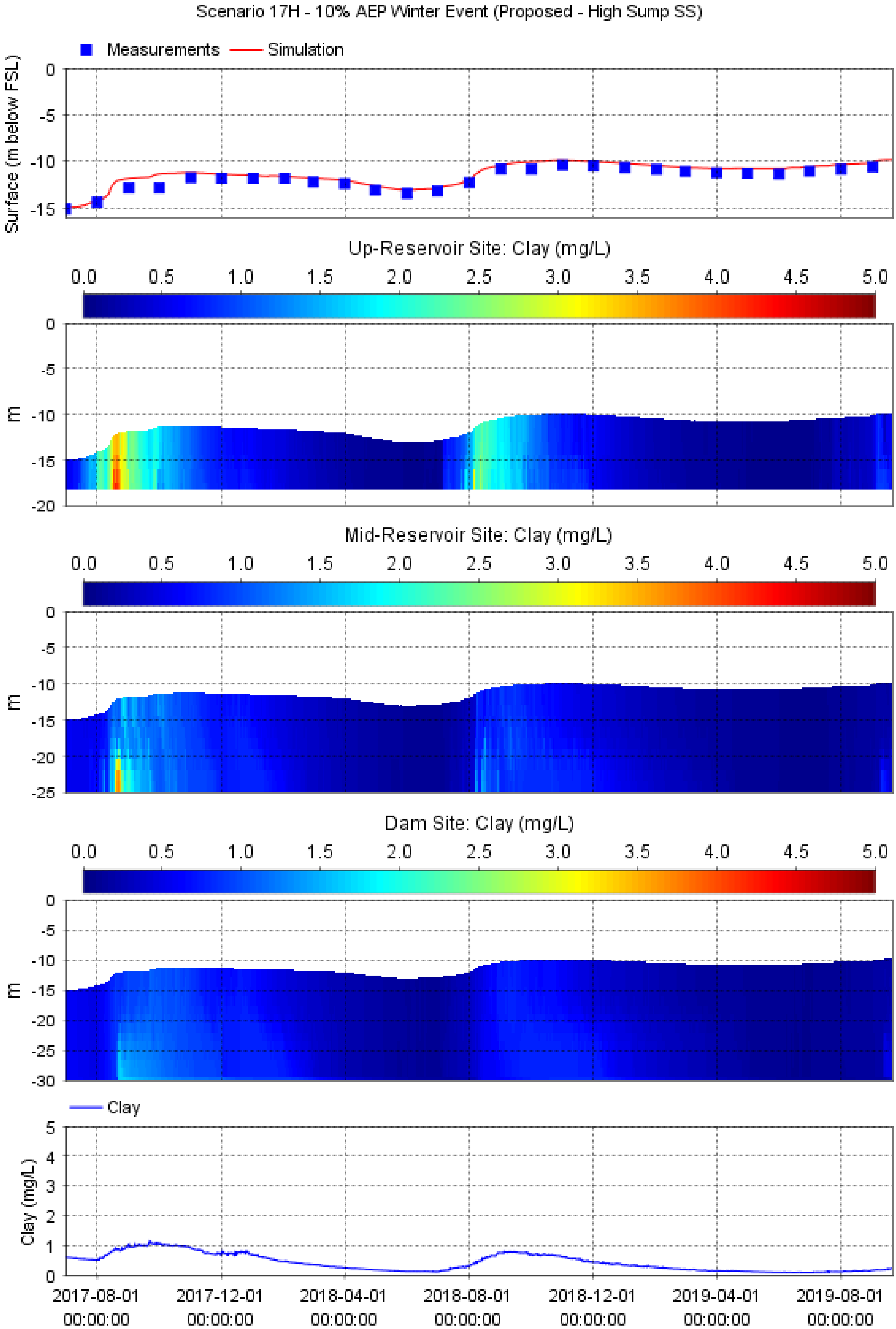

Figure 150 ***SDD simulated levels of clay for scenario 17H (winter proposed case 10% AEP flood event) with high drainage failure SS levels.***

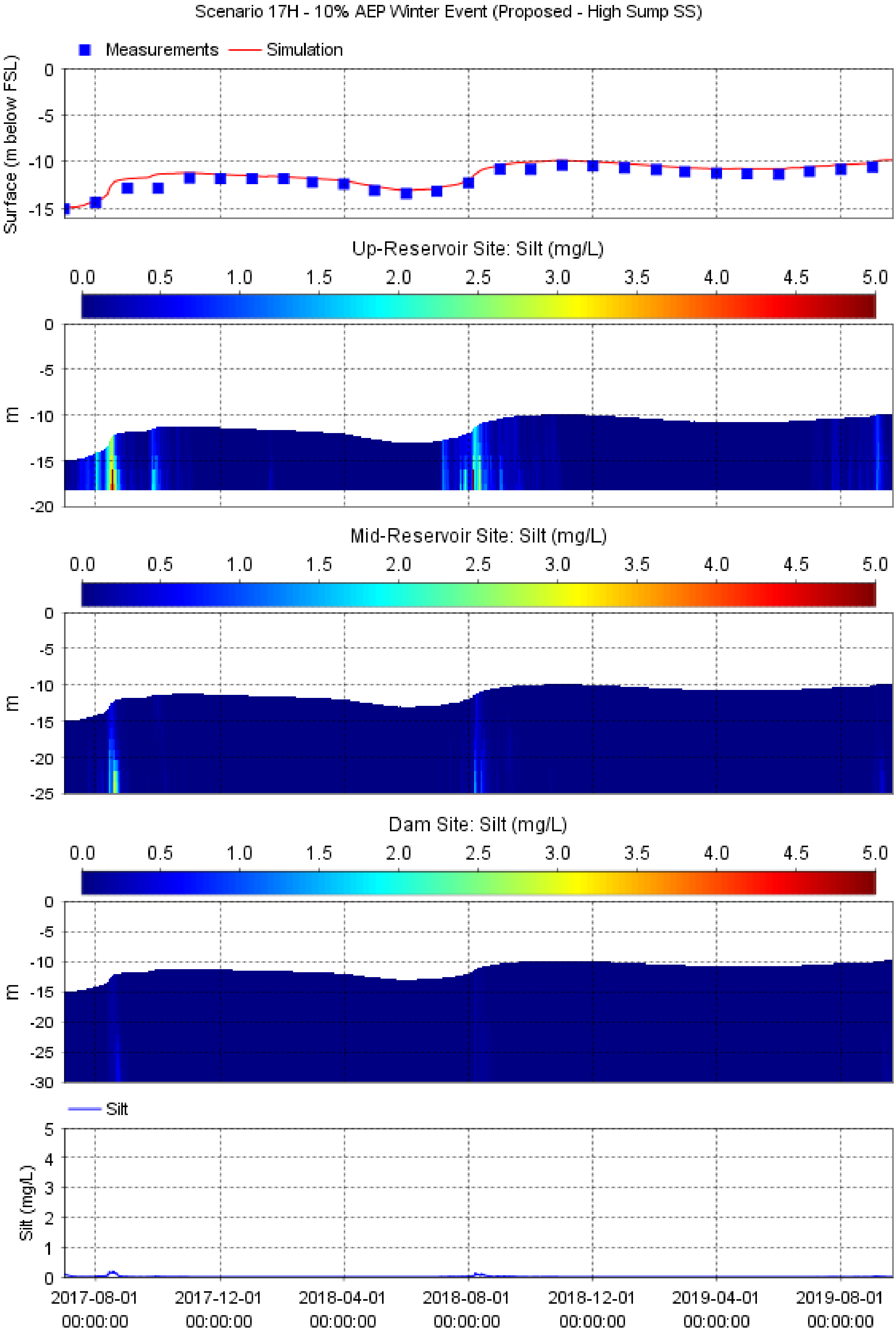

Figure 151 ***SDD simulated levels of silt for scenario 17H (winter proposed case 10% AEP flood event) with high drainage failure SS levels.***

Appendix I

SPD: 1% and 10% AEP Flood Event Inputs (Moderate Drainage Failure SS Levels)

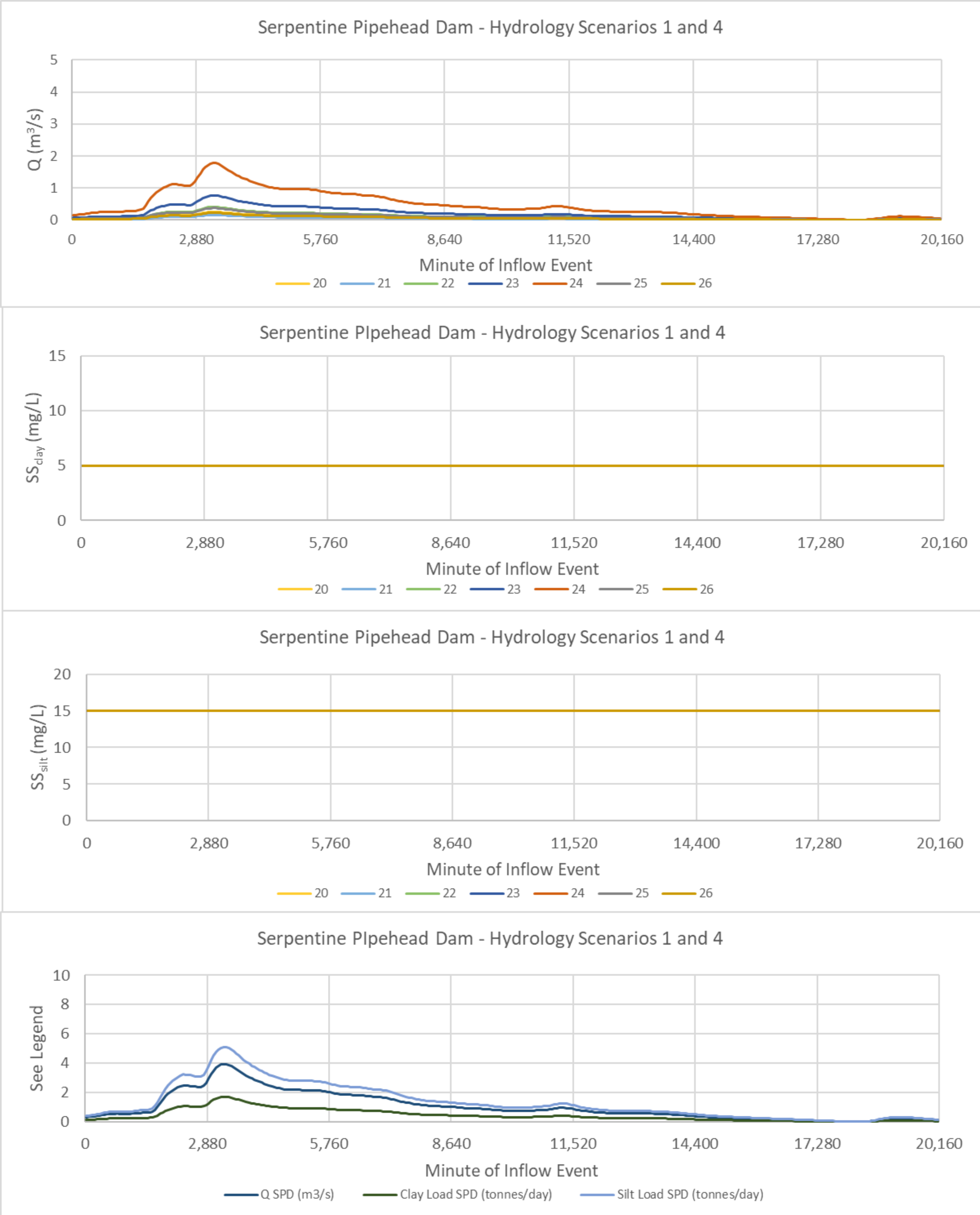

***Figure 152** SPD hydrology and suspended solids inputs for scenarios 1 and 4.*

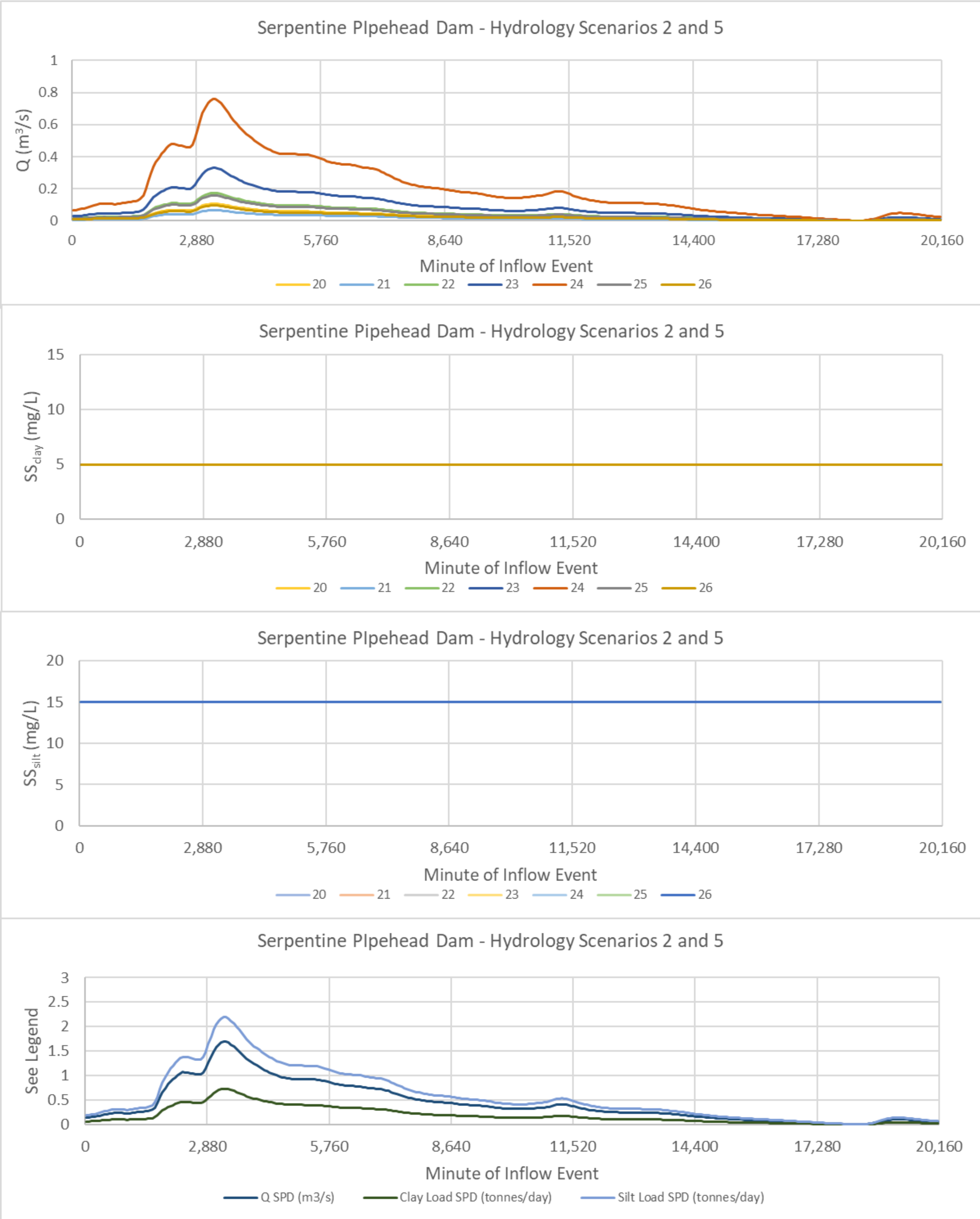

Figure 153 ***SPD hydrology and suspended solids inputs for scenarios 2 and 5.***

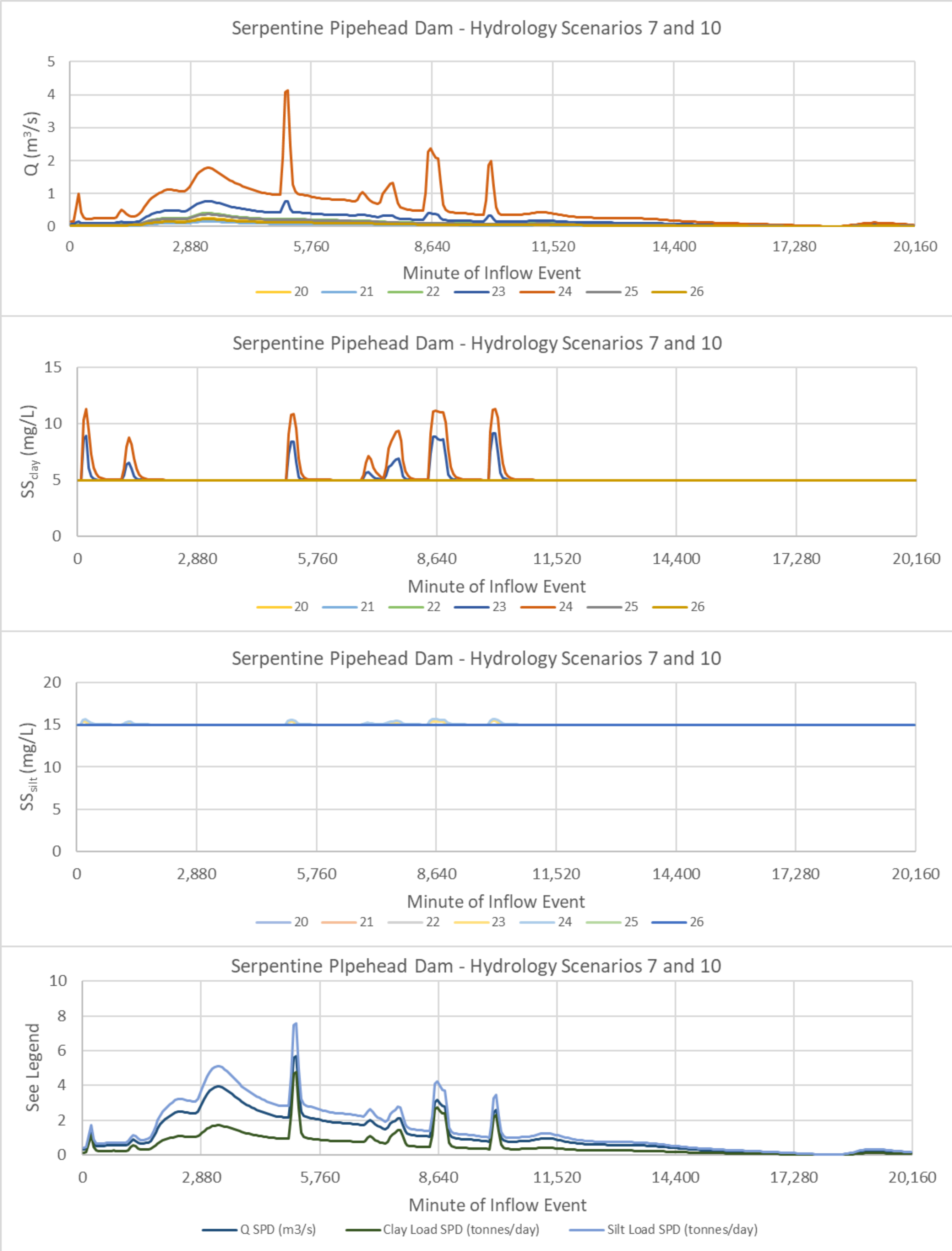

Figure 154 SPD hydrology and suspended solids inputs for scenarios 7 and 10 with moderate drainage failure SS levels.

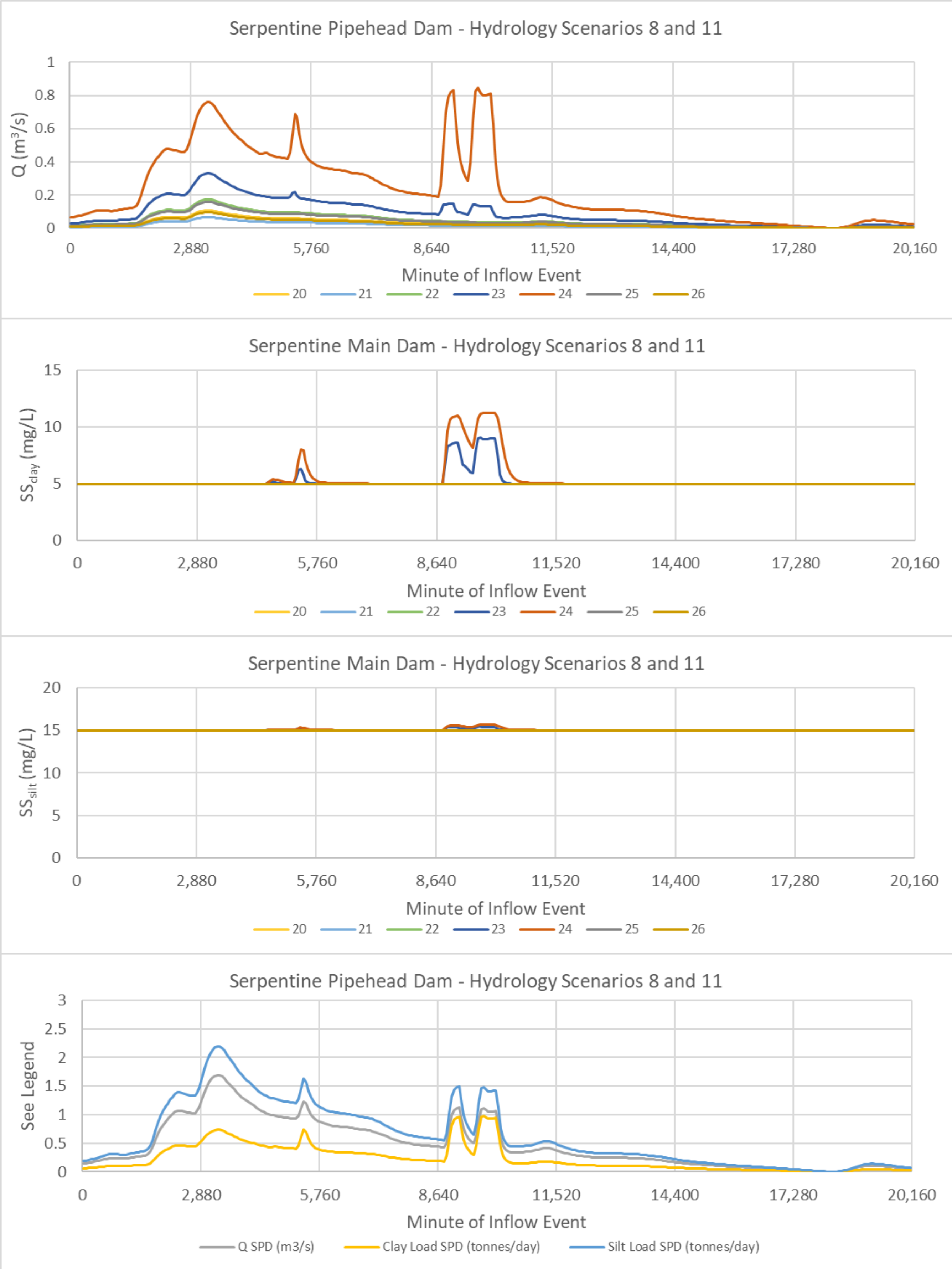

***Figure 155** SPD hydrology and suspended solids inputs for scenarios 8 and 11 with moderate drainage failure SS levels.*

Appendix J

SPD: 1% and 10% AEP Flood Event Simulations (Moderate Drainage Failure SS Levels)

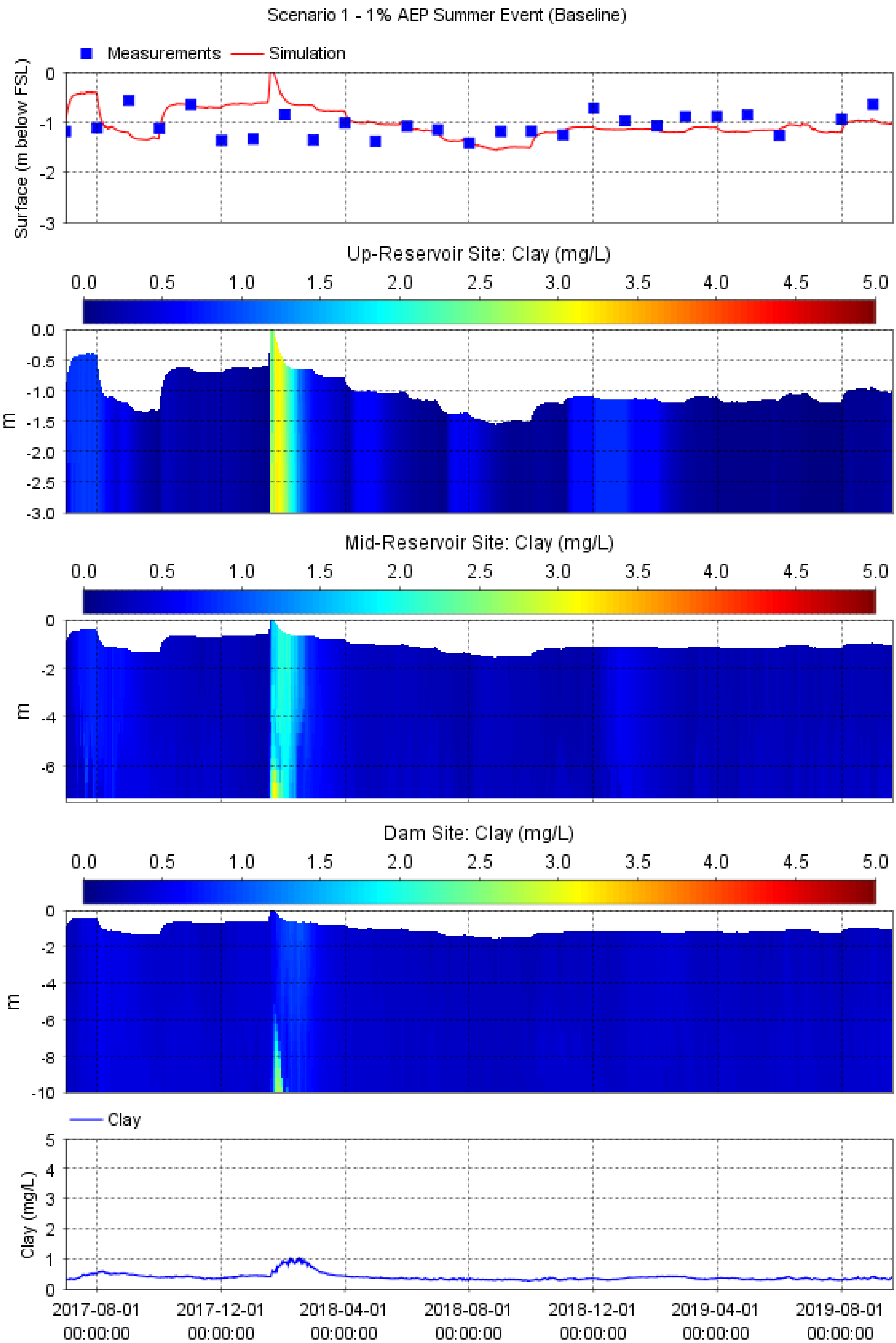

Figure 156 SPD simulated levels of clay for scenario 1 (summer baseline case 1% AEP flood event).

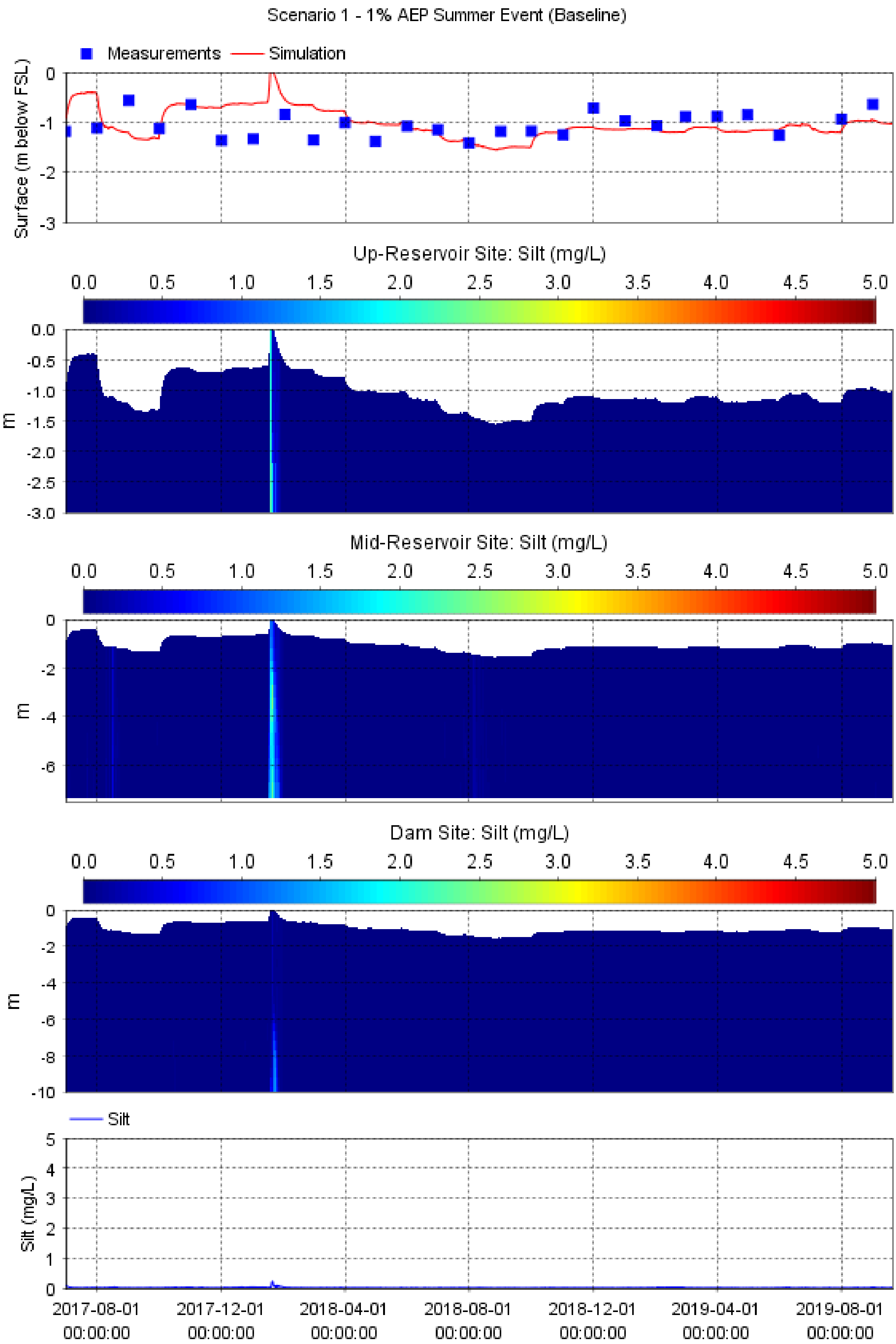

Figure 157 ***SPD simulated levels of silt for scenario 1 (summer baseline case 1% AEP flood event).***

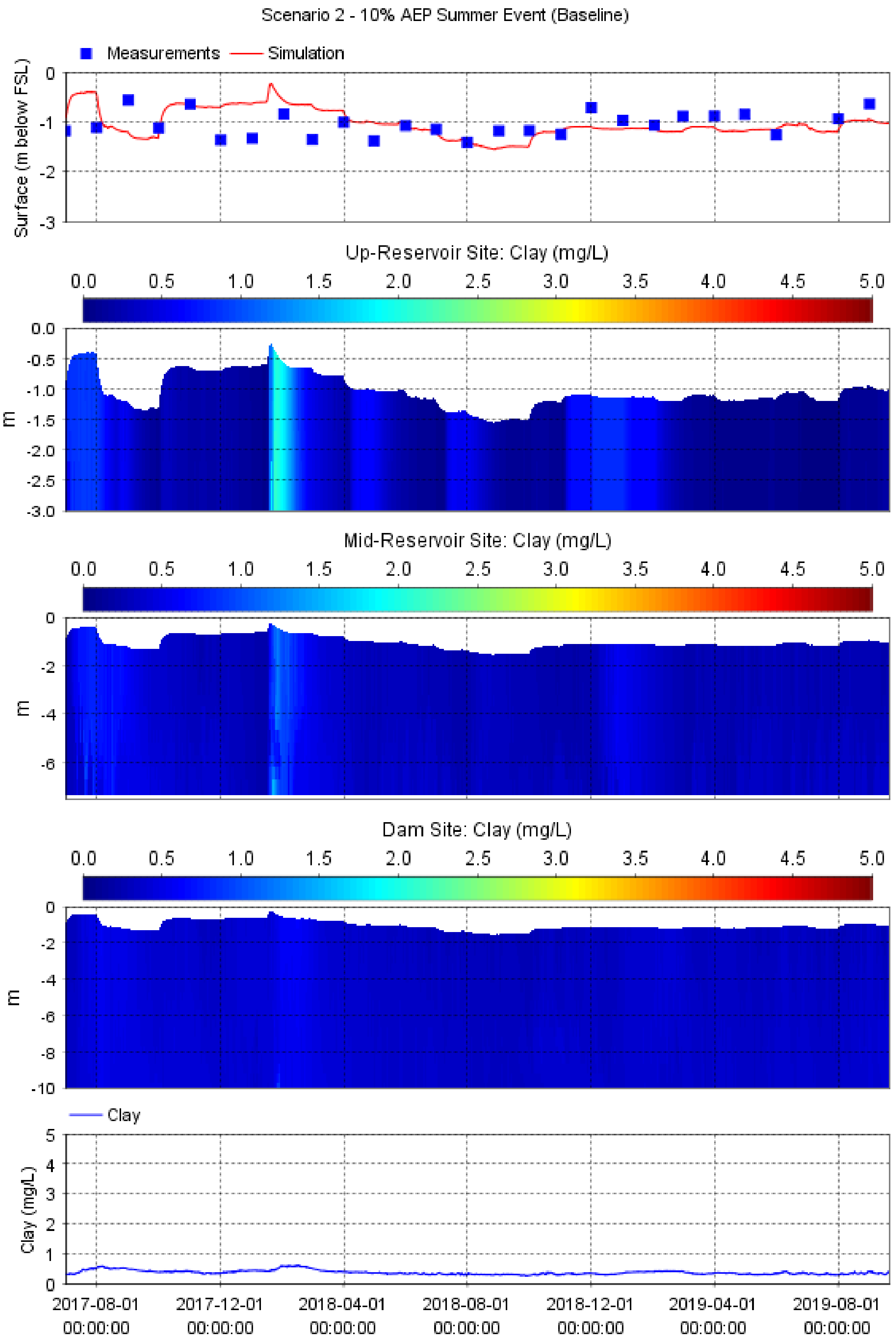

Figure 158 SPD simulated levels of clay for scenario 2 (summer baseline case 10% AEP flood event).

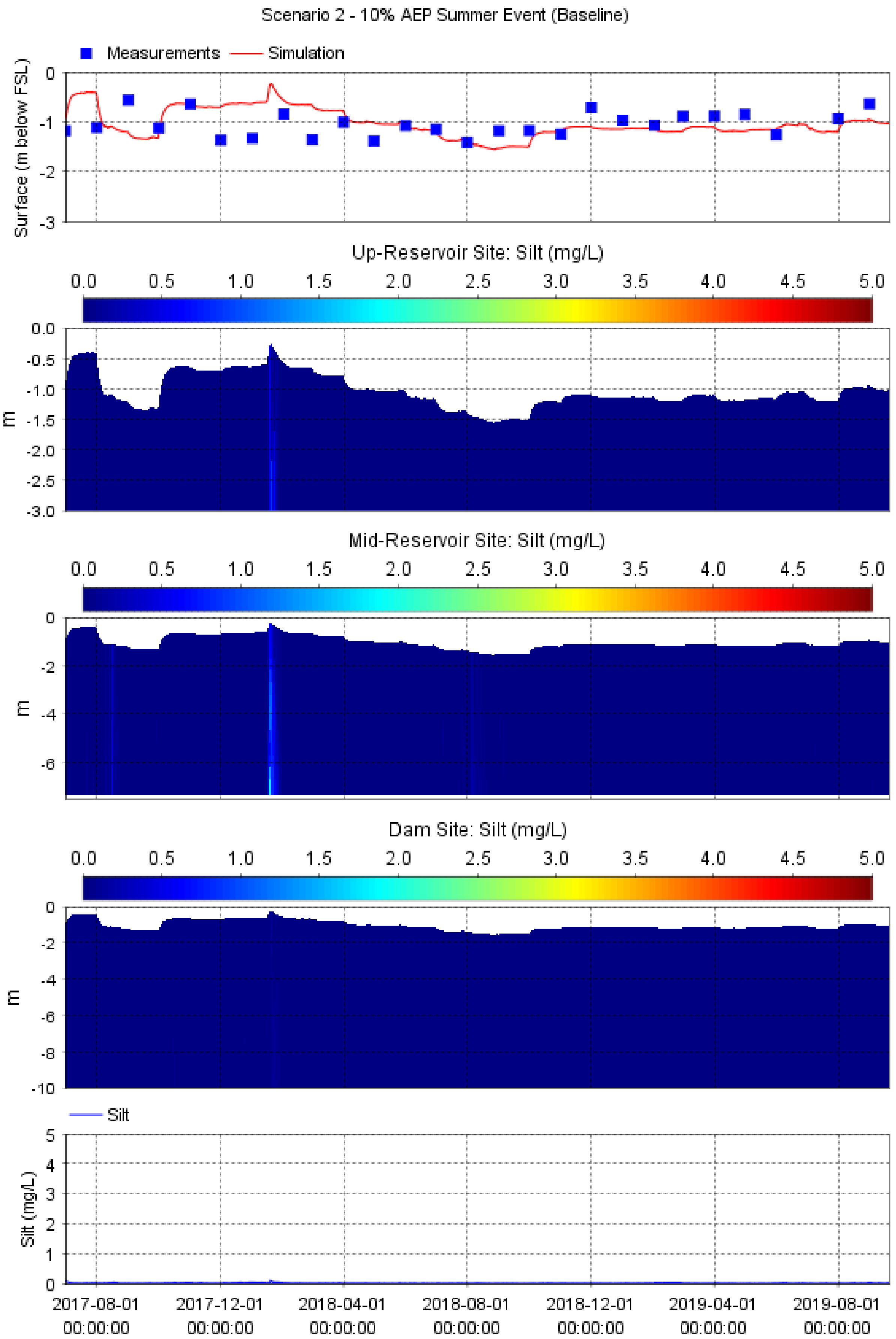

Figure 159 ***SPD simulated levels of silt for scenario 2 (summer baseline case 10% AEP flood event).***

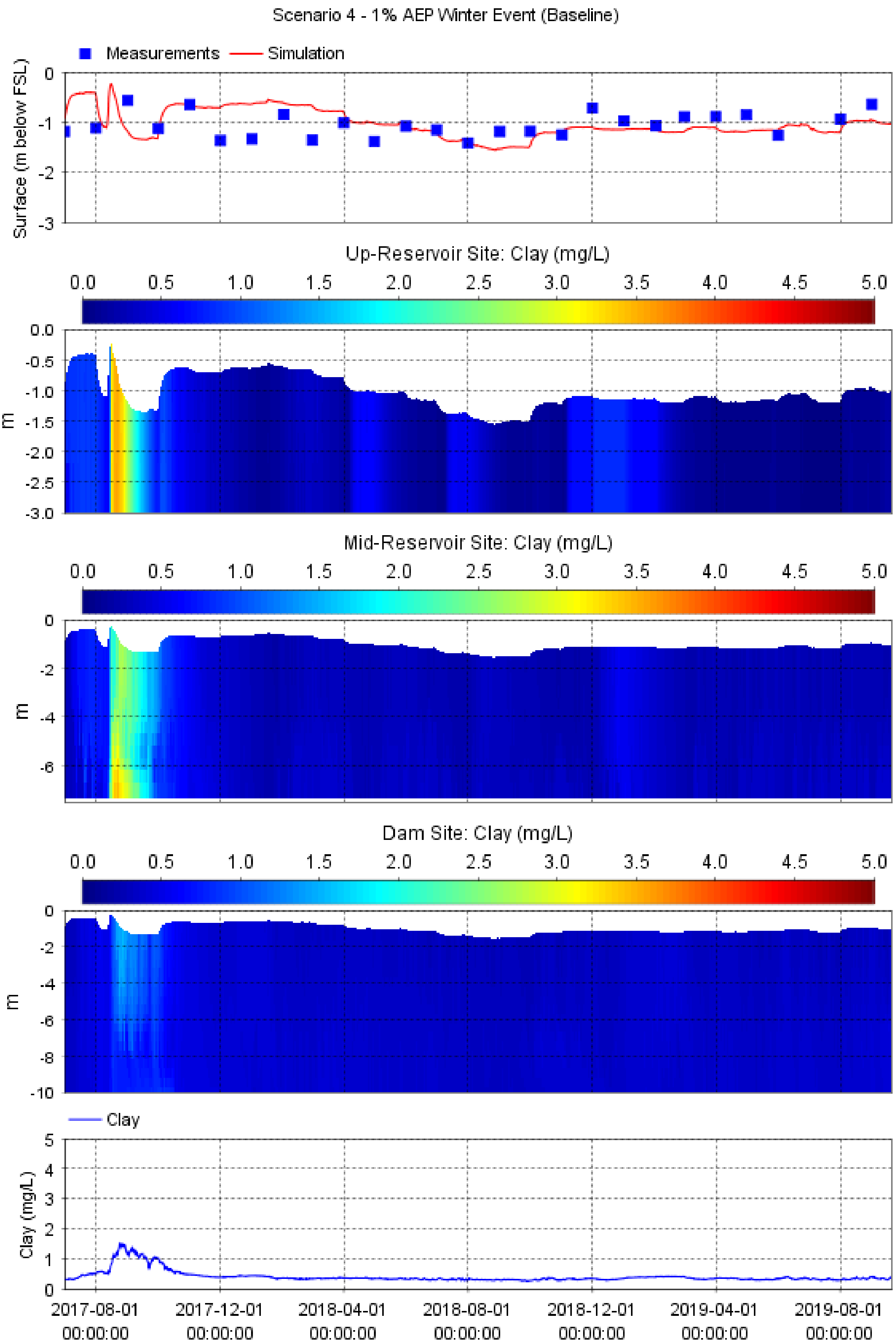

Figure 160 SPD simulated levels of clay for scenario 4 (winter baseline case 1% AEP flood event).

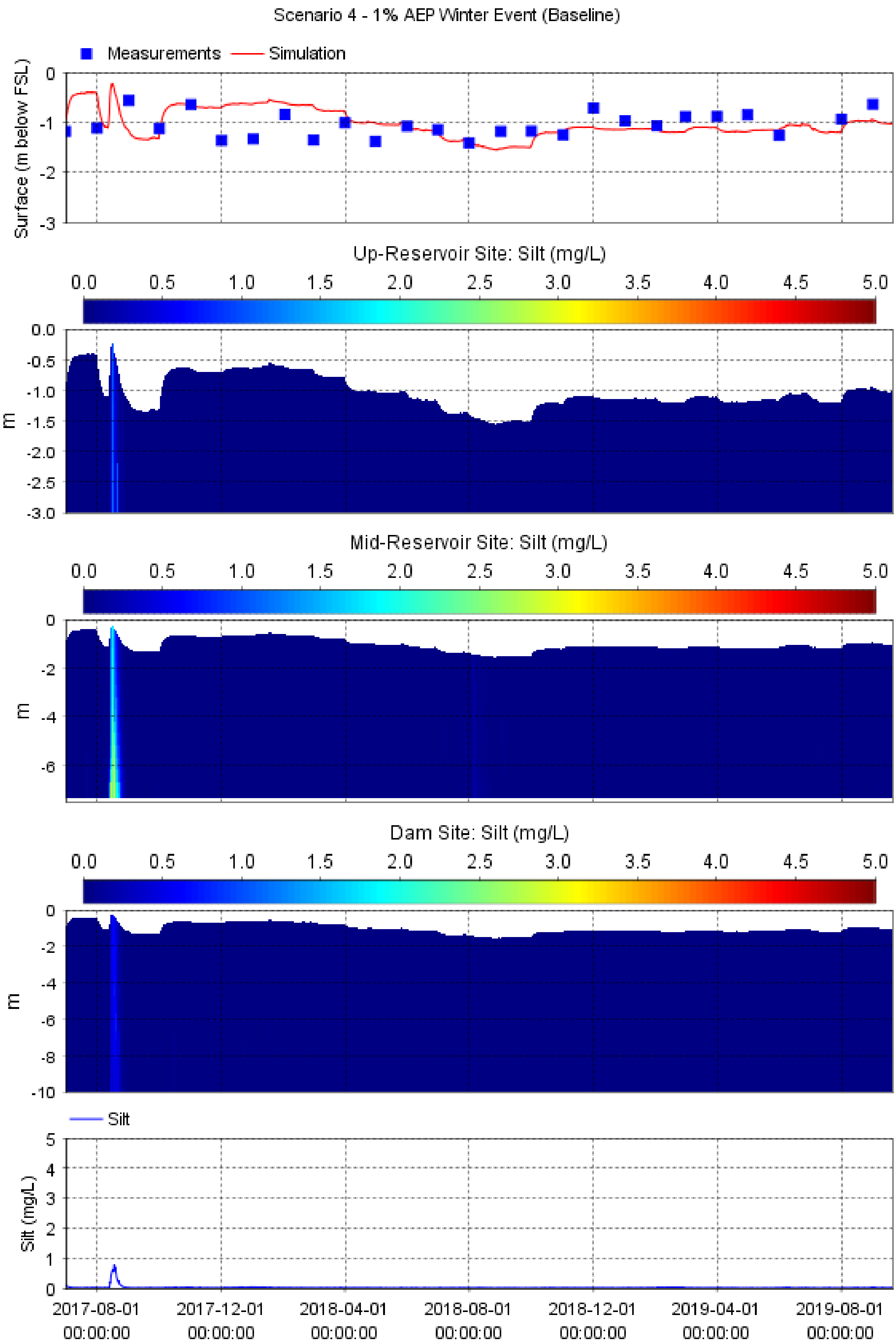

Figure 161 SPD simulated levels of silt for scenario 4 (winter baseline case 1% AEP flood event).

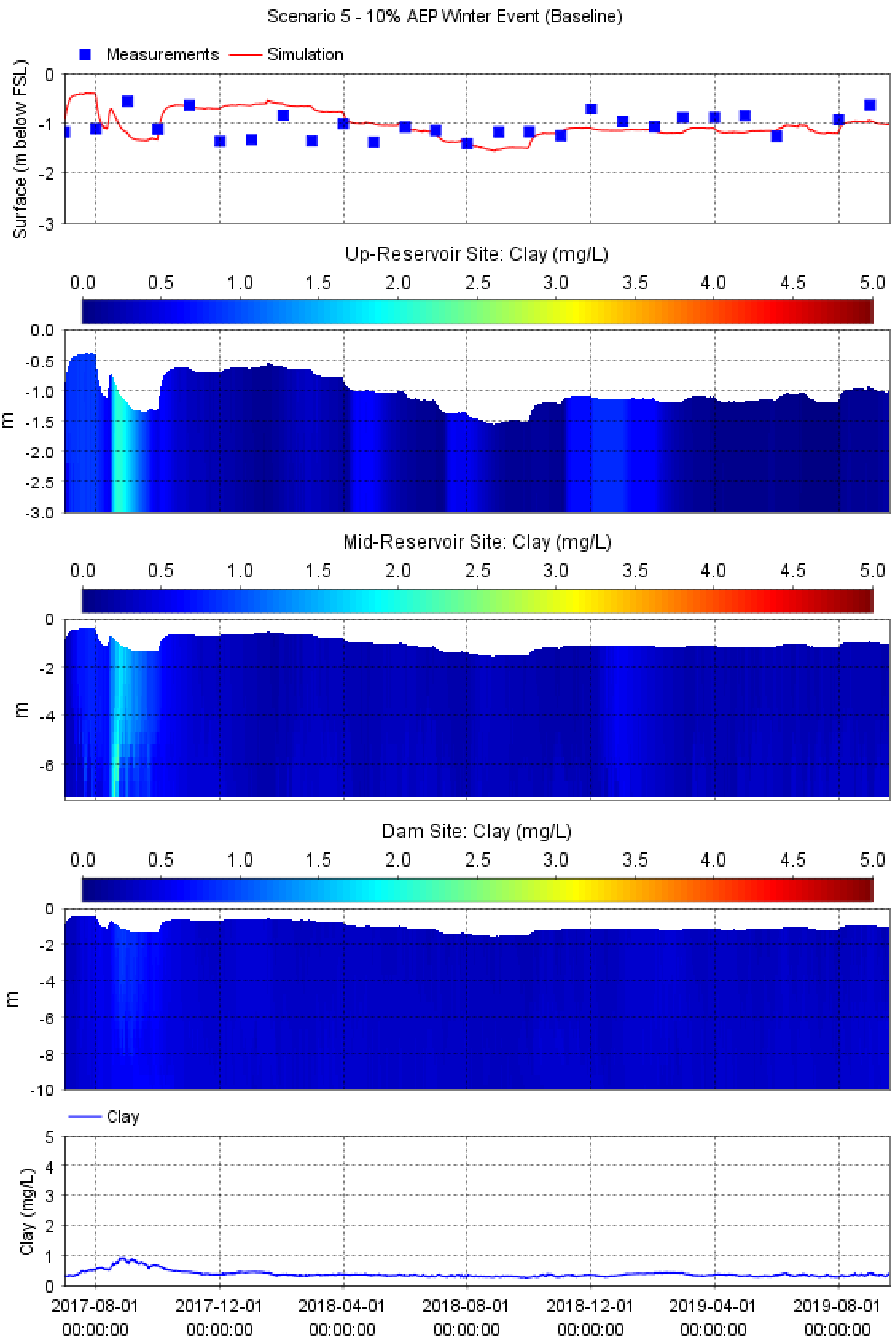

Figure 162 SPD simulated levels of clay for scenario 5 (winter baseline case 10% AEP flood event).

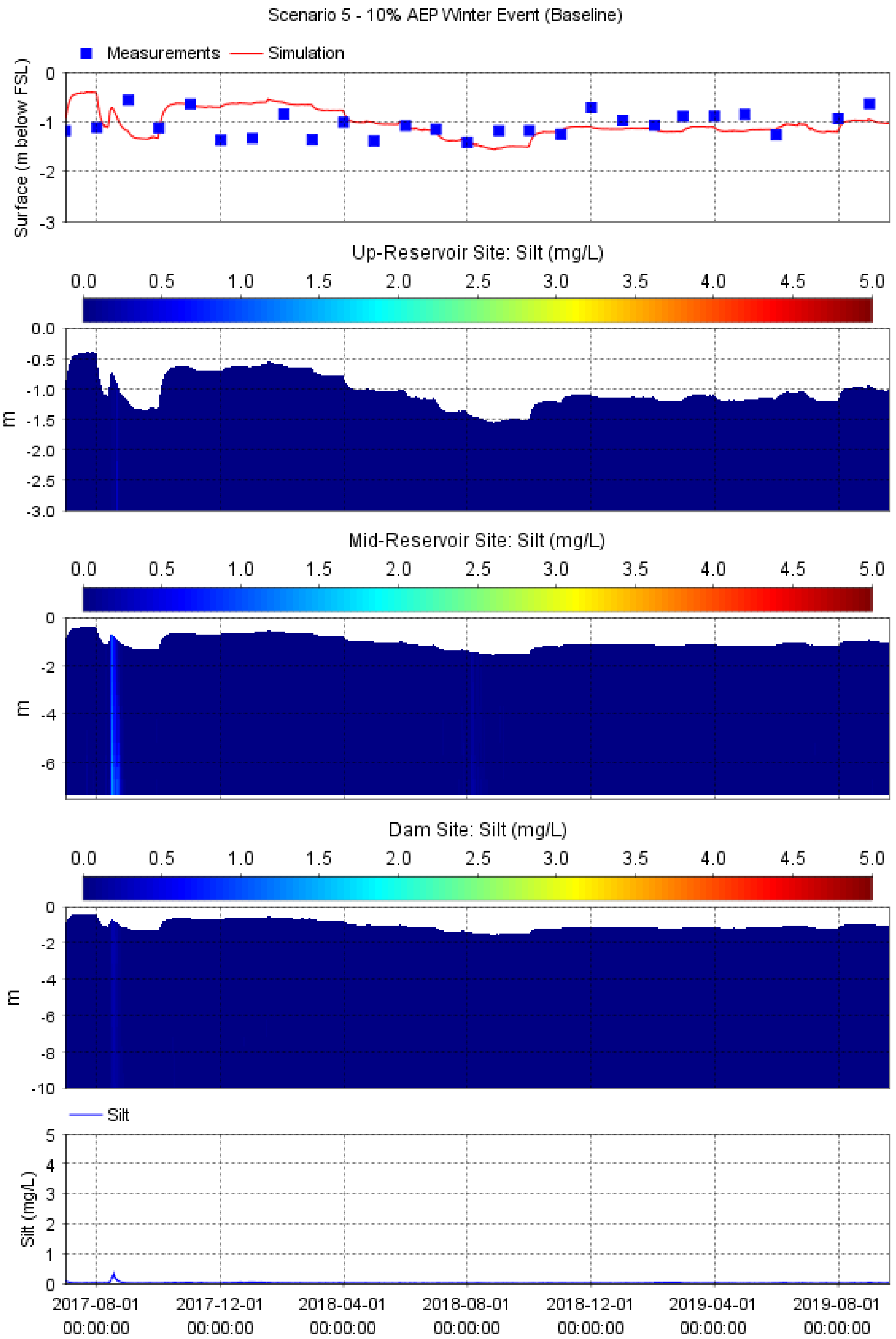

Figure 163 ***SPD simulated levels of silt for scenario 5 (winter baseline case 10% AEP flood event).***

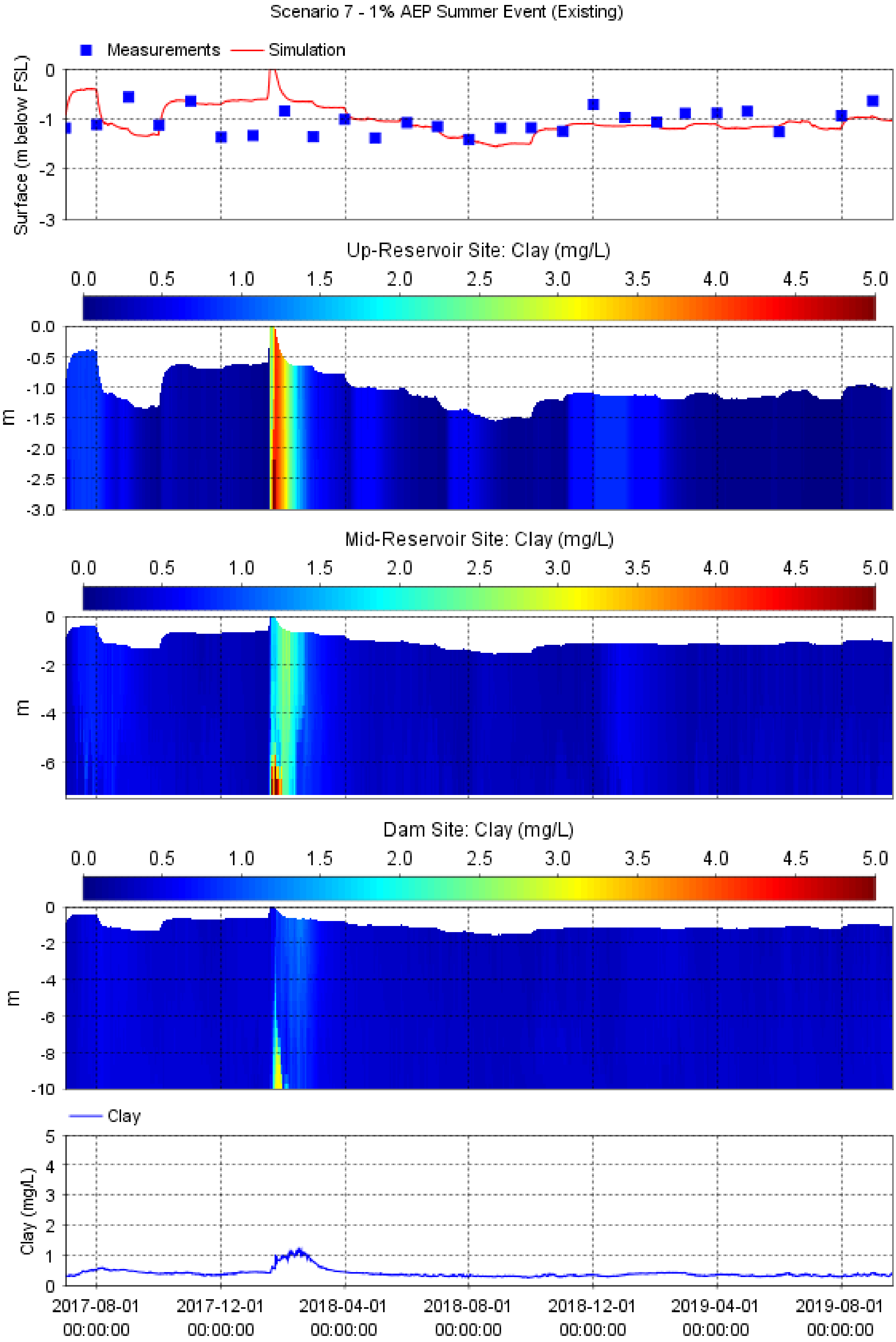

Figure 164 *SPD simulated levels of clay for scenario 7 (summer existing case 1% AEP flood event) with moderate drainage failure SS levels.*

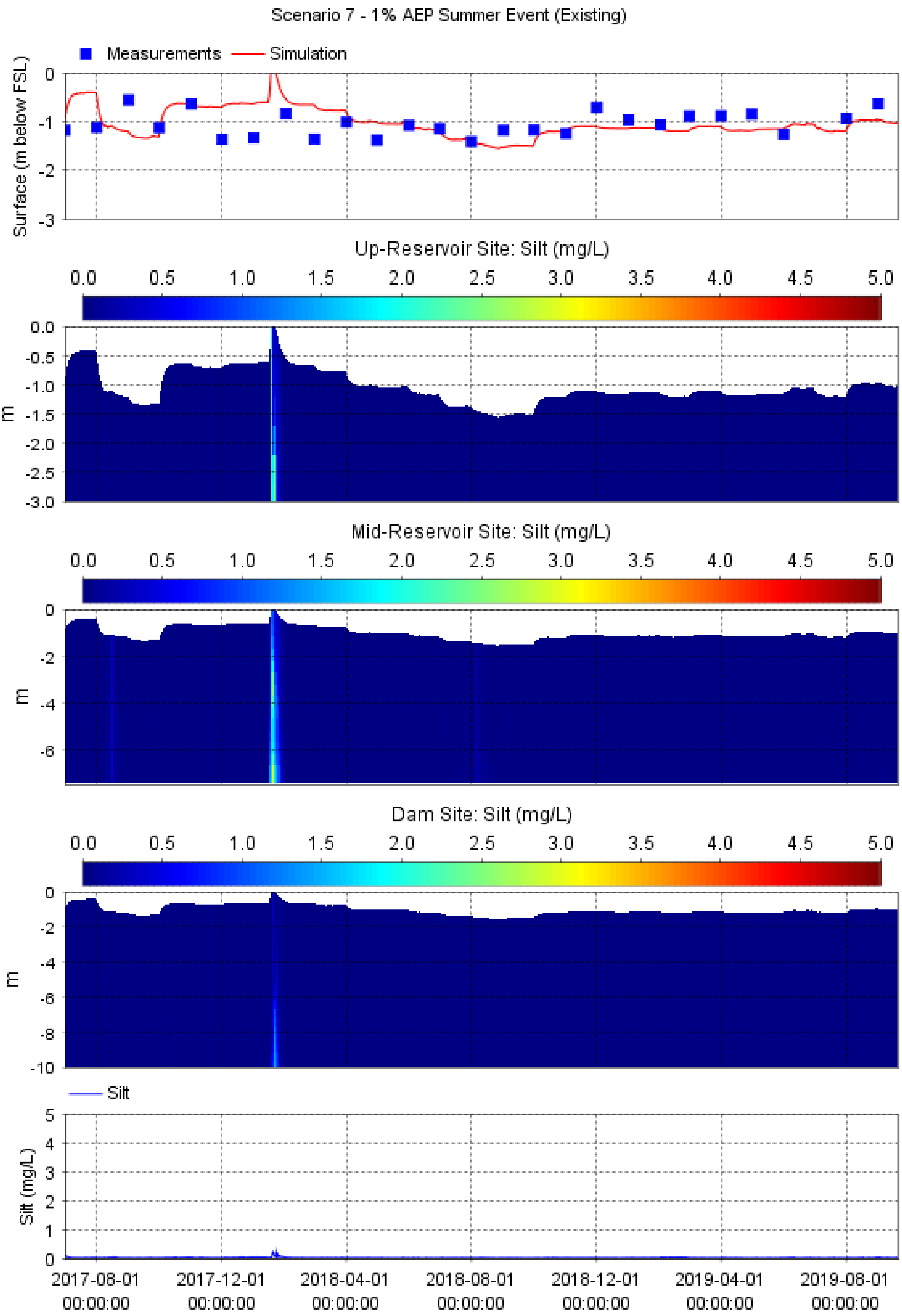

Figure 165 ***SPD simulated levels of silt for scenario 7 (summer existing case 1% AEP flood event) with moderate drainage failure SS levels.***

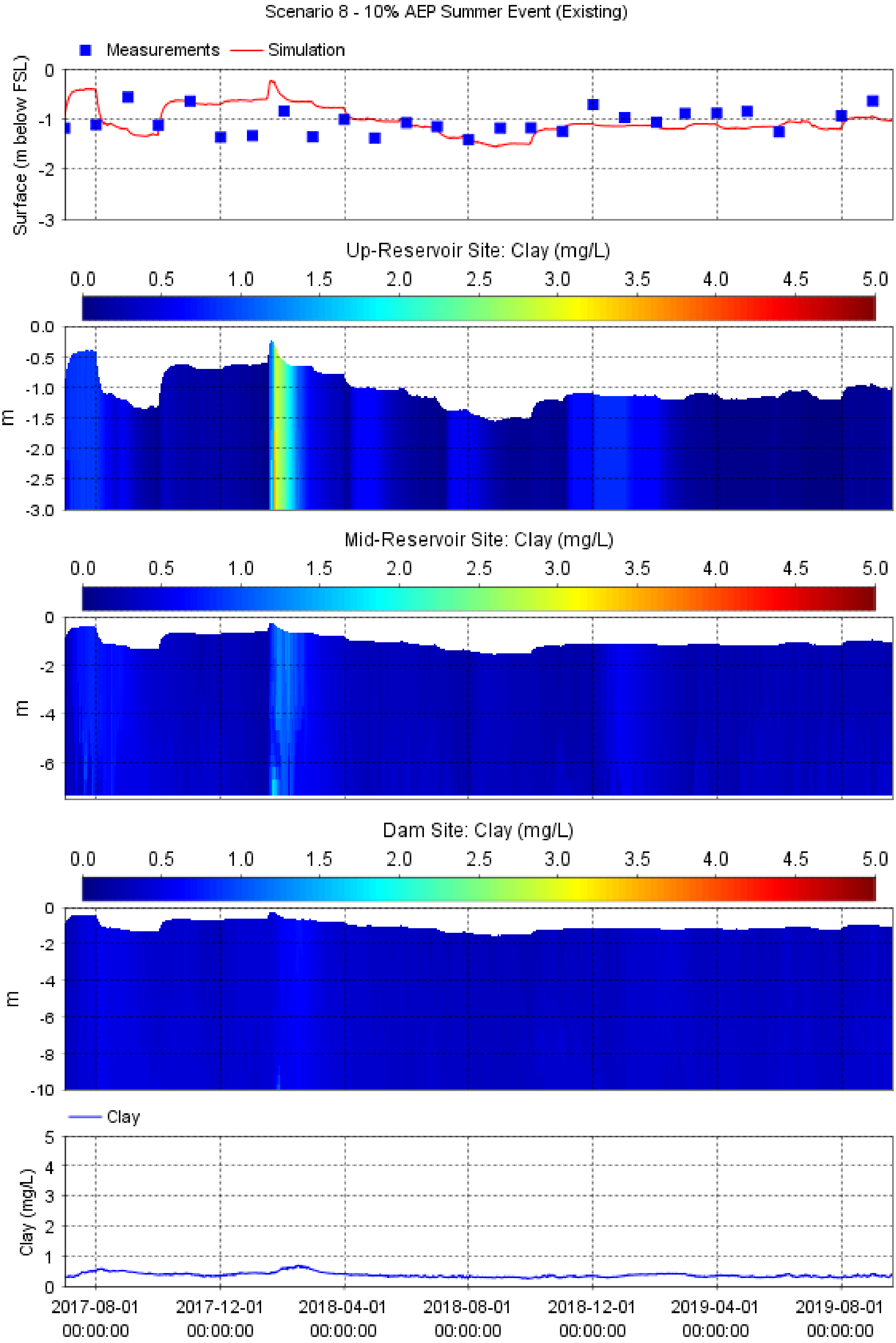

Figure 166 ***SPD simulated levels of clay for scenario 8 (summer existing case 10% AEP flood event) with moderate drainage failure SS levels.***

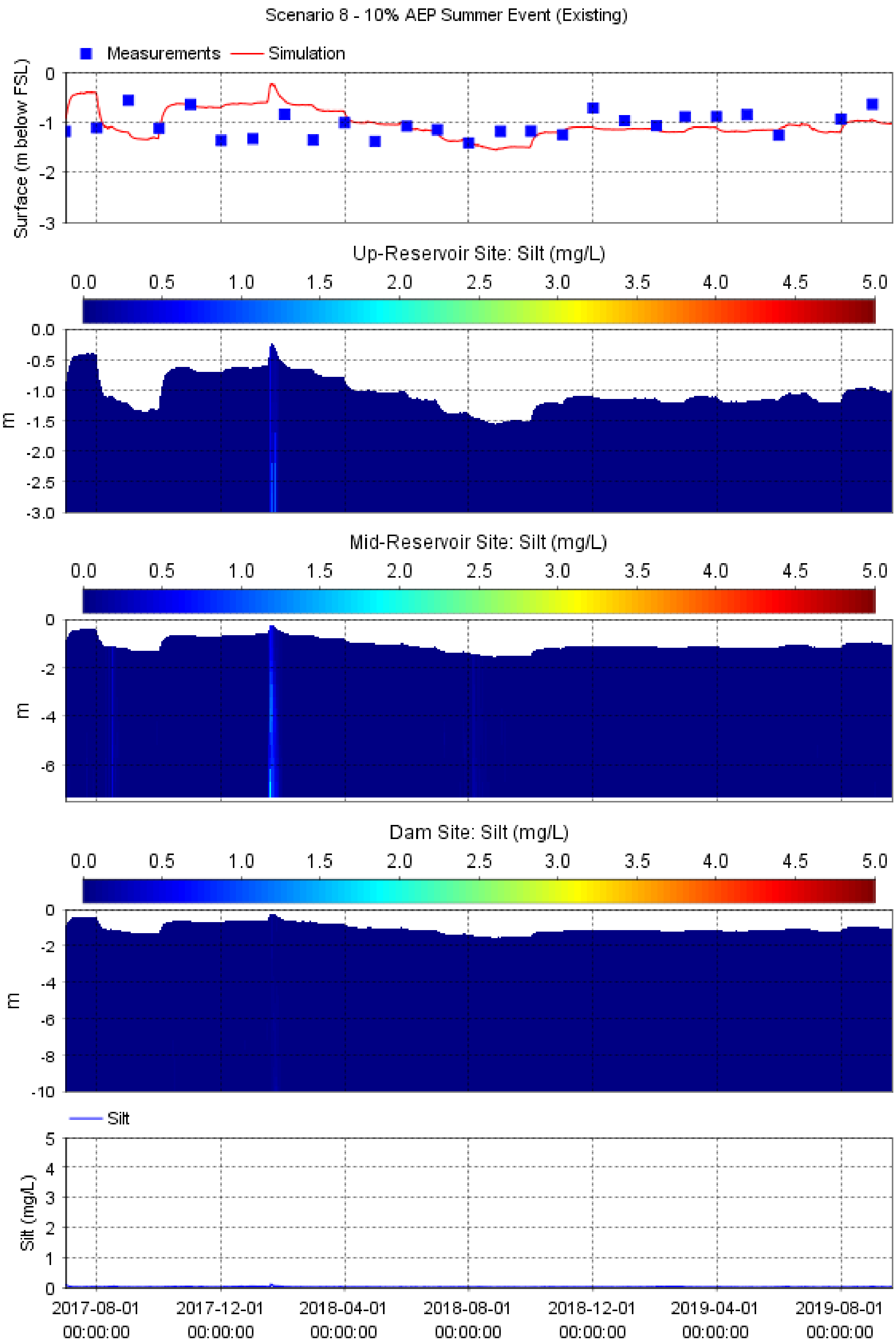

Figure 167 SPD simulated levels of silt for scenario 8 (summer existing case 10% AEP flood event) with moderate drainage failure SS levels.

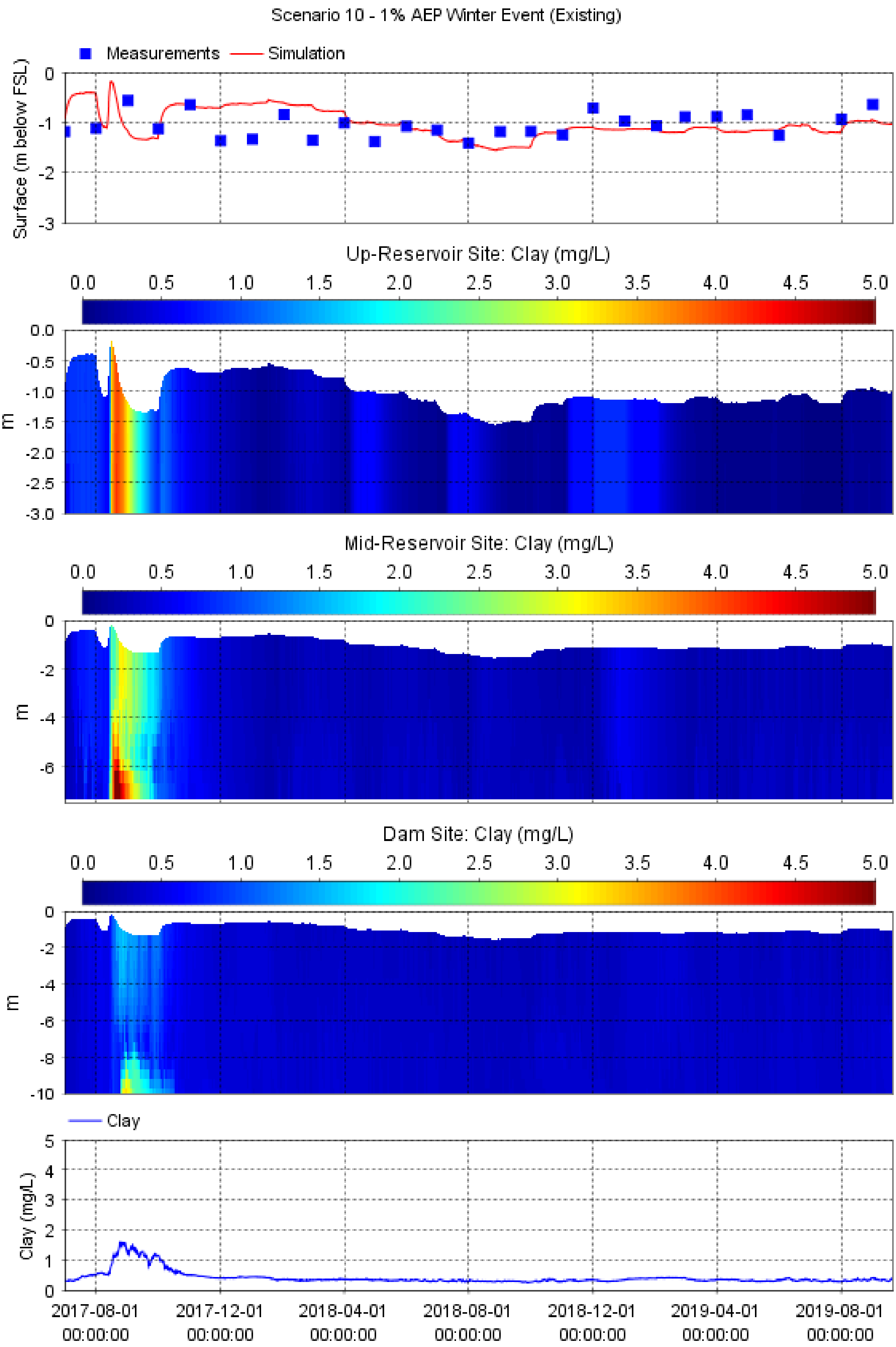

Figure 168 ***SPD simulated levels of clay for scenario 10 (winter existing case 1% AEP flood event) with moderate drainage failure SS levels.***

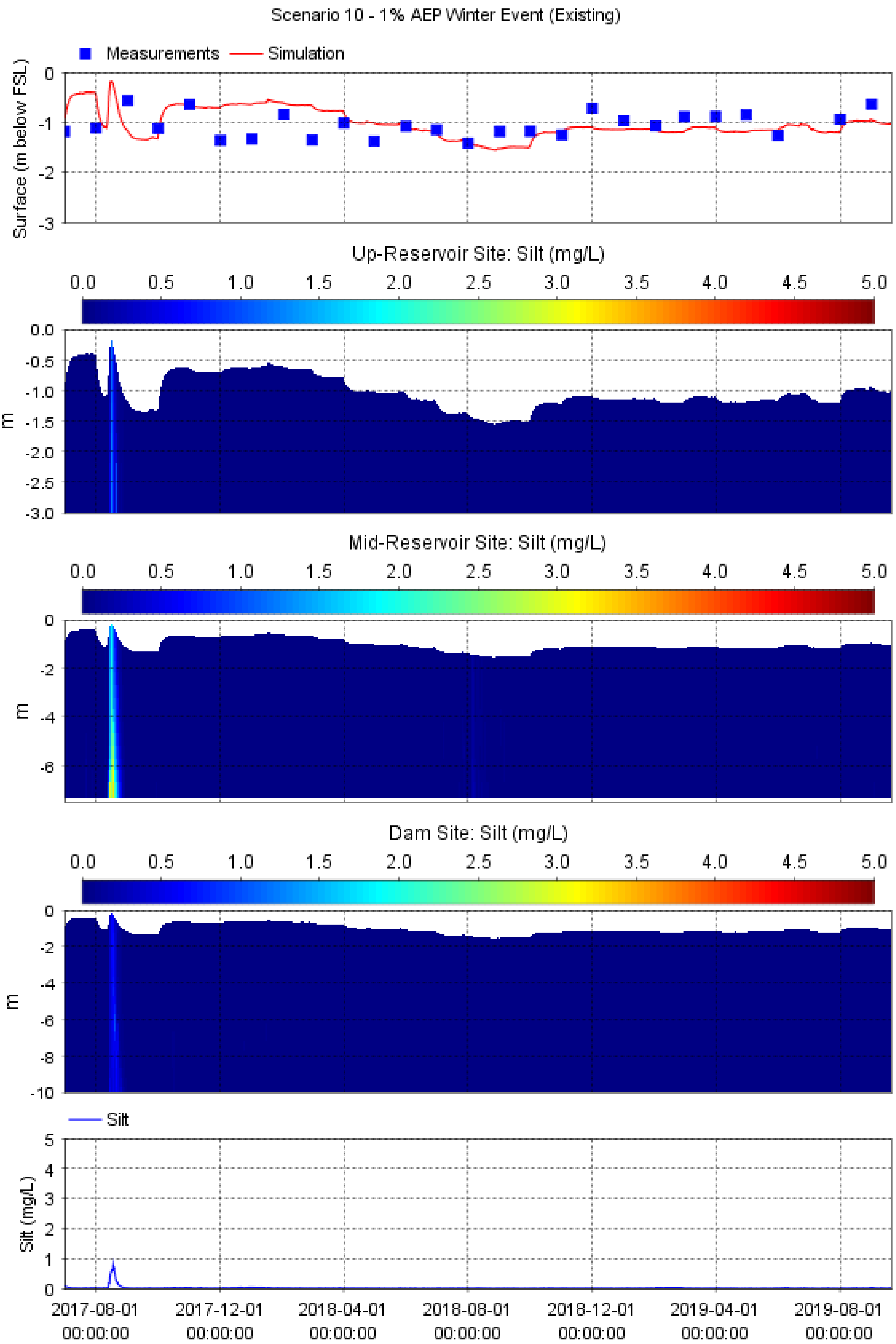

Figure 169 ***SPD simulated levels of silt for scenario 10 (winter existing case 1% AEP flood event) with moderate drainage failure SS levels.***

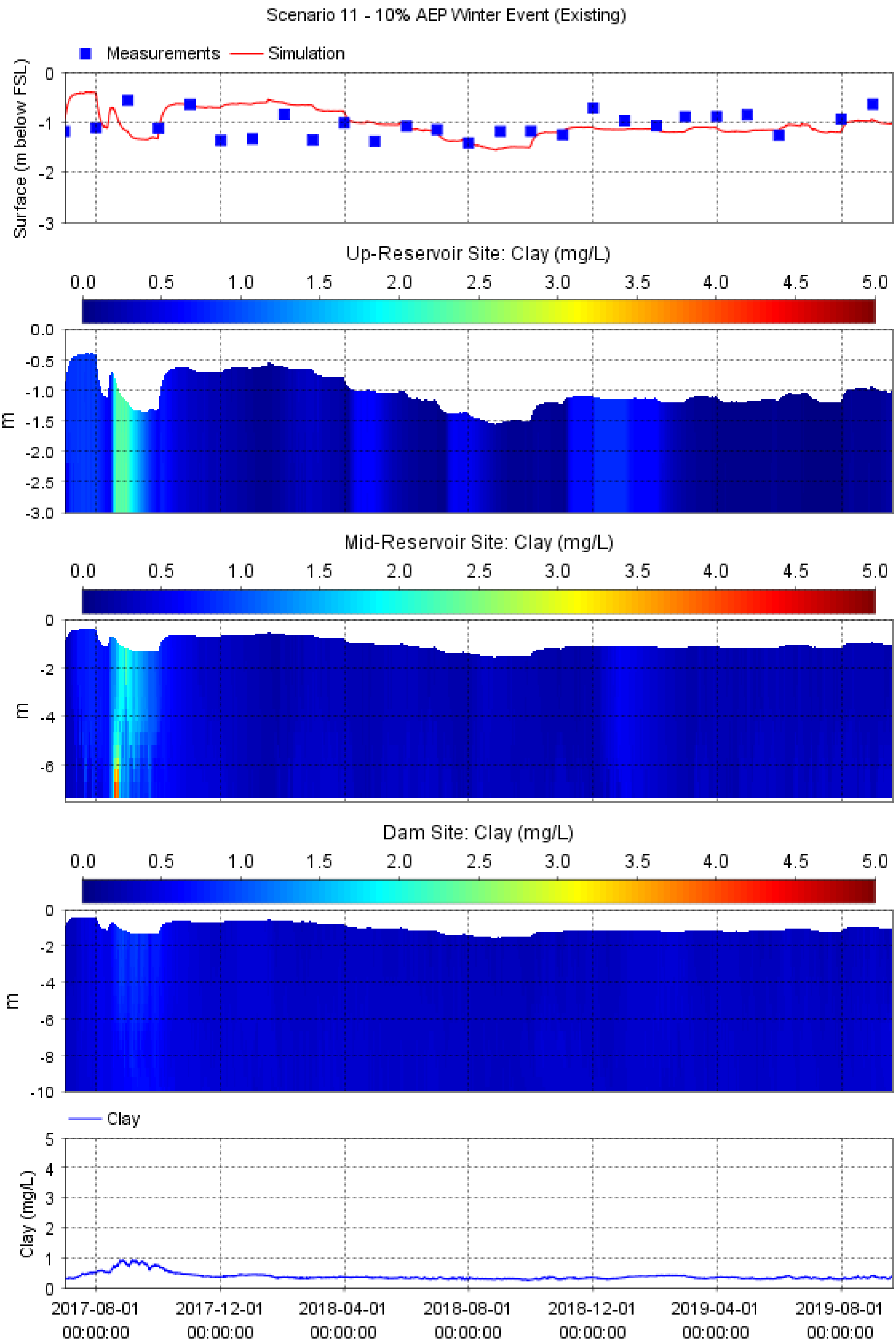

Figure 170 SPD simulated levels of clay for scenario 11 (winter existing case 10% AEP flood event) with moderate drainage failure SS levels.

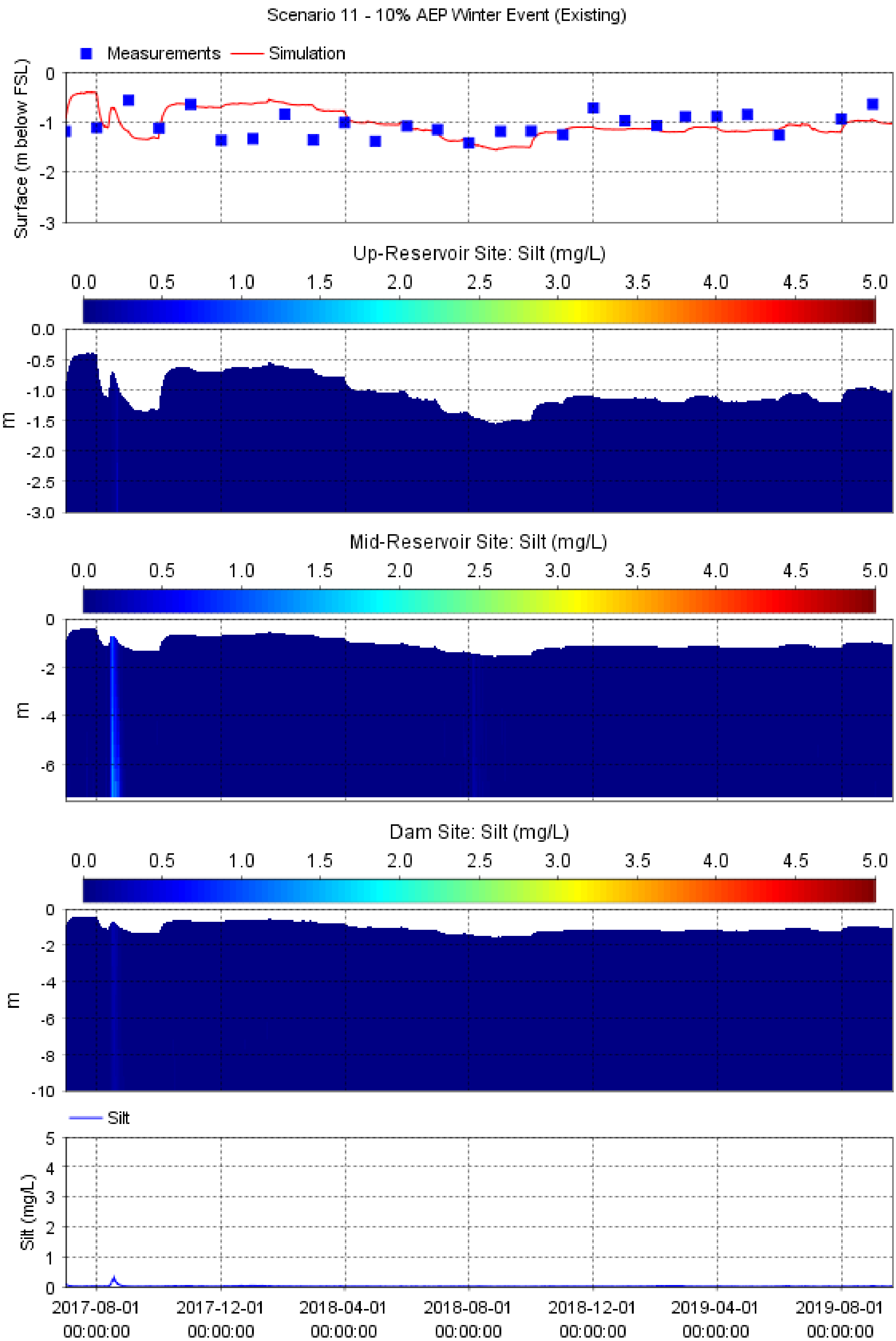

Figure 171 ***SPD simulated levels of silt for scenario 11 (winter existing case 10% AEP flood event) with moderate drainage failure SS levels.***

Appendix K

SPD: 1% and 10% AEP Flood Event Inputs (High Drainage Failure SS Levels)

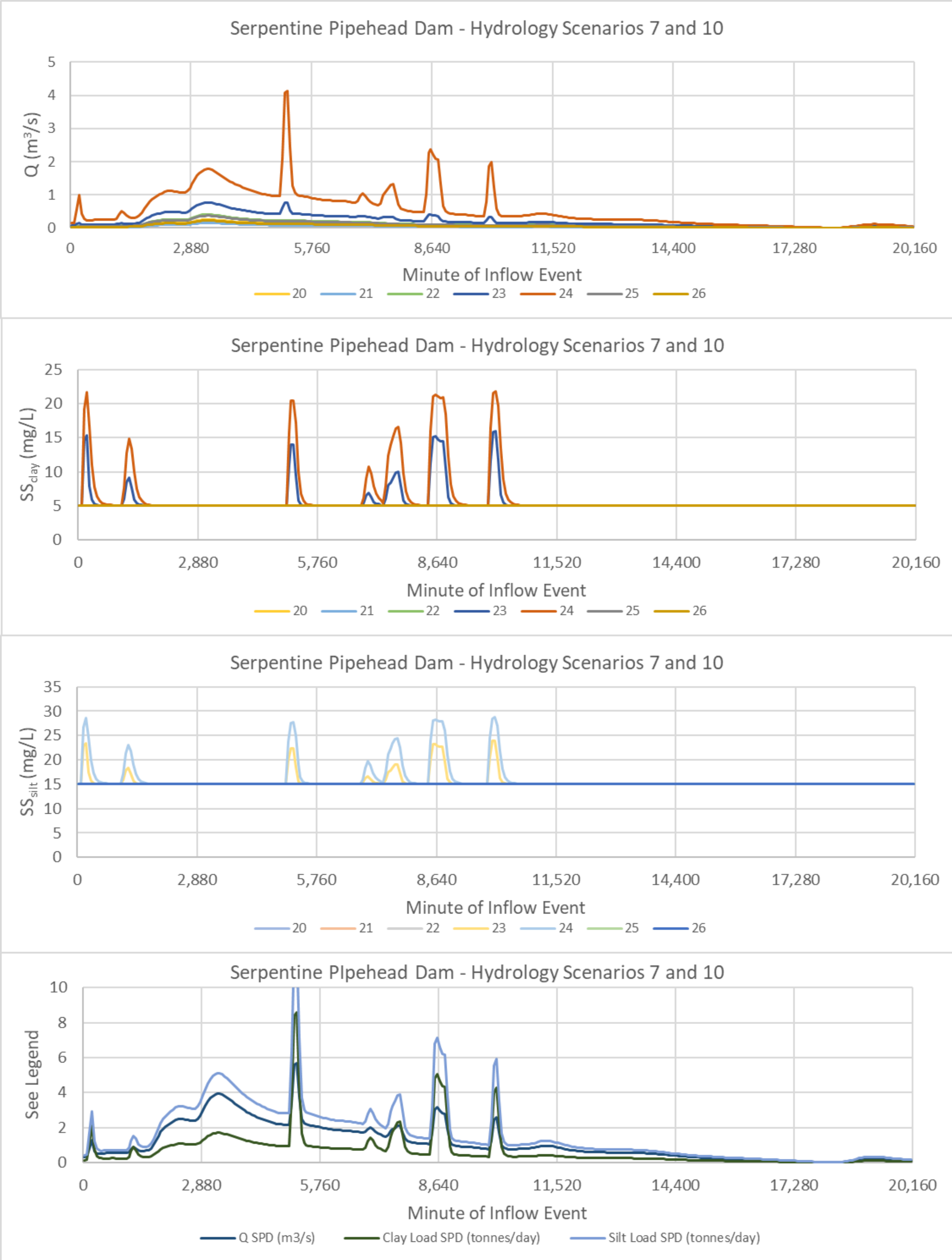

Figure 172 SPD hydrology and suspended solids inputs for scenarios 7H and 10H with high drainage failure SS levels.

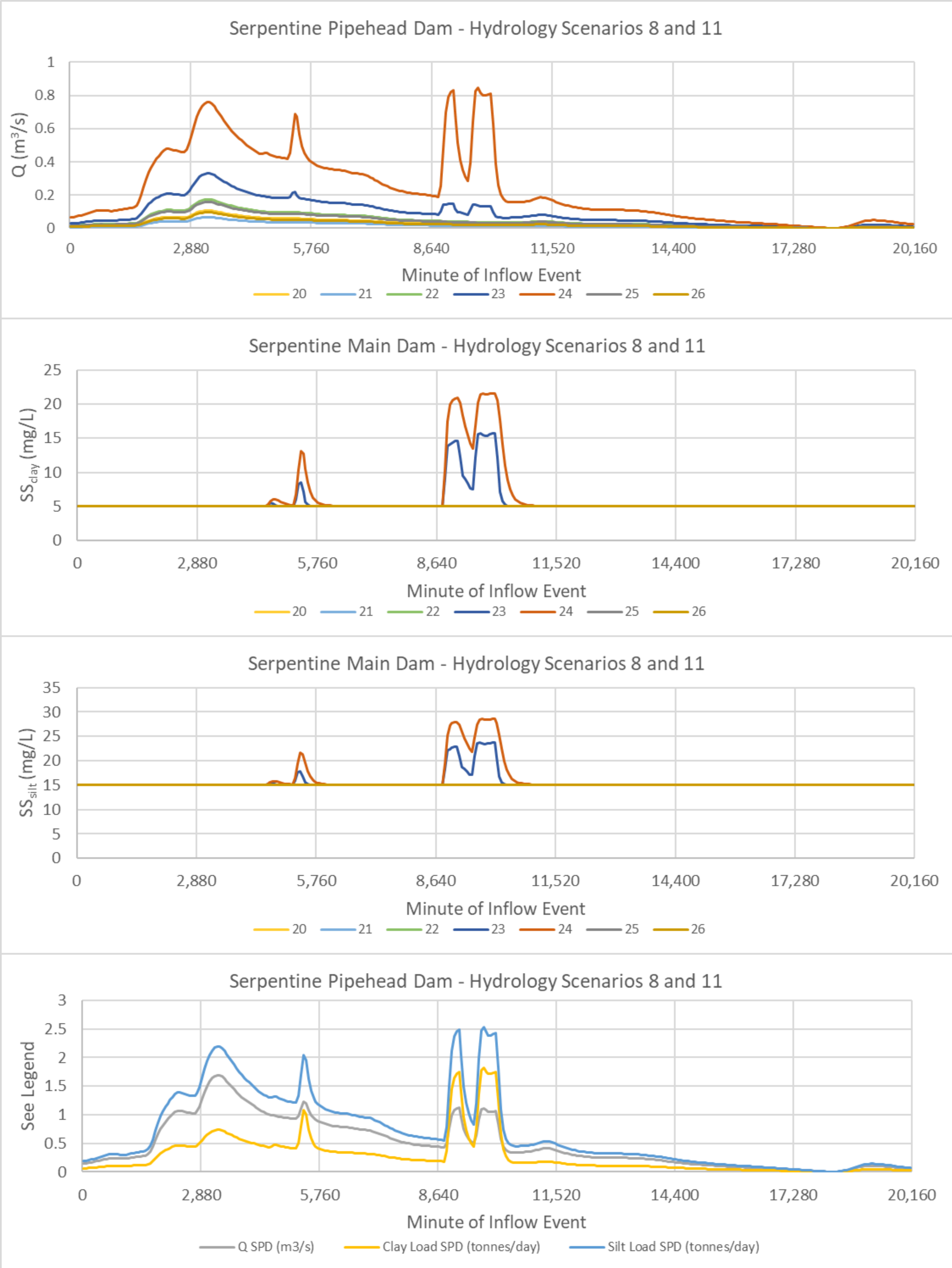

Figure 173 ***SPD hydrology and suspended solids inputs for scenarios 8H and 11H with high drainage failure SS levels.***

Appendix L

SPD: 1% and 10% AEP Flood Event Simulations (High Drainage Failure SS Levels)

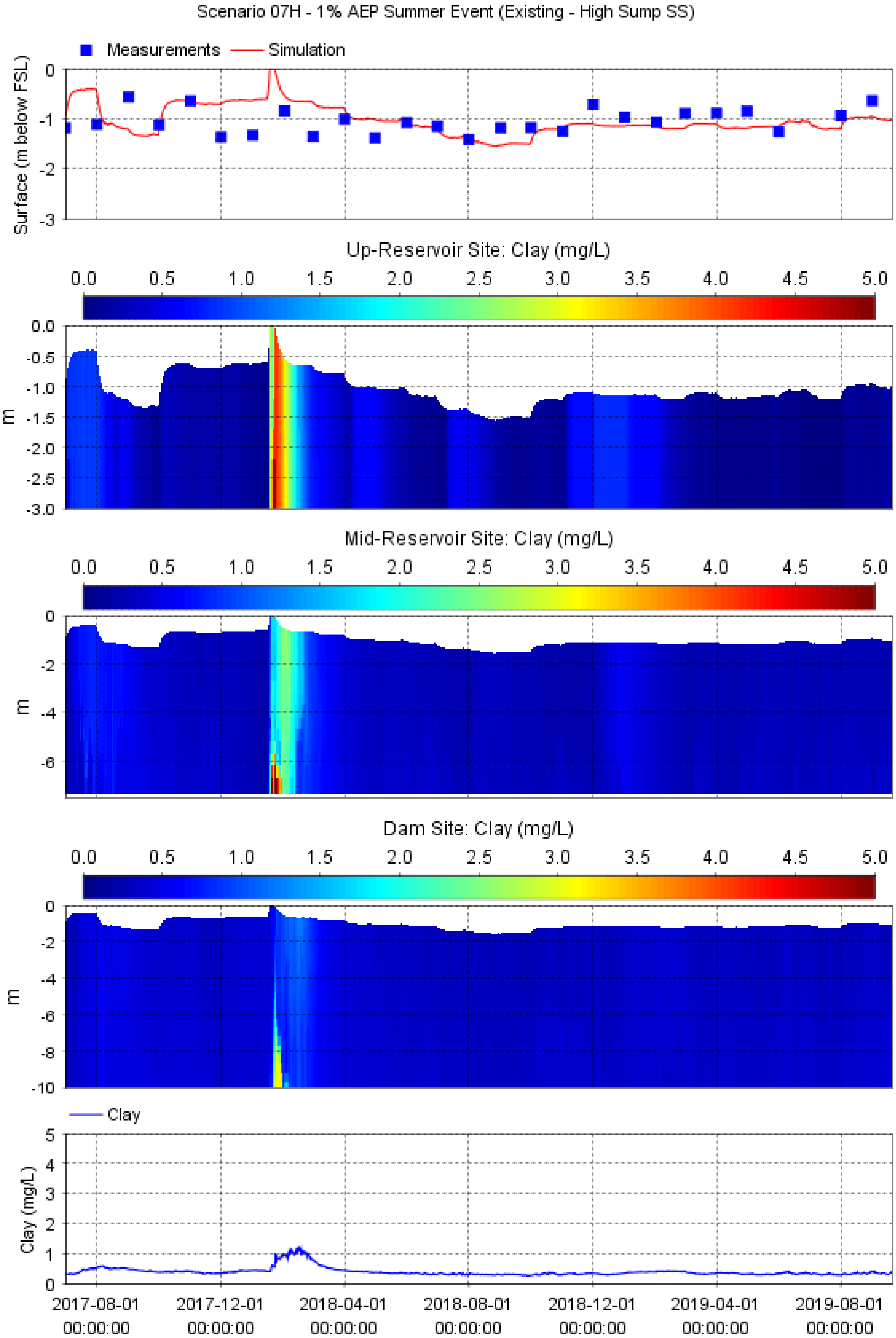

Figure 174 SPD simulated levels of clay for scenario 7H (summer existing case 1% AEP flood event) with high drainage failure SS levels.

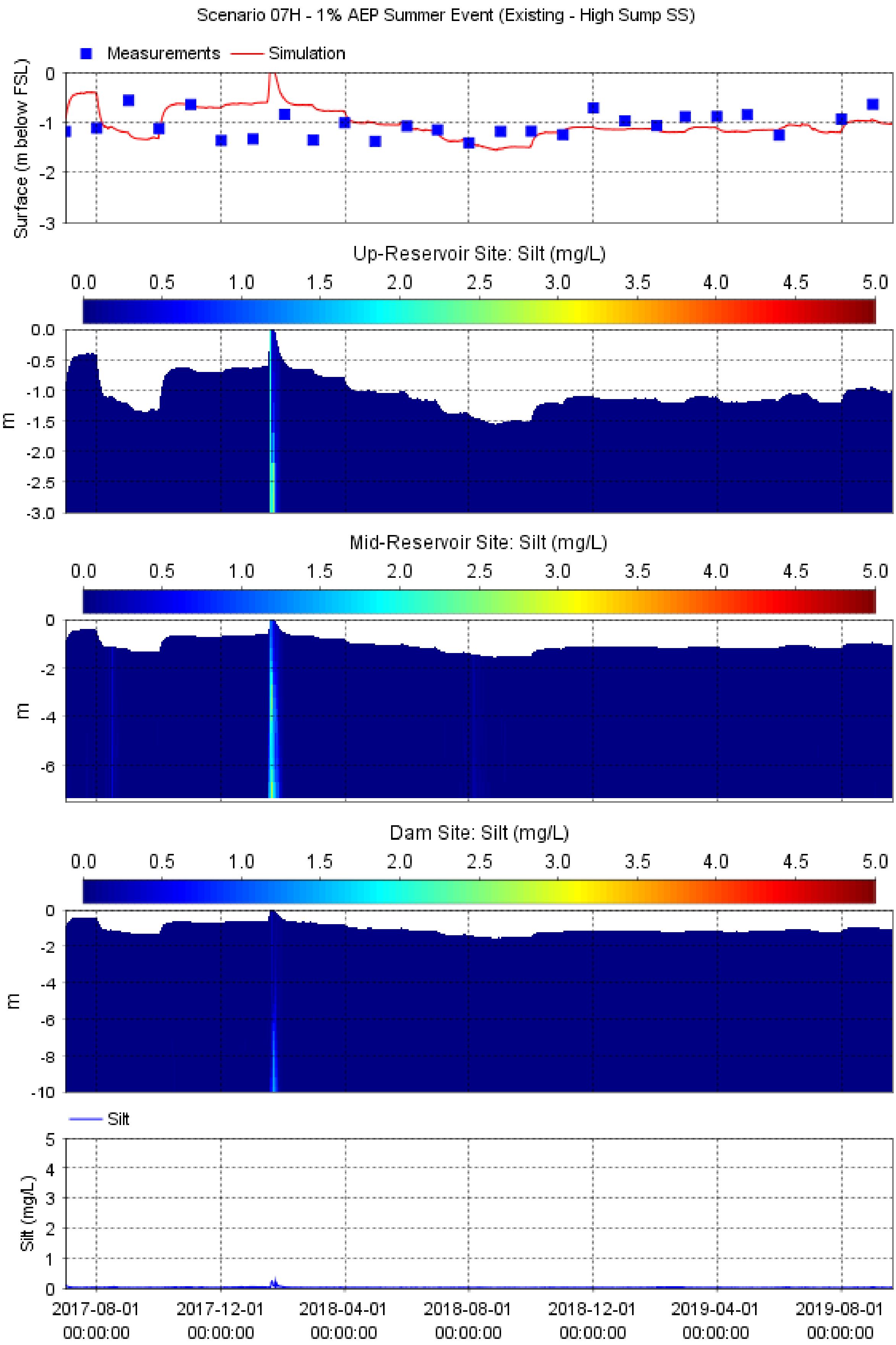

Figure 175 SPD simulated levels of silt for scenario 7H (summer existing case 1% AEP flood event) with high drainage failure SS levels.

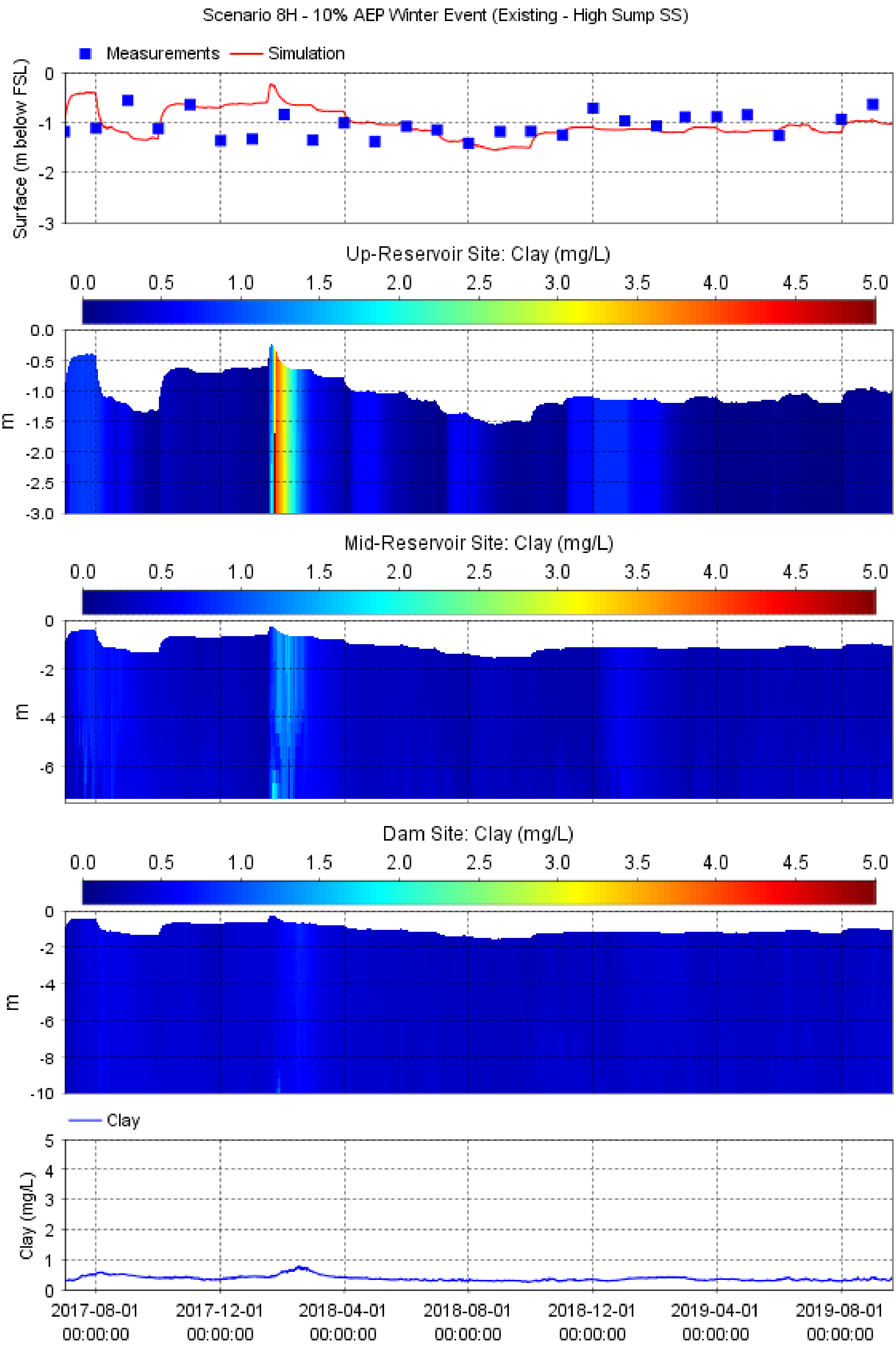

Figure 176 *SPD simulated levels of clay for scenario 8H (summer existing case 10% AEP flood event) with high drainage failure SS levels.*

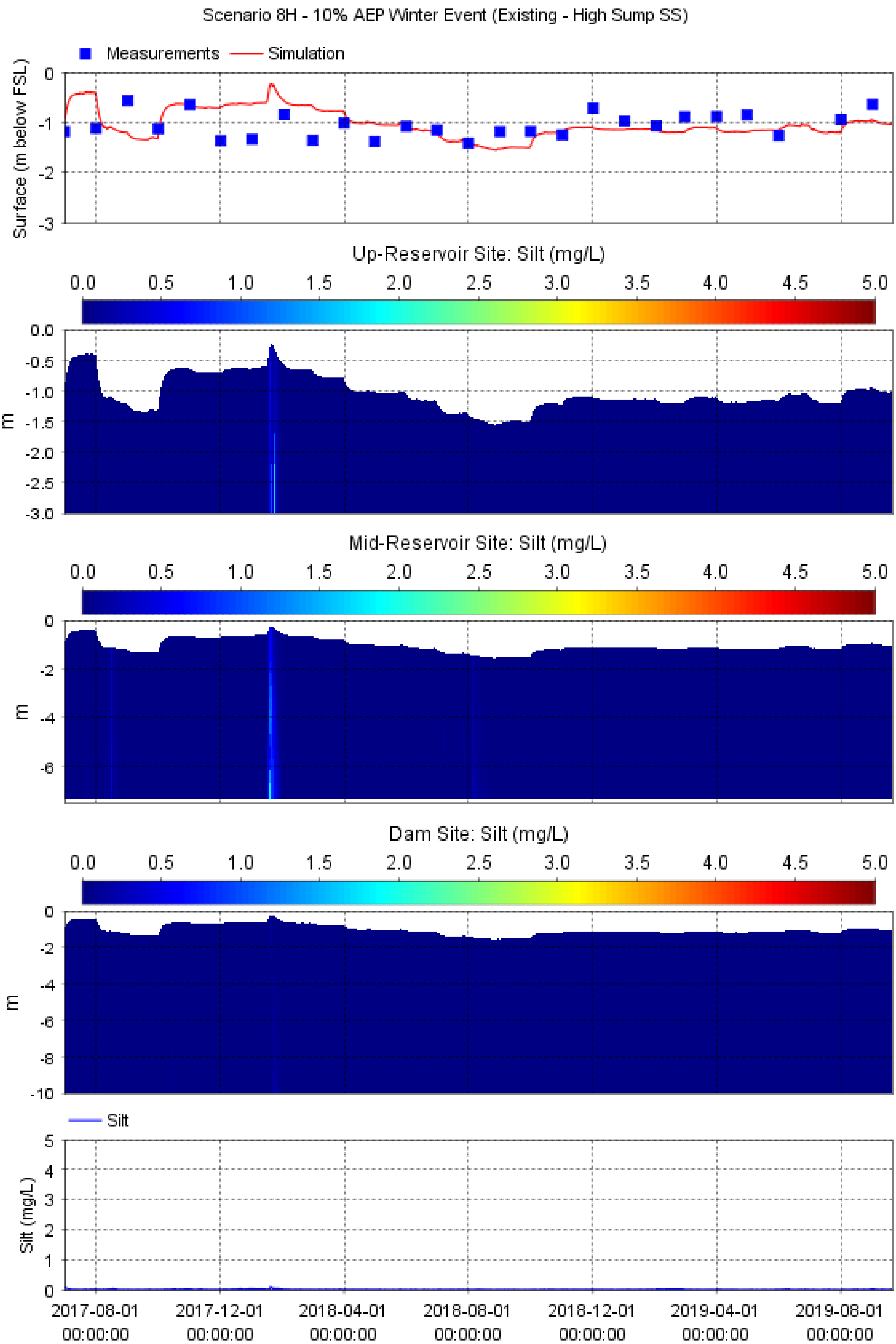

Figure 177 SPD simulated levels of silt for scenario 8H (summer existing case 10% AEP flood event) with high drainage failure SS levels.

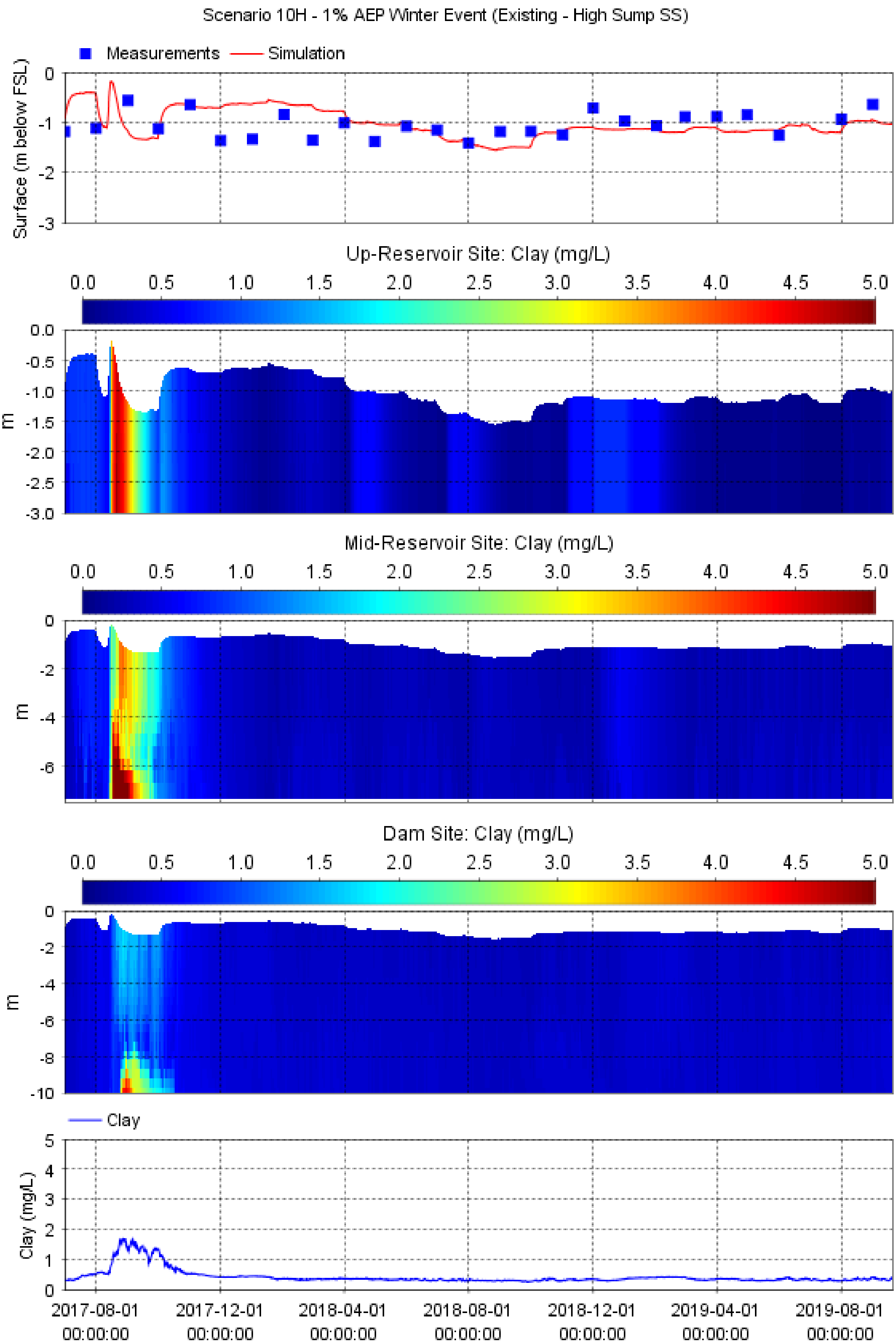

Figure 178 ***SPD simulated levels of clay for scenario 10H (winter existing case 1% AEP flood event) with high drainage failure SS levels.***

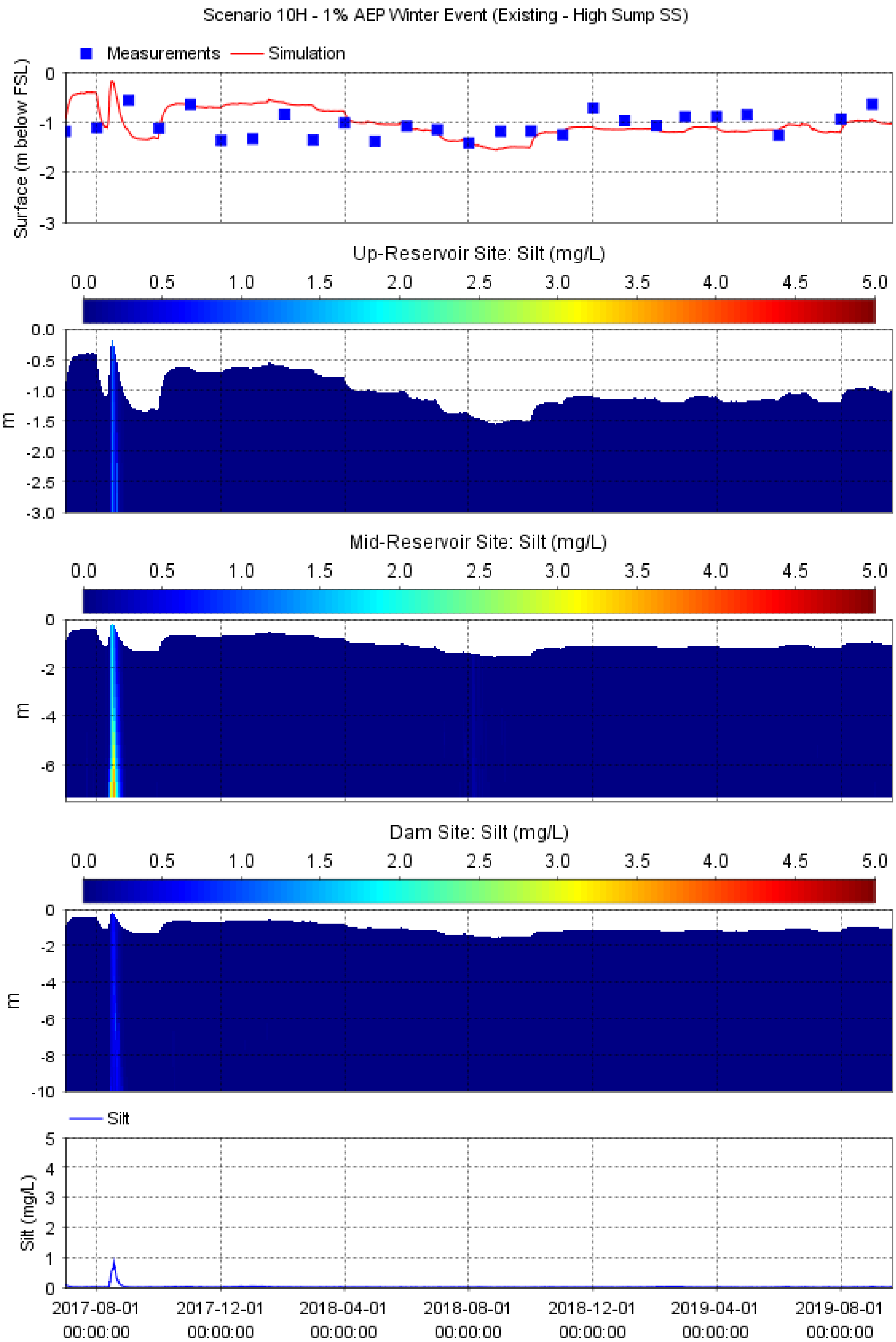

Figure 179 ***SPD simulated levels of silt for scenario 10H (winter existing case 1% AEP flood event) with high drainage failure SS levels.***

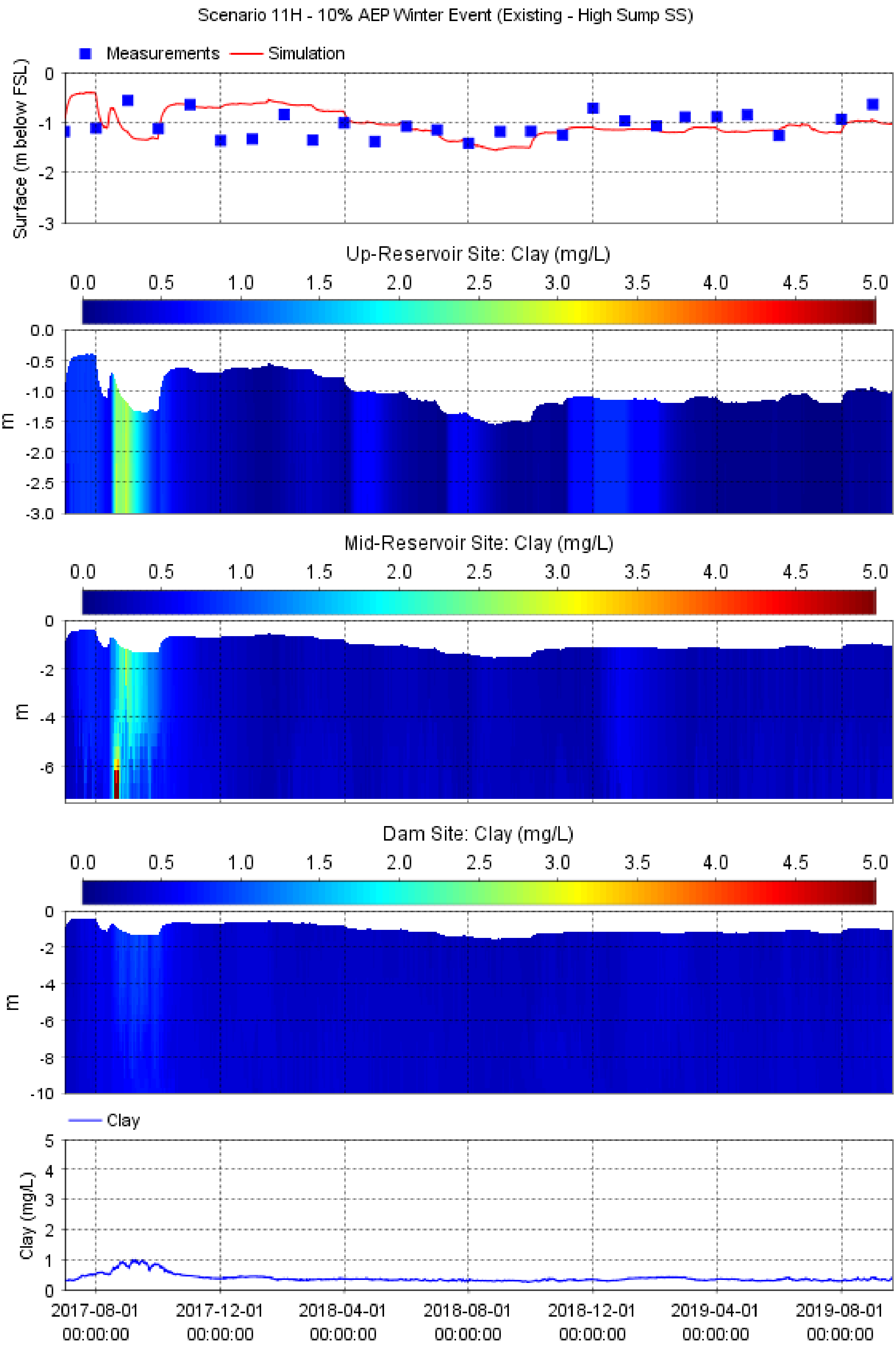

Figure 180 ***SPD simulated levels of clay for scenario 11H (winter existing case 10% AEP flood event) with high drainage failure SS levels.***

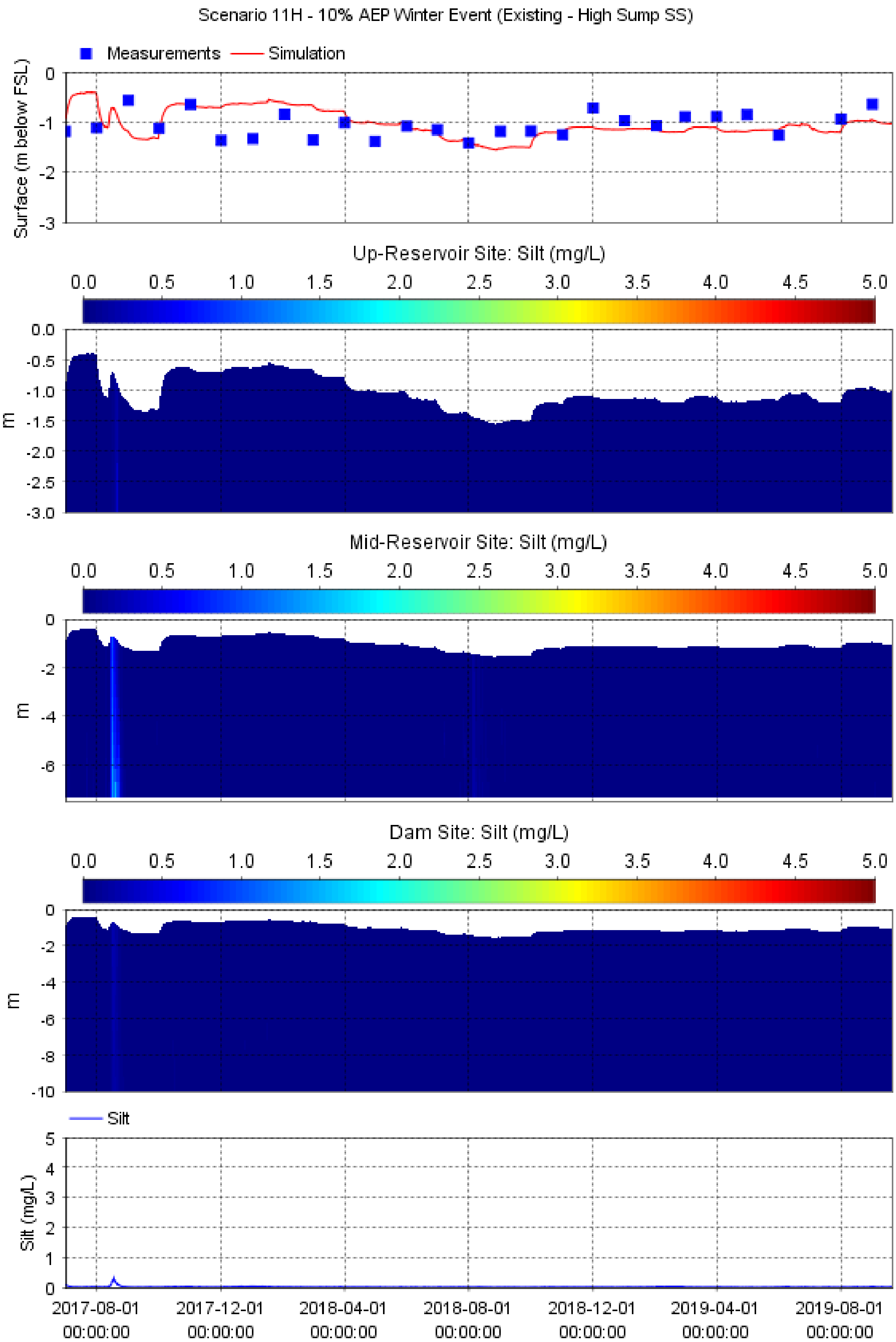

Figure 181 *SPD simulated levels of silt for scenario 11H (winter existing case 10% AEP flood event) with high drainage failure SS levels.*

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Appendix G

Turbidity risk assessment workings

The turbidity modelling uses a wide range of input variables to assess the consequence of the hazardous event. Table G.17 qualitatively rates the likelihood and consequence of the model scenarios for the purpose of assigning an overall risk rating.

Table G.17 Scenario probabilities

Scenario ID	Catchment clearing	Synthetic flow event season	Synthetic Storm event and draimage failure rate[12]	Event likelihood
01	Baseline (No mining effects on SS)	2017 Summer	1% AEP with no drainage failures	Rare
02			10% AEP with no drainage failures	Unlikely
03			1 E.Y. with no drainage failures	Likely
04		2018 Winter	1% AEP with no drainage failures	Rare
05			10% AEP with no drainage failures	Unlikely
06			1 E.Y. with no drainage failures	Likely
07	Existing	2017 Summer	1% AEP with 75% drainage failures	Rare
08			10% AEP with 30% drainage failures	Unlikely
09			1 E.Y. with 5% drainage failures	Likely
10		2018 Winter	1% AEP with 75% drainage failures	Rare
11			10% AEP with 30% drainage failures	Unlikely
12			1 E.Y. with 5% drainage failures	Likely
13	Proposed	2017 Summer	1% AEP with 75% drainage failures	Rare
14			10% AEP with 30% drainage failures	Unlikely
15			1 E.Y. with 5% drainage failures	Likely
16		2018 Winter	1% AEP with 75% drainage failures	Rare
17			10% AEP with 30% drainage failures	Unlikely
18			1 E.Y. with 5% drainage failures	Likely

[12] Zero sump failure for areas with existing mining activity in all baseline scenarios.

Appendix H

Turbidity risk at other scales

Turbidity risk at other scales

Historically, the failure of individual drainage barriers and the associated turbid discharge events has been of little consequence to the drinking water system. The "Stone 3" in-pit containment failure on the 6th September 2020 discharged turbid runoff to a stream discharging to the Serpentine Reservoir. Alcoa's instream turbidity monitor SE53 located 1.2 km downstream recorded peak turbidity in excess of 110 NTU between 6th and 7th September. Water quality measurements and sampling within the reservoir undertaken on the 9th September 2020 indicate turbidity levels of up to 3.5 NTU approximately 3 km downstream of the failure, decreasing to <1 NTU approximately 4.7 km downstream of the failure. No increase in turbidity was observed at the offtake during the subsequent 15th September monitoring round (<=0.3 NTU) nor on the 20th October monitoring round (<=0.2 NTU). Long term offtake turbidity measurements demonstrate that the despite a history of turbid discharge incidents, turbidity at the offtake has not changed from background levels.

Individual pit-scale drainage failures can increase local turbidity levels but are insufficient to impact drinking water quality. Assessing risk at the drinking water catchment scale is therefore the preferred approach for drinking water risk assessments, so that the impact of multiple failures at the critical offtake point can be understood. Nevertheless, there is value in assessing risk at the pit and sub-catchment scales to understand local environmental risks as described below.

Pit scale turbidity risk

There are a multitude of causal factors that may lead to a turbidity discharge event. These causal factors are currently under investigation by the Alcoa Mining and Management Program. Anecdotal evidence suggests that geographic factors such as catchment slope may increase the likelihood of a drainage failure and a turbidity event. Slope is a known factor for erosion rates and can increase the failure risk of drainage structures due to higher runoff velocities. However, soil loss is less sensitive to the slope length than to any other soil loss factor (Jain & Singh, 2003).

Alcoa long term planning method

It is reasonable to assume that the closer a drainage failure is to a sensitive receptor, the higher the consequence is to that receptor. Alcoa have developed a semi-quantitative draft long-term planning approach for assessing risk, that considers slope as a proxy for likelihood, and location factors as a proxy for consequence. The location factors include both administrative boundaries (e.g., RPZ), and proximity to stream zone vegetation. The risk assessment scoring procedure results in a risk score from low to high, with the very highest risk areas deemed too risky to be mined. It is important to note that this risk assessment approach is inconsistent with ADWG (NHMRC, 2011) and inconsistent with the approach adopted in this drinking water risk assessment report. However, the approach is useful for assessing the relative risk of mining pits, the relative requirement for barriers, and as an input for assessing sub-catchment scale risk.

Table H.1 Pit scale turbidity risk criteria (Alcoa, 2020)

Points	Pit risk rating	Location	Proximity to stream	Slope
0	Mining Exclusion Area	OCA1	1st & 2nd order streams: - 20m from edge of stream zone. - If no vegetation is present, 20m from grade changes defining water flow channels/centre of stream channel. 3rd order + streams (outside OCA2): - 30m beyond stream zone vegetation. 1000m upstream of top water level of PDWSA reservoirs: - 50m beyond stream zone vegetation.	>16°
1	High	RPZ or Serpentine Pipehead catchment	<200m beyond stream zone vegetation	8°-16°

Points	Pit risk rating	Location	Proximity to stream	Slope
2	Moderate	Proclaimed catchment, offsite environmentally sensitive surface water catchment, or private drinking water supply	200-500m beyond stream zone vegetation	3°-8°
3	Low	Offsite surface water catchment, nonenvironmentally sensitive	500-1000m beyond stream zone vegetation	1°-3°
4	Insignificant	Onsite water catchment	>1000m beyond stream zone vegetation	<1°

Table H.2 Pit scale risk scoring (Alcoa, 2020)

Total pit risk score	Pit risk rating
0-2	Extreme
3-5	High
6-8	Moderate
9+	Low

RUSLE method

A tool based on the Revised Universal Soil Loss Equation (RUSLE) was developed by GHD to estimate annual soil loss, described in detail in Appendix J. The tool is a quantitative alternative to the Alcoa long term planning method and can be used for both planning and design purposes. In the absence of site-specific evidence, the tool does not account for downstream factors presumed to cause attenuation and dilution, and ignores prescribed zones such as the RPZ. The tool has been applied to the proposed Holyoake and Myara North clearing areas, estimating erosion rates in tonnes per hectare per annum.

Results

Results of the pit scale assessment are plotted in Figure H.1 and Figure H.2, and mapped in Figure H.3 to Figure H.6 below. Note that the Holyoake pits are yet to be defined, large contiguous clearing areas have been assumed, and therefore erosion rates are likely to be overestimated.

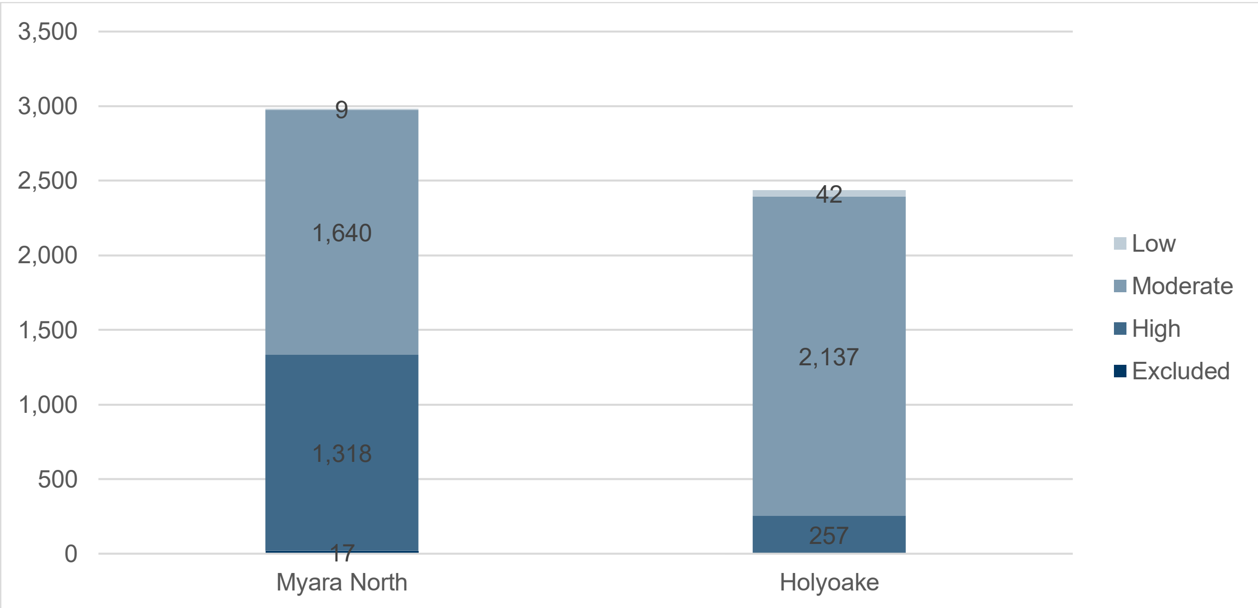


Figure H.1 Pit scale turbidity risk by mining region

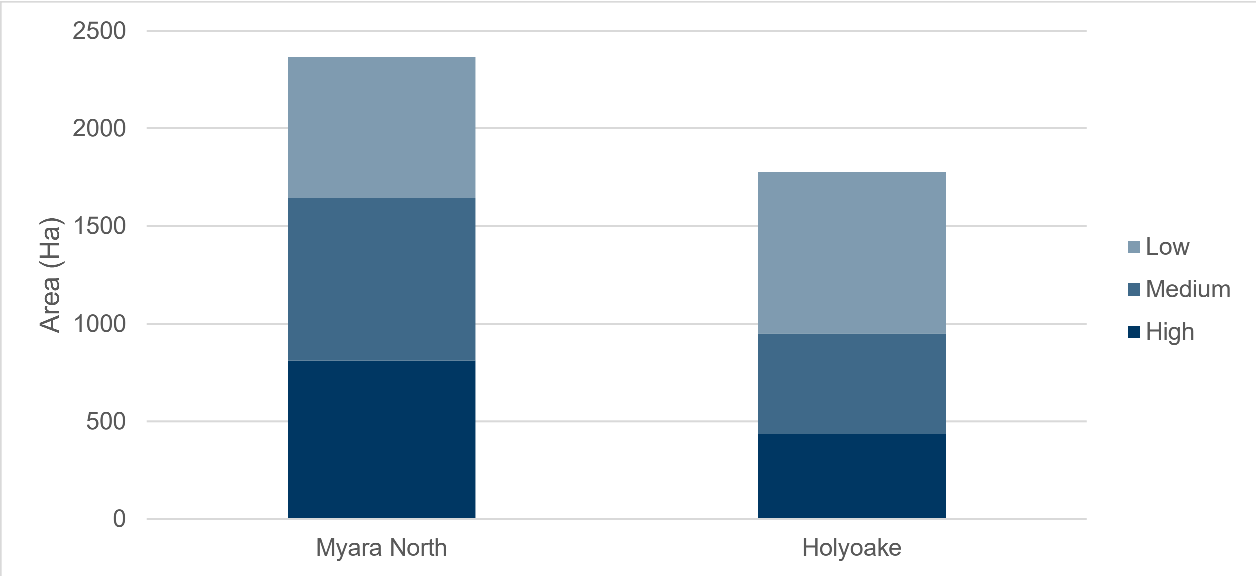


Figure H.2 ***Pit scale erosion rates by mining region***

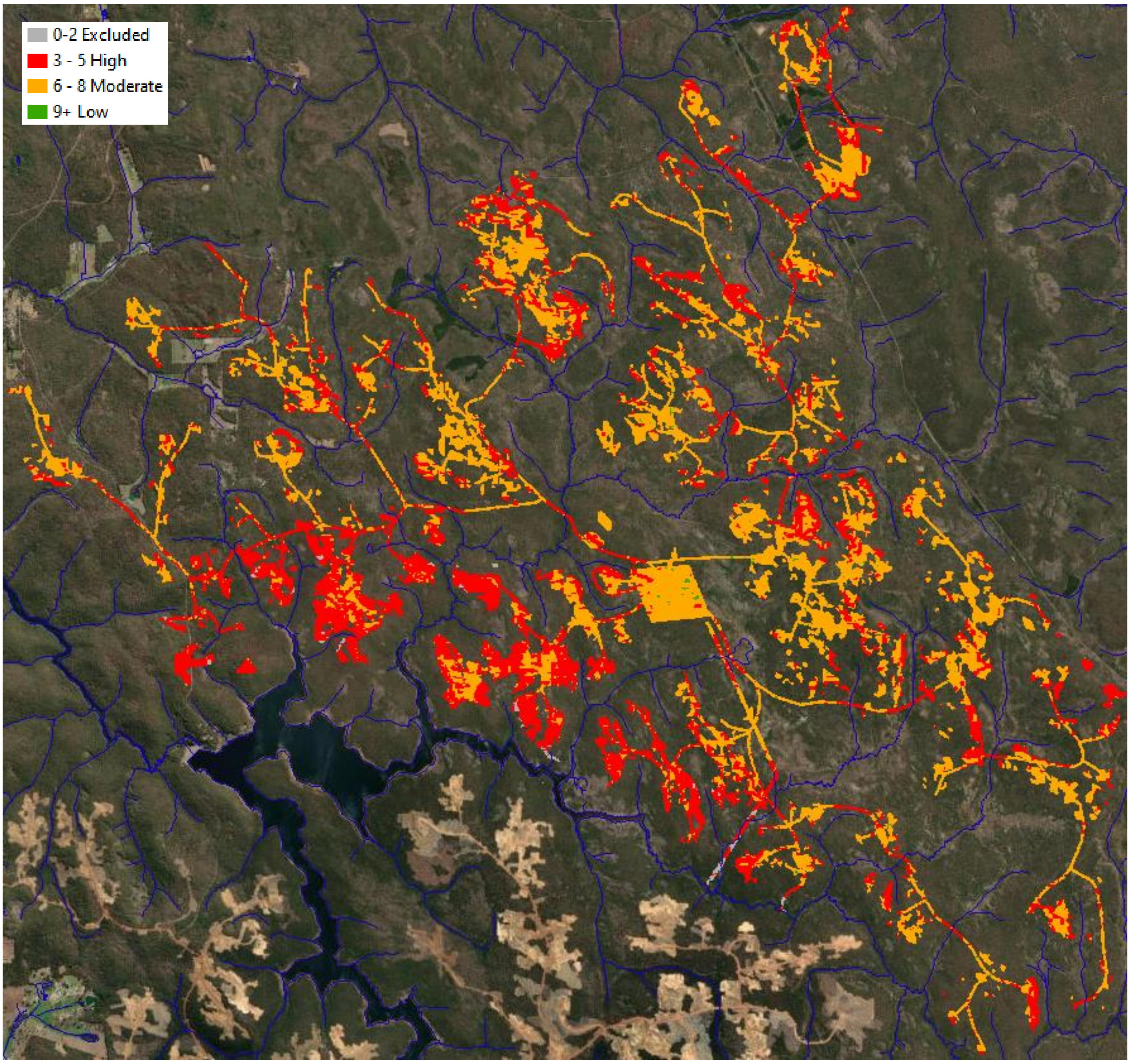


Figure H.3 Myara North pit scale turbidity risk (Alcoa long term planning method)

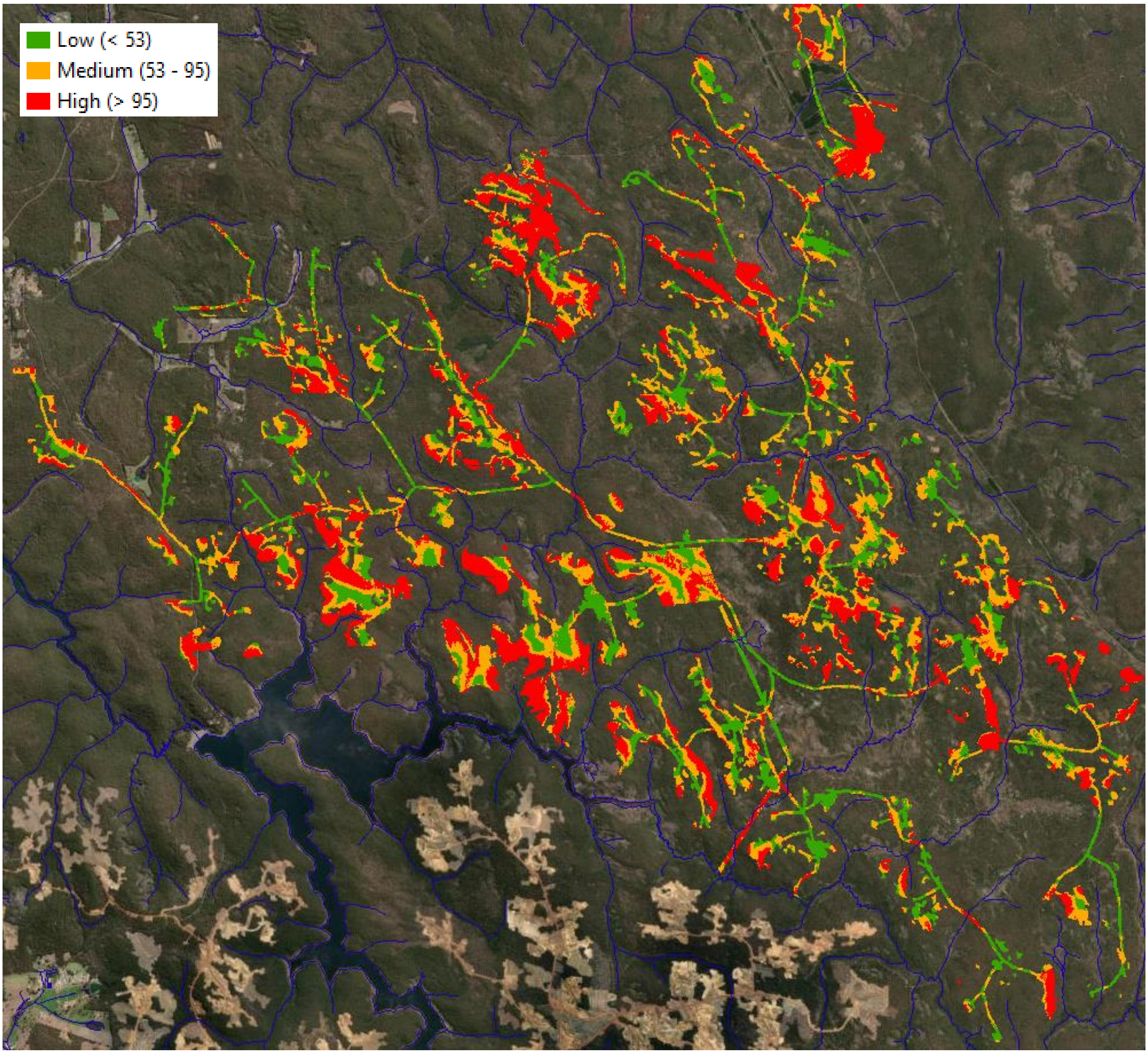


Figure H.4 Myara North pit scale erosion rate (t/ha/a, RUSLE method)

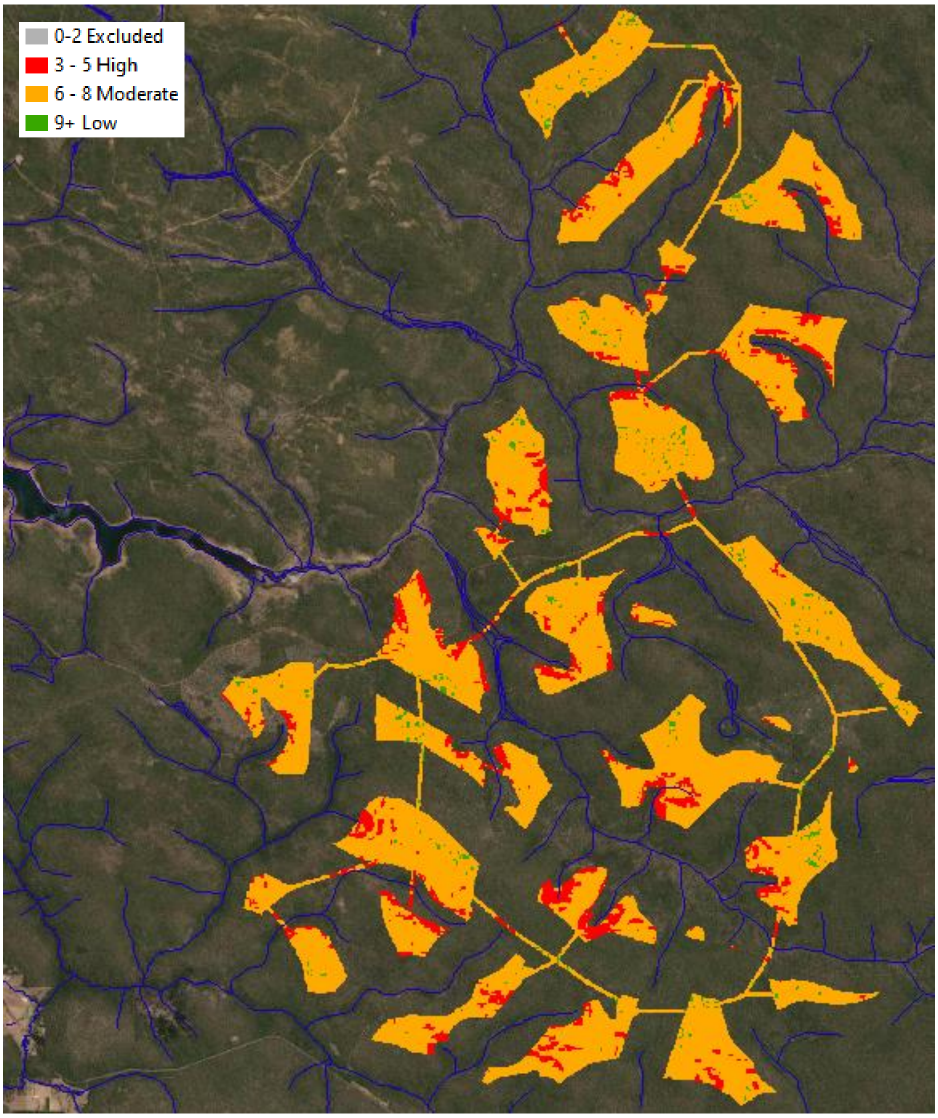


Figure H.5 ***Holyoake pit scale turbidity risk (Alcoa long term planning method)***

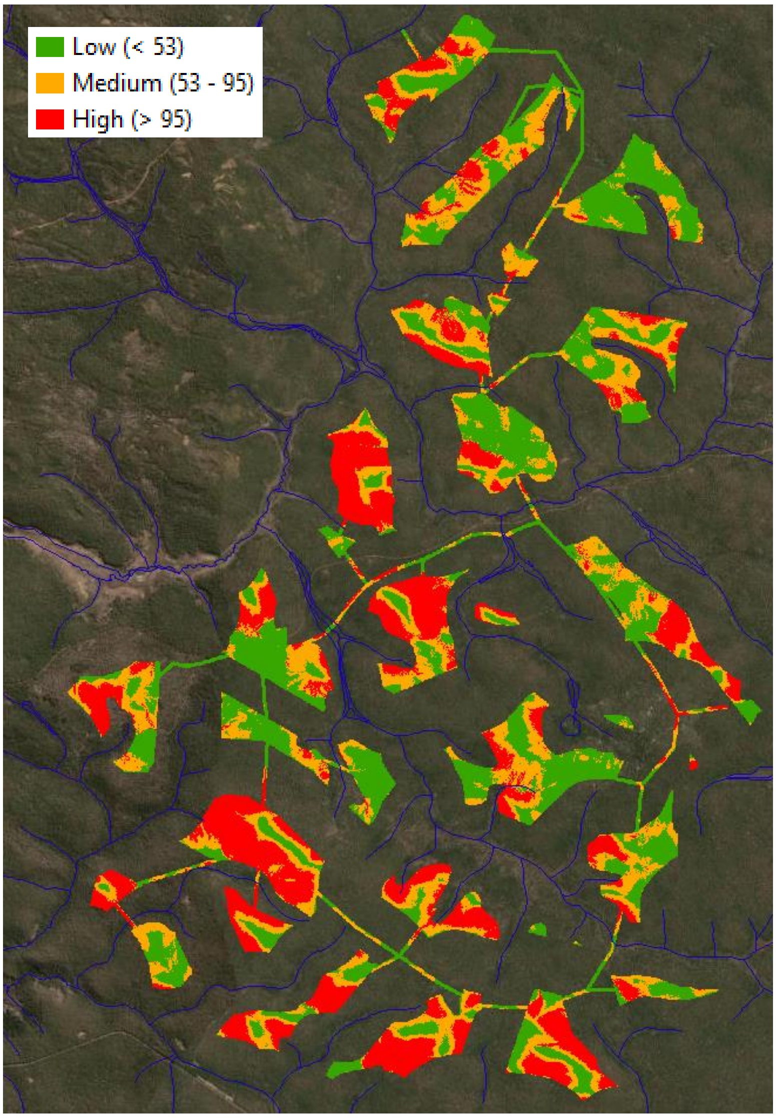


Figure H.6 ***Holyoake pit scale erosion rate (t/ha/a, RUSLE method)***

Sub-catchment scale turbidity risk

RUSLE method

At the sub-catchment scale, pit-scale risks combine to produce a turbidity risk that may be higher or lower than the contributing pit-scale risks. A sub-catchment with a high proportion of clearing has a higher likelihood of generating turbid discharge. The consequence of such an event may also be higher, depending on the size and location of the sub-catchment.

A procedure for estimating sub-catchment scale turbidity discharge risk is currently under development by the MMP. In the absence of an agreed approach, the following approach is adopted. Note that this risk assessment approach is inconsistent with ADWG (NHMRC, 2011), inconsistent with the approach adopted in this drinking water risk assessment report, and is only suitable for assessing the relative risk of mining sub-catchments and the relative requirement for barriers. The scoring method presented in Equation H.1 and Table H.3 produces an even distribution of low, medium and high-risk catchments. Sub-catchments were supplied by Water Corporation and limit the analysis to the Serpentine and South Dandalup PDWSA's.

Equation H.1 ***Sub-catchment risk score***

$$Sub - catchment\ unmitigated\ soil\ loss\ (t.ha^{-1}.a^{-1}) = \frac{Cleared\ area\ annual\ soil\ loss\ potential\ (t.a^{-1})}{Sub - catchment\ area\ (ha)}$$

Table H.3 Risk area criteria

Sub-catchment unmitigated soil loss (t/ha/a)	Relative risk
Bottom third (<5.1)	Low
Middle third (5.1-12.6)	Medium
Top third (>12.6)	High

Results

Results of the sub-catchment scale risk assessment are tabulated in Table H.4, plotted in Figure H.7, and mapped in Figure H.8 and Figure H.9 below.

Table H.4 Sub-catchment scale turbidity risk

Sub-catchment	Clearing area as a proportion of catchment area (%)	Sub-catchment unmitigated soil loss (t/ha/a)	Relative risk rating
HO01	0%	0.2	Low
HO02	31%	14.6	High
HO03	19%	9.8	Medium
HO04	3%	1.9	Low
HO05	26%	20.6	High
HO06	22%	10.3	Medium
HO07	13%	4.2	Low
HO08	14%	6.9	Medium
MN01	22%	17.1	High
MN02	3%	1.6	Low
MN03	25%	18.7	High
MN04	17%	14.5	High
MN05	14%	8.4	Medium
MN06	35%	42.7	High
MN07	22%	14.6	High
MN08	16%	8.9	Medium
MN09	20%	13.1	High
MN10	18%	11.5	Medium
MN11	3%	1.2	Low
MN12	6%	3.1	Low
MN13	5%	2.0	Low
MN14	14%	8.9	Medium
MN15	3%	1.4	Low

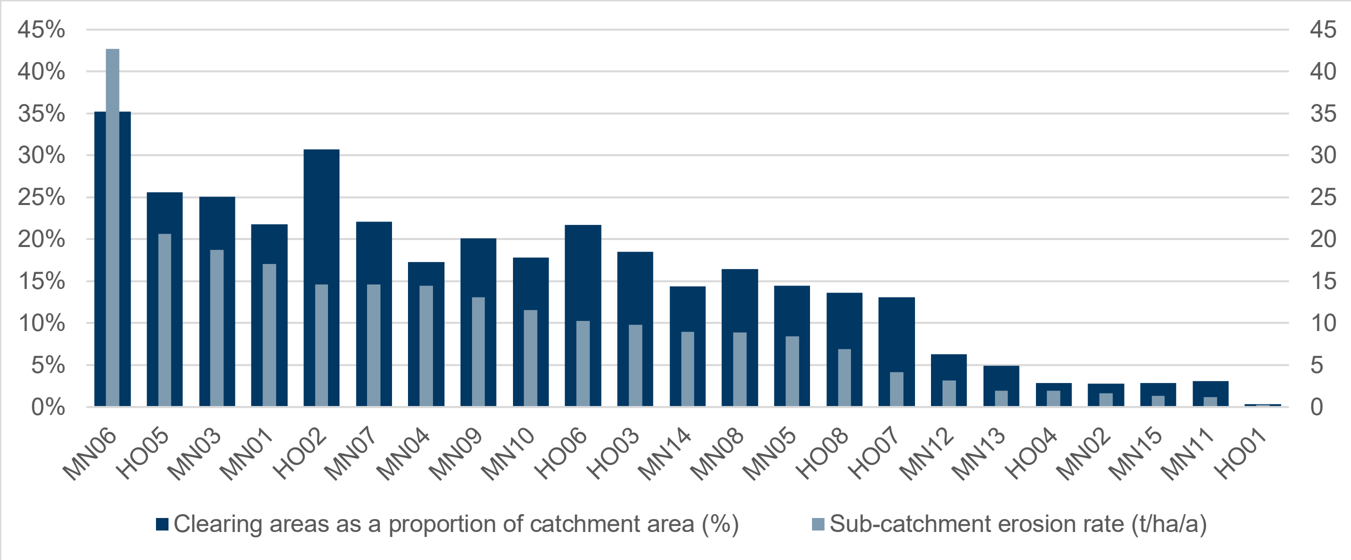


Figure H.7 ***Sub-catchment scale turbidity risk***

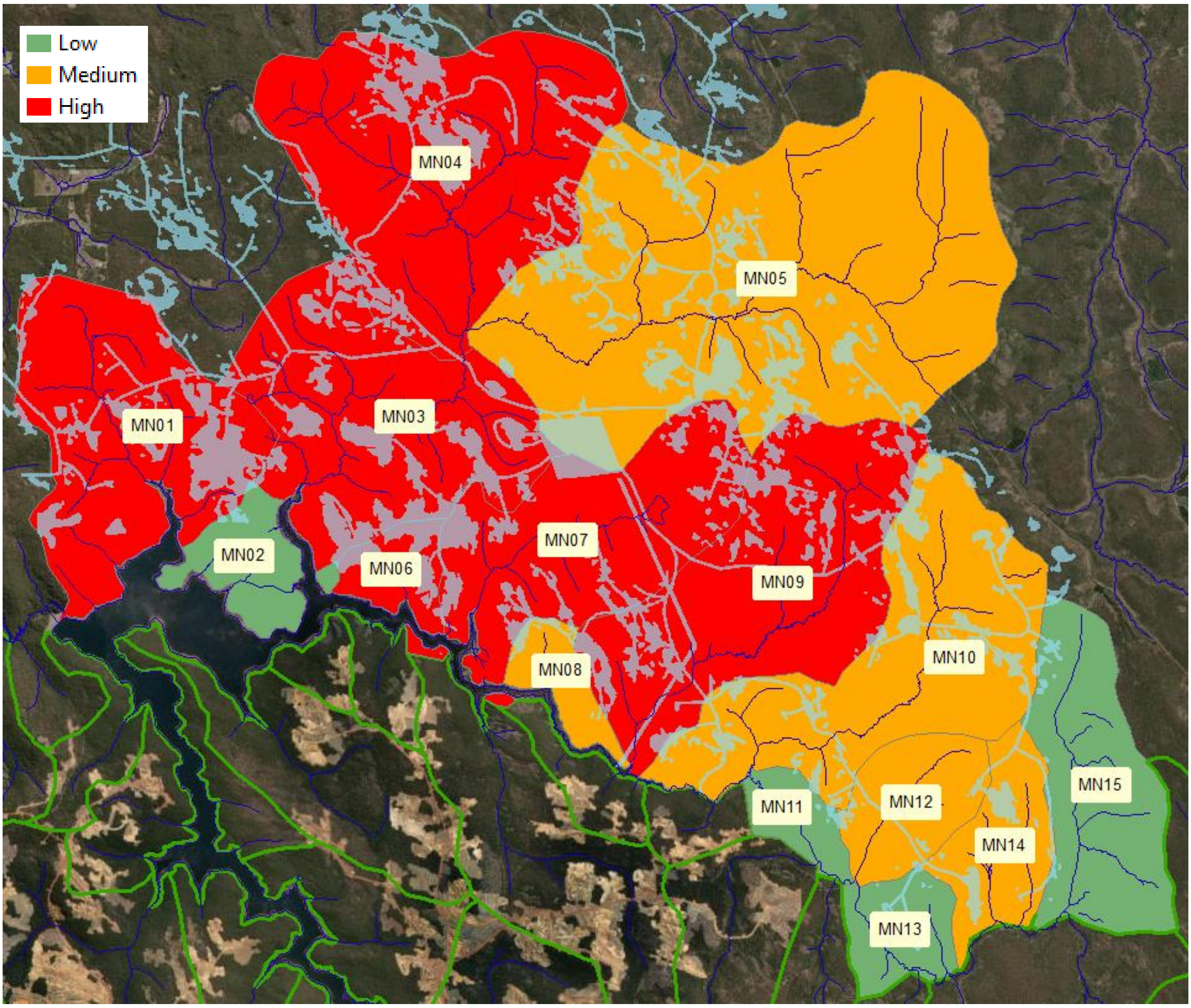


Figure H.8 ***Myara North sub-catchment scale turbidity risk***

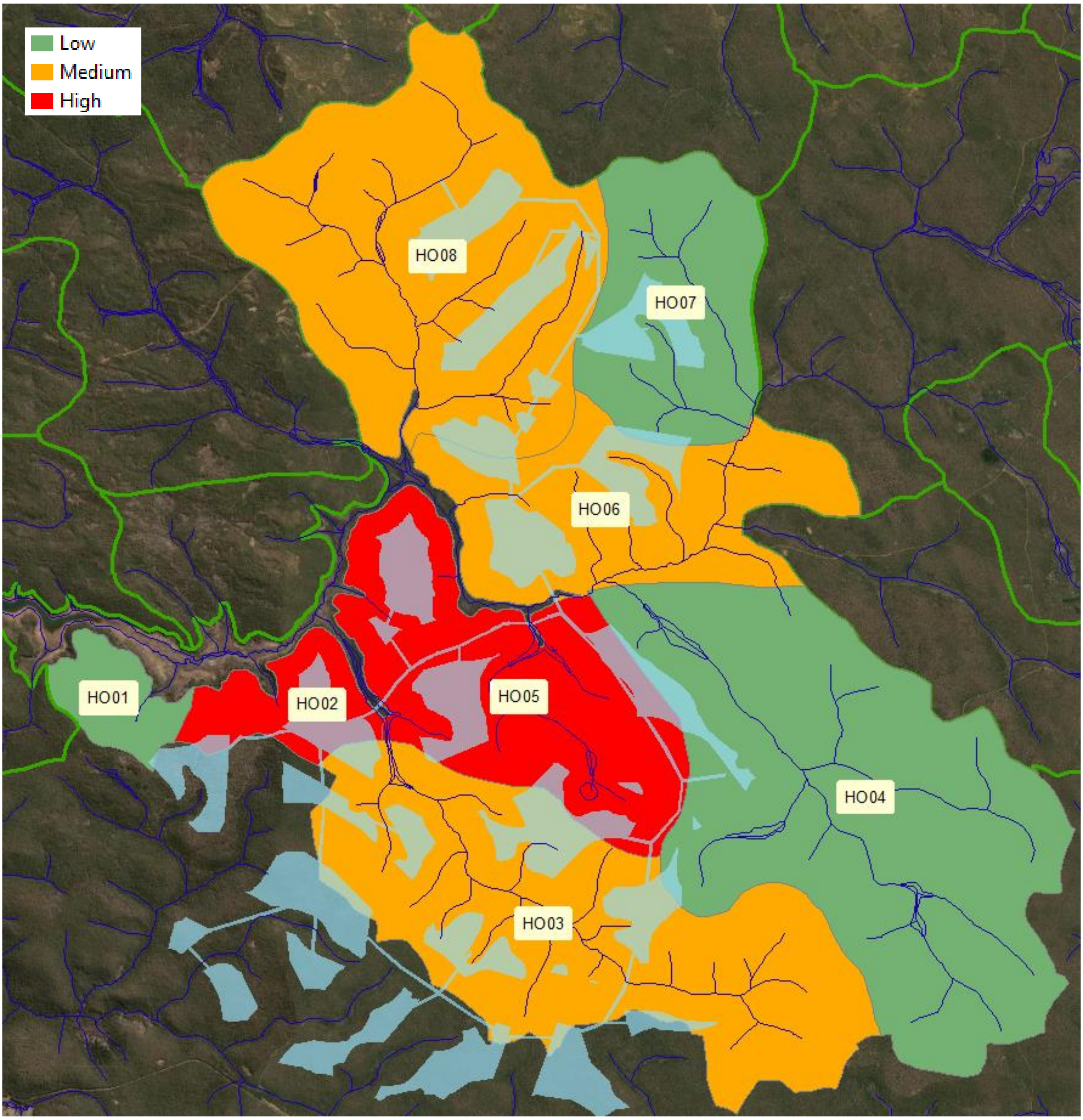


Figure H.9 *Holyoake sub-catchment scale turbidity risk*

Appendix I

Barriers

Table I-1 Likelihood criteria

	ADWG example description	Water Corporation Corporate Description	Water Corporation Corporate Frequency
ALMOST CERTAIN	Is expected to occur in most circumstances	The event is expected or known to occur more than once per year	Will occur more than once a year
LIKELY	Will probably occur in most circumstances	Known to re-occur approximately annually. Known to occur across like industries or within corporation.	Will occur once per year
POSSIBLE	Might occur or should occur at some time	The event should occur at some time. Has occurred several times across like industries.	Will occur once every 5 years
UNLIKELY	Could occur at some time	The event could occur at some time. Known to have occurred once or twice within industry.	Will occur once in 10 years
RARE	May occur only in exceptional circumstances	The event may occur in exceptional circumstances. An example of this has occurred historically, but is not anticipated.	Will occur once in 30 years or less

Note: These tables only list barriers upstream of the reservoir offtake. Whilst Australian Drinking Water Guidelines (NHMRC, 2011) require consideration of the system wholistically, other physical and procedural barriers downstream of the offtake under the responsibility of Water Corporation are not included. Failure likelihoods represent probability of failure of the individual barrier (in isolation). Overall likelihood of the hazardous event occurring is the combination of multiple barrier failures, many of which are sequential as illustrated in the accompanying figures. For events not 100% correlated, the joint probability is less than the individual probabilities. For example, the probability of a *Cryptosporidium* infected worker being on-site, ignoring inductions, not having work breaks, not using ablutions, not reporting illness, having access to sensitive parts of the catchment, not observing signage, defecating in these parts of the catchment, not bagging their waste, not reporting the incident, a rainfall event occurring soon after the waste event, and the buffers, streams and reservoir not sufficiently treating and attenuating the viral load has been conservatively rated as “Unlikely”, compared to higher probabilities for individual barrier failures.

Preventative barriers to pathogen discharge and transport

Table I-2 Barriers and preventative measures to pathogens – workforce in the field

CSM ref	Barrier	Description and function	Example	Potential barrier failures	Barrier fail safes, performance evidence and residual likelihood of failure	How performance may be further improved, or uncertainties addressed
1	Demountable ablution block (existing)	Crib room and ablution block provided within mine region at a location closer to active mine pits to support field workforce working away from mine facilities. Ablution block drains to a tank, which is periodically pumped out by a tanker for off-site disposal at a licensed facility.	**Crib room and ablution block, Myara mine region** 	1. Workforce do not travel to ablutions block. 2. Spillage during tank pump out, or from tank leakage or overflow. 3. Spillage from mine road accident during tanker transport.	**Failsafe:** • Mine road collision avoidance system, mine road berms and drainage capture spills. **Performance evidence:** Not available **Likelihood:** • LIKELY that some workforce members do not use ablutions block, including those in remote mine pits or exploration areas. • UNLIKELY that spillage occurs during tank pump out, or from tank leakage or overflow. • RARE that mine road accident occurs involving sewage tanker.	Document frequency and volume of tank pump outs. Additional barriers 6-9 proposed to prevent workforce toileting in the field.
2	Mandated work breaks (existing)	Work breaks provide opportunity for field staff to access ablutions block or mine facilities.	n/a	1. Workforce do not use work breaks to travel to ablutions block or mine facilities.	**Failsafe:** n/a **Performance evidence:** n/a **Likelihood:** LIKELY	Additional barriers 6-9 proposed to prevent workforce toileting in the field.

CSM ref	Barrier	Description and function	Example	Potential barrier failures	Barrier fail safes, performance evidence and residual likelihood of failure	How performance may be further improved, or uncertainties addressed
3	Haul truck refuelling at mine facilities (existing)	Haul truck refuelling provides opportunity for field staff to access ablutions at mine facilities.	n/a	1. Workforce do not use ablutions during refuelling operations.	**Failsafe:** n/a **Performance evidence:** n/a **Likelihood:** **LIKELY**	Additional barriers 6-9 proposed to prevent workforce toileting in the field.
4	Workforce education (existing)	Inductions for all staff and contractors at commencement and regular refreshers, including: • Drinking water catchment sensitivity • Pathogen risks • Mandatory procedures	n/a	1. Workforce do not understand or disregard induction information.	**Failsafe:** • Include in Alcoa's site induction requirements. **Performance evidence:** n/a **Likelihood:** **POSSIBLE**	Additional barriers 6-9 proposed to prevent workforce toileting in the field.
5	Workforce health monitoring / reporting (existing)	Employees and contractors are encouraged, and required, to not attend the workplace if unwell, particularly if experiencing specific gastrointestinal symptoms, or contact with individuals with gastrointestinal symptoms. This requirement is communicated in the inductions and regular refresher training.	n/a	1. Infected workforce member is asymptomatic and does not declare contact. 2. Infected workforce member is symptomatic and does not comply with requirements	**Failsafe:** • Include in Alcoa's Authority to Proceed HSE permitting process. **Performance evidence:** n/a **Likelihood:** **LIKELY** for asymptomatic worker, **UNLIKELY** for symptomatic worker	Additional barriers 6-9 proposed to prevent workforce toileting in the field
6	Waste bagging / removal (proposed)	A procedure where all human waste will be bagged and contained and disposed of off-site appropriately is proposed.	n/a	1. Human error / non-compliance with waste removal procedures.	**Failsafe:** • Include in Alcoa's Authority to Proceed HSE permitting process. **Performance evidence:** n/a **Likelihood:** **POSSIBLE**	n/a
7	Incident reporting / response (proposed)	All accidental human waste discharges to be reported and cleaned up consistent with a hazardous material spill.	n/a	1. Human error / non-compliance with incident response procedures.	**Failsafe:** • Include in Alcoa's Authority to Proceed HSE permitting process. **Performance evidence:** n/a **Likelihood:** **POSSIBLE**	n/a
8	Drinking water protection signs (proposed)	Hazard signs installed at active mine pits, with warning statement on drinking water protection and mandatory off-site waste disposal.		1. Human error / non-compliance with signs.	**Failsafe:** n/a **Performance evidence:** n/a **Likelihood:** **POSSIBLE**	n/a
9	Workforce access restrictions (proposed)	It is proposed that access within designated buffers from streams and reservoirs, is only permitted to those employees and contractors that have completed the appropriate training package,	n/a	1. Human error / non-compliance with access restrictions.	**Failsafe:** • Include in Alcoa's Authority to Proceed HSE permitting process. **Performance evidence:** n/a	n/a

CSM ref	Barrier	Description and function	Example	Potential barrier failures	Barrier fail safes, performance evidence and residual likelihood of failure	How performance may be further improved, or uncertainties addressed
		to understand the drinking water catchment sensitivity, and mandatory procedures to minimise those risk. Refresher training is to occur annually with acknowledgement of employee and contractor obligations.			**Likelihood:** POSSIBLE	
10	Riparian / reservoir buffers – overland flow attenuation (existing)	In the event of failure in barriers 1 to 9, a human stool will be deposited in the field, which may or may not be buried in soil. Pathogens will be attenuated over several months through natural processes. In the event of heavy rainfall and the stool being shallow buried or not buried, the stool may be washed out and pathogens travel downslope via overland flow. Pathogens will attenuate during overland flow due to filtration in Jarrah forest understorey vegetation and litter layer. Overland flow is unlikely to reach streams unless there are heavy rainfall / wet catchment conditions.	**Jarrah forest vegetation with an intact understorey and litter layer** 	1. Staff walk into buffer for privacy and stool is deposited closer to stream / reservoir. 2. Overland flow transitions to shallow channels with preferential flow that short-circuits filtration by vegetation and litter. 3. Jarrah forest understorey has a patchy surface coverage amongst a varying litter layer. 4. Litter layer is consumed by bushfire and thereafter recovers over a period of several years. 5. Presence of granite outcrops downslope, potentially limiting the filtration and increasing runoff.	**Fail safes:** n/a **Performance evidence:** n/a Studies of bushfires confirm increased runoff, turbidity and pathogens from burnt catchments. **Likelihood:** • LIKELY for staff to walk through buffer • POSSIBLE for heavy rainfall to occur within a few months following stool discharge. • POSSIBLE for limited filtration to occur downslope.	n/a
11	Seasonal stream attenuation (existing)	Streams flow seasonally for several months of the year and then are dry. Pathogens will attenuate if discharging to a dry stream and there is no flow for a few to several months. Limited attenuation may occur in flowing streams however travel time is likely to be in the order of minutes to hours until discharge into the reservoir.	**39 Mile Brook seasonally dry stream bed** 	1. Seasonal flow is likely to occur during winter/spring which is when stool washout and overland flow are most likely to occur.	**Fail safes:** n/a **Performance evidence:** Stream gauging confirms seasonal stream flow from June to December for 39 Mile Brook and Big Brook **Likelihood:** • LIKELY for streamflow to occur when stool washout and overland flow occurs.	n/a
12	Reservoir attenuation (existing)	Serpentine Dam is the downstream reservoir for the Myara and Myara North mine facilities. South Dandalup Dam is the downstream reservoir for the Holyoake mine facilities. Dilution and inactivation of pathogens due to natural mixing and retention processes in the reservoir.	**Serpentine Dam reservoir viewed from the dam wall** 	1. Short circuiting by stool discharges close to offtake at dam walls. 2. Thermal stratification during summer. 3. Low reservoir levels following a sequence of low rainfall years.	**Fail safes:** • No mining (and thus field activities) in Serpentine Pipehead Dam PDWSA. **Performance evidence:** n/a Hydrodynamic modelling with conservative assumptions (low reservoir water levels, summer discharge). **Likelihood:** • POSSIBLE for stool washout to result in exceedance of drinking water criteria at Serpentine Dam offtake. • UNLIKELY for stool washout to result in exceedance at South Dandalup Dam offtake.	n/a

CSM ref	Barrier	Description and function	Example	Potential barrier failures	Barrier fail safes, performance evidence and residual likelihood of failure	How performance may be further improved, or uncertainties addressed

Table I-3 ***Barriers and preventative measures to pathogens – workforce at mine facilities***

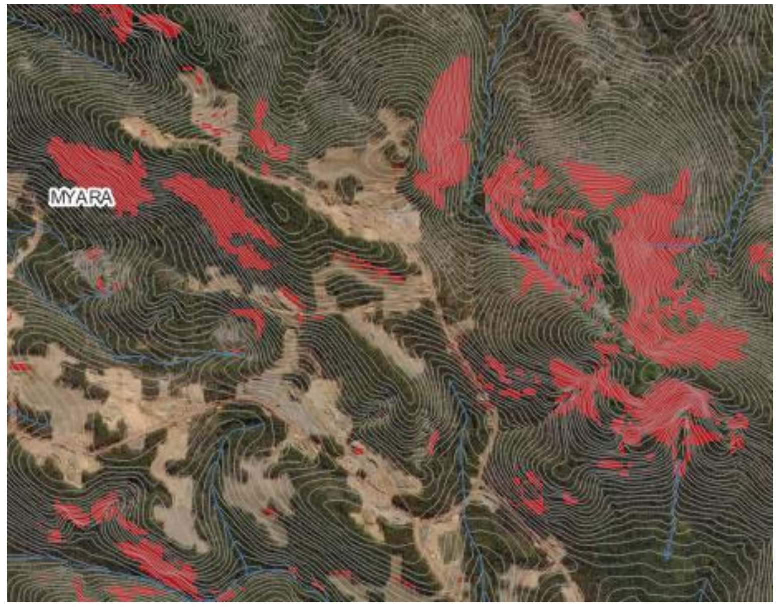
CSM ref	Barrier	Description and function	Example	Potential barrier failures	Barrier fail-safes , performance evidence and residual likelihood of failure	How performance may be further improved, or uncertainties addressed
1	Reservoir protection zone (existing)	Mine facilities are located outside of the RPZ, increasing travel pathways and attenuation for pathogens prior to discharge into the reservoir.	n/a	n/a	n/a	n/a
2	Sewage treatment and disinfection (existing)	Mine facilities sewage treated at a Sewage Treatment Plant (STP) and smaller ablution blocks (e.g. fuel bay facility) to an Aerated Treatment Unit (ATU).. Treatment comprises: • Primary and secondary treatment to reduce suspended solids and biological oxygen demand • Disinfection with chlorine.	**Biomax C100 unit at Myara mine facilities** 	1. Failure of mechanical systems such as aeration blower or irrigation pump causing overflow of semi or untreated sewage. 2. Chlorine disinfection (30 minutes contact) will reduce the load of bacteria, viruses and some protozoa, but will not reduce the load of some protozoa (e.g. *Cryptosporidium*).	**Fail safes:** • STP has an alarm and two days emergency storage in the event of a failure in the mechanical systems. • Gravity based chlorination reduces mechanical components. • Routine inspections and maintenance **Performance evidence:** Biomax report[2] minimum effluent quality as: • 30 mg/L suspended solids • 20 mg/L 5 day BOD 10 faecal coliform CFU per 100 mL **Likelihood:** • UNLIKELY for sewage overflow to occur from the STP emergency storage	n/a
3	Treated sewage effluent irrigation (existing)	Drip irrigation of treated effluent over Jarrah forest vegetation within the mine facilities complex. Water is lost to evapotranspiration, with some leaching of effluent to prevent build up of salts. Pathogens are captured in the shallow soil layer and die-off through natural processes.	**Effluent irrigation area at Myara mine facilities** 	1. Washout of irrigation area with upslope catchment runoff during a major storm event. 2. Shallow soils over rock causing ponding and runoff of effluent. 3. Irrigation over winter/spring results in ponding and runoff of effluent and/or leaching of effluent through the subsurface.	**Fail safes:** • Myara facilities irrigation area drains into surface drainage system that discharges into stormwater drainage ponds **Performance evidence:** n/a **Likelihood:** • POSSIBLE for irrigation area runoff	• Siting of irrigation area to minimise upslope catchment area. • Perimeter bund installed to divert upslope catchment runoff and retain irrigation area runoff from 1% AEP storm event. • Siting of irrigation area over a minimum soil depth of 1 m.
4	Overland flow attenuation (existing)	In the event of failure in barriers 2 or 3, sewage or treated effluent will travel via overland flow downslope of the STP or	**Jarrah forest vegetation with an intact understorey and litter layer**	1. Overland flow transitions to shallow channels with preferential flow that short-circuits filtration by vegetation	**Fail safes:** n/a **Performance evidence:** n/a Studies of bushfires confirm	• Effluent irrigation area will be located at least 100 m from nearest stream, and located to maximise the travel distance to drinking water

[2] https://biomax.com.au/products/

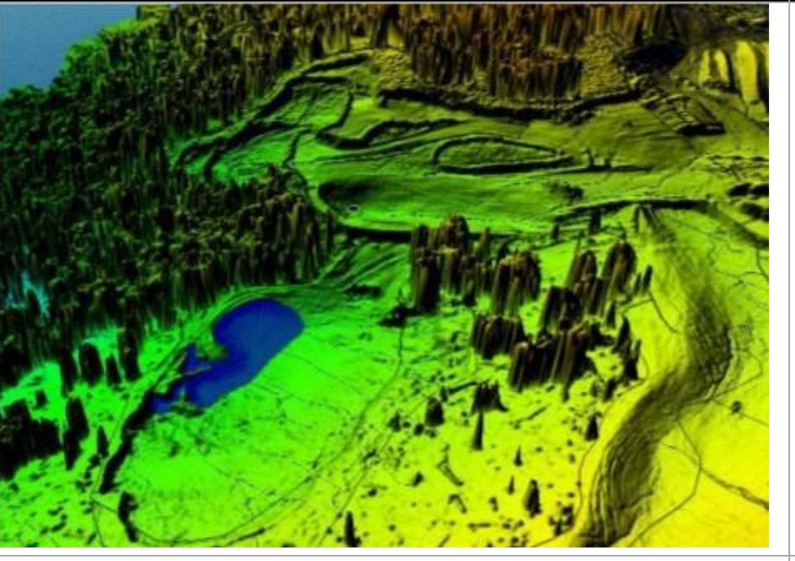
CSM ref	Barrier	Description and function	Example	Potential barrier failures	Barrier fail-safes , performance evidence and residual likelihood of failure	How performance may be further improved, or uncertainties addressed
		irrigation area. Pathogens will attenuate during overland flow due to filtration in Jarrah forest understorey vegetation and litter layer. Overland flow is unlikely to reach streams unless there is heavy rainfall / wet catchment conditions.		and litter. 2. Jarrah forest understorey has a patchy surface coverage amongst a varying litter layer. 3. Litter layer is consumed by bushfire and thereafter recovers over a period of several years. 4. Presence of granite outcrops downslope, potentially limiting the filtration and increasing runoff.	increased runoff, turbidity and pathogens from burnt catchments. **Likelihood:** • LIKELY for overland flow to occur if irrigation area overflow is occurring during a major storm event. • POSSIBLE for limited filtration to occur	reservoirs, as far as is practicable. • Effluent irrigation area will not be located upslope of granite outcrops.
5	Subsurface flow attenuation (existing)	In the event of performance of barriers 2 and 3, pathogens may be transported with infiltration through the unsaturated zone and then transported downslope with groundwater. Pathogens will be filtered in the subsurface matrix and attenuate through natural processes.	n/a	1. Downslope seepage faces where groundwater expresses during winter/spring, causing overland flow. 2. Presence of granite outcrops downslope, causing overland flow.	**Fail safes:** n/a **Performance evidence:** n/a **Likelihood:** • UNLIKELY for limited attenuation to occur	• Effluent irrigation area will not be located upslope of granite outcrops.
6	Seasonal stream attenuation (existing)	Streams flow seasonally for several months of the year and then are dry. Pathogens will attenuate if discharging to a dry stream and there is no flow for a few to several months. Limited attenuation may occur in flowing streams however travel time is likely to be in the order of minutes to hours until discharge into the reservoir.	**39 Mile Brook seasonally dry stream bed** 	1. Seasonal flow is likely to occur during winter/spring which is when irrigation area overflow and overland flow are most likely to occur.	**Fail safes:** n/a **Performance evidence:** Stream gauging confirms seasonal stream flow from June to December for 39 Mile Brook and Big Brook **Likelihood:** • LIKELY for streamflow to occur when other barriers are failing.	n/a
7	Reservoir attenuation (existing)	Serpentine Dam is the downstream reservoir for the Myara and Myara North mine facilities. South Dandalup Dam is the downstream reservoir for the Holyoake mine facilities. Dilution and inactivation of pathogens due to natural mixing and retention processes in the reservoir.	**Serpentine Dam reservoir viewed from the dam wall** 	1. Thermal stratification during summer. 2. Low reservoir levels following a sequence of low rainfall years.	**Fail safes:** n/a **Performance evidence:** Hydrodynamic modelling with conservative assumptions (low reservoir water levels, summer discharge). **Likelihood:** • UNLIKELY for STP or irrigation overflows transported overland or subsurface into reservoirs to result in exceedance of drinking water criteria.	n/a

Preventative barriers to sediment discharge and transport

Table I-4 Barriers and preventative measures to turbid discharge

CSM ref	Barrier	Description and function	Example	Potential barrier failures	Barrier fail-safes, performance evidence and residual likelihood of failure	How performance may be further improved, or uncertainties addressed
1	Mine slope planning considerations (existing)	Mine planning currently exclude areas with slope exceeding 15.9 degrees due to safety and the ability to meet current completion criteria (physical and surface safety and stability). Slope is a demonstrated key factor in the generation of channelised flow, higher runoff velocities and volumes, and higher soil erosion.	**Aerial image illustrating areas in red where slope exceeds 16 degrees** 	n/a	**Fail safes:** n/a **Performance evidence:** n/a **Likelihood:** • RARE for slopes greater than 15.9 degrees to be mined.	n/a
2	Staged and seasonal approach to development and clearing (existing)	Mine development, mining and rehabilitation occurs in a staged manner within a mine region. The average timeframe between clearing and completion of mine rehabilitation is 3-4 years.	**Aerial image illustrating staged clearing, mining, and rehabilitation** 	• Potential for rehabilitation timeframes to exceed 4 years due to staging and resourcing.	**Fail safes:** n/a **Performance evidence:** Alcoa monitoring demonstrates that the majority of mine pits are rehabilitated within 3-4 years of clearing. **Likelihood:** • LIKELY that there will be turbid discharge for exposed soils over 3-4 years in the absence of other barriers.	n/a
3	Clearing contour windrows (existing)	Cleared wood waste is arranged in windrows on the contour, prior to burning or reuse. Windows intercept runoff to prevent flow concentration and subsequent erosion of mine pit and overflow of drainage	**Clearing windows, Myara mine region**	1. Temporary, seasonal barrier. 2. Non-engineered barrier of variable capacity, which may be overtopped by major storm events. 3. Placement off-contour causes concentrated runoff.	**Fail safes:** n/a **Performance evidence:** Alcoa has recorded failure of clearing contour windows at the Huntly Mine. **Likelihood:** • LIKELY for contour banks to	Risk based mine drainage controls in accordance with Alcoa Drainage Management Manual

CSM ref	Barrier	Description and function	Example	Potential barrier failures	Barrier fail-safes, performance evidence and residual likelihood of failure	How performance may be further improved, or uncertainties addressed
		protection shots. Clearing contour windrows are a temporary, seasonal barrier applied as cleared wood waste is available.		4. Damage by vehicles and machinery post placement.	fail based on the evidence	
4	In-pit drainage (existing)	Engineered and maintained mine drainage bunds and trenches intercept and convey runoff and sediment to in-pit sumps, preventing uncontrolled discharge	**n/a**	1. Defects in design or construction resulting in inadequate capacity to meet catchment runoff. 2. Damage by vehicles and machinery post placement.	**Fail safes:** • Inspection and maintenance. **Performance evidence:** There is documented and anecdotal evidence of structures performing as designed. **Likelihood:** • POSSIBLE for bunds and trenches to fail	Risk based mine drainage controls in accordance with Alcoa Drainage Management Manual
5	In-pit drainage protection shots (existing)	Drainage shots, also called water shots, comprise shallow (~1.8 m) blasted or ripped ground on the downslope perimeter of each mine pit. Drainage shots capture and infiltrated surface runoff within the blasted voids.	**Drainage protection shots, Myara mine region** 	1. Overflow due to incoming channelised / concentrated surface runoff that exceeds infiltrative / sediment capacity. 2. Overflow due to shallow groundwater reducing infiltrative capacity. 3. Overflow due to sediment accumulation over time. 4. Variability in regolith can affect infiltration capacity.	**Fail safes:** n/a **Performance evidence:** Alcoa has recorded drainage protection shot overflows each year at the Huntly Mine. **Likelihood:** • LIKELY for drainage protection slots to fail based on the evidence	Risk based mine drainage controls in accordance with Alcoa Drainage Management Manual
6	In-pit sumps (existing)	Some mine pits have in-pit sumps that collect runoff from pit floors and/or in-pit drainage. In-pit sumps are designed to retain runoff from major storm events.	**3D model illustrating in-pit storage shaded blue**	1. Sump overflow due to inadequate capacity to meet catchment runoff or groundwater conditions, or lack of maintenance.	**Fail safes:** • Sump inspection, pump out, sediment removal and repair. **Performance evidence:** Alcoa has recorded sump overflows each year at the Huntly Mine. **Likelihood:** LIKELY for in-pit storages to fail based on the evidence	Risk based mine drainage controls in accordance with Alcoa Drainage Management Manual

CSM ref	Barrier	Description and function	Example	Potential barrier failures	Barrier fail-safes, performance evidence and residual likelihood of failure	How performance may be further improved, or uncertainties addressed
						
7	Interception sumps (existing)	All paved areas at mine facilities and all haul roads drain to interception sumps. Paved areas upstream of major rivers (e.g. Big Brook) drain to triple interceptor sumps. All sumps are designed to retain rainfall from major storm events.	**Haul road sumps at Myara mine region**  	1. Sump overflow due to inadequate capacity to meet catchment runoff or groundwater conditions, or lack of maintenance.	**Fail safes:** • Sump inspection, pump out, sediment removal and repair. **Performance evidence:** Alcoa has recorded sump overflows each year at the Huntly Mine. **Likelihood:** • **LIKELY** for sump overflows.	Risk based mine drainage controls in accordance with Alcoa Drainage Management Manual
8	Rehabilitation revegetation prescription (existing)	Revegetation establishes a native understorey and overstorey with more than 80 per cent of the floristic diversity of un-mined forest. Substantial establishment of understorey coverage within five years.	**Five year old rehabilitation, Huntly Mine**	1. Drought or bushfire resulting in loss of saplings prior to re-establishment of a seed bank and lignotubers.	**Fail safes:** • Local reuse of topsoil that maintains floristic diversity. • Contemporary prescription has reduced fertiliser that reduces dominance of leguminous shrubs and increases floristic diversity.	n/a

CSM ref	Barrier	Description and function	Example	Potential barrier failures	Barrier fail-safes, performance evidence and residual likelihood of failure	How performance may be further improved, or uncertainties addressed
					• Rehabilitation monitoring and completion criteria. • Remedial works following drought or bushfire. **Performance evidence:** Monitoring of rehabilitation has demonstrated that completion criteria are achieved in the majority of mine pits. **Likelihood:** • UNLIKELY for revegetation to fail completion criteria within a given mine pit.	
9	Rehabilitation substrate prescription (existing)	Rehabilitation substrate includes deep ripping of regolith, application of minimum 200 mm overburden/topsoil and ripping on the contour. Deep ripping promotes infiltration of runoff into the regolith. Application of minimum overburden provides a gravel-sand layer that protects finer grained regolith materials from erosion. Contour ripping creates a furrowed surface that promotes retention and infiltration of runoff.	**Rehabilitation substrate prior to revegetation, Myara mine region** 	1. Insufficient overburden placement can expose finer grained materials to erosion. 2. Ripping off contour can result in flow concentration and erosion.	**Fail safes:** • Exploration drilling defines overburden depths. • Local reuse of overburden within mine pits. • Revegetation completion within 12 months. **Performance evidence:** Ripping has been demonstrated to create a permeable substrate. Alcoa has recorded rehabilitation pit overflows each year at the Huntly Mine. **Likelihood:** • LIKELY for some rehabilitated pits to develop soil erosion.	n/a
10	Rehabilitation landscape prescription (existing)	Rehabilitation prescription limits final landform to slopes less than 16 degrees. Downslope toe of rehabilitated pits can have a reverse batter that creates a 'sunken' landform that retains surface runoff and prevents discharge.		1. Final landform does not meet prescription requirements. 2. Downslope toe grades to surrounding land or otherwise provides limited capacity to retain runoff.	**Fail safes: n/a** **Performance evidence:** LiDAR analysis of rehabilitated pits indicates that the majority may retain limited depths of runoff. **Likelihood:** • POSSIBLE for some rehabilitated pits to overflow	Rehabilitated mine pits designed and executed to prevent overflow during a 1 per cent 24hr AEP rainfall event.
11	Overland flow attenuation (existing)	In the event of failure in barriers 1 to 9, overflows from mine pits or haul road sumps will travel via overland flow downslope. Sediment will attenuate during overland flow due to filtration in Jarrah forest understorey vegetation and litter layer.	**Jarrah forest vegetation with an intact understorey and litter layer**	1. Mine pit or sump overflow discharge generates channelised flow through the slope that short circuits filtration. 2. Overland flow transitions to shallow channels with preferential flow that short-circuits filtration by vegetation and litter. 3. Jarrah forest understorey has a patchy surface coverage amongst a varying litter layer. 4. Litter layer is consumed by bushfire and thereafter recovers	**Fail safes:** • Operational Control Areas maintain minimum overland flow distances to streams or reservoirs. **Performance evidence:** n/a Studies of bushfires confirm increased runoff and turbidity from burnt catchments. **Likelihood:** • LIKELY for overland flow to occur when mine pit or haul	n/a

CSM ref	Barrier	Description and function	Example	Potential barrier failures	Barrier fail-safes, performance evidence and residual likelihood of failure	How performance may be further improved, or uncertainties addressed
				over a period of several years.	road sump overflow occurs. • POSSIBLE for limited filtration to occur	
12	Stream attenuation (existing)	In the event of failure of barrier 10, sediment laden runoff will discharge into streams. Sediment in stream flow may be subject to deposition, filtration and dilution prior to discharge into the reservoir	**Serpentine River flowing in June 2020** 	1. Fine sediment fractions (e.g. clays) remain suspended in stream flows and are transported with higher stream velocities during major storm events in the catchment.	**Fail safes:** • Operational Control Areas maintain minimum stream distances to reservoirs. **Performance evidence:** n/a **Likelihood:** • LIKELY for fine sediments to remain suspended in stream flow during major storm events.	n/a
13	Reservoir attenuation (existing)	Serpentine Dam is the downstream reservoir for the Myara and Myara North mine facilities. South Dandalup Dam is the downstream reservoir for the Holyoake mine facilities. Dilution and settlement of sediment in the reservoir.	**Serpentine Dam reservoir viewed from the dam wall** 	1. Thermal stratification during summer. 2. Low reservoir levels following a sequence of low rainfall years. 3. Sediment is predominantly fine grained (i.e. clayey), reducing the effectiveness of reservoir settlement.	**Fail safes: n/a** **Performance evidence:** Water quality monitoring in Serpentine Dam and South Dandalup Dam from 2000-2020 demonstrates that mining and rehabilitation in the catchment does not causes any increasing trend in turbidity at the offtake. Hydrodynamic modelling with conservative assumptions (low reservoir water levels, summer discharge). **Likelihood:** • RARE for a failure of more than 50 per cent of all mine pits and sumps that results in turbidity at offtake to exceed drinking water criteria.	n/a

Preventative barriers to hydrocarbon discharge and transport

Table I-5 ***Preventative barriers to hydrocarbon discharge and transport***

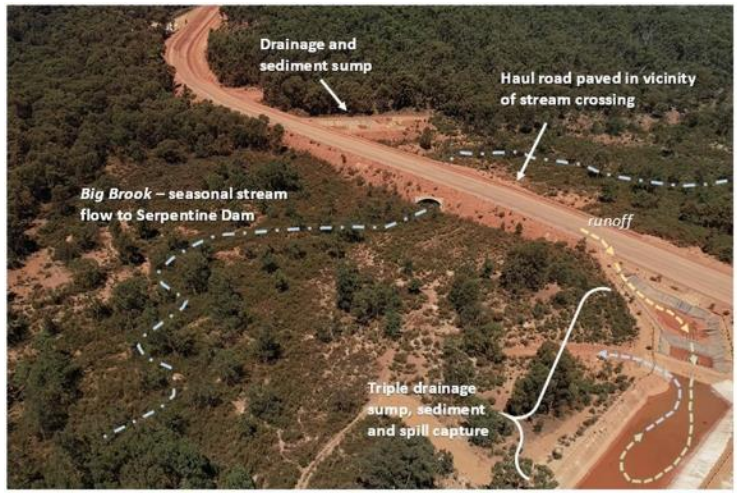
CSM ref	Barrier	Description and function	Example	Potential barrier failures	Barrier fail-safes, performance evidence and residual likelihood of failure	How performance may be further improved, or uncertainties addressed
1	Reservoir protection zone (existing)	Mine facilities are located outside of the RPZ, increasing travel and attenuation pathways for hydrocarbons prior to discharge into the reservoir.	n/a	n/a	n/a	n/a
2	Vehicle fuel bays (existing)	Mine facilities heavy and light vehicle fuel bays service haul trucks, other wheeled heavy vehicles and light vehicles. Fuel bays include: • Roofs to prevent ingress of rainfall. • Sealed floors to contain spills and leaks.	**Heavy vehicle fuel bay at Myara mine facilities – front**  **Heavy vehicle fuel bay at Myara mine facilities – rear**  **Light vehicle fuel bay at Myara mine facilities**	1. Spills or leaks during refuelling operations due to vehicle collision, ripped hose or dropped nozzle.	**Fail safes:** • Bollards and guide chains to prevent vehicle collisions / damage. • Automatic boom gate over heavy vehicle while refuelling to prevent vehicle departure causing ripped hose or free nozzle. • Automatic cut off valves to prevent spills in event of ripped hose or free nozzle. • Spill response kits. • Floors drain to the oily water treatment system. **Performance evidence:** Site monitoring of existing Huntly Mine drainage systems demonstrate that hydrocarbons are collected by the oily water system. **Likelihood:** • POSSIBLE for hydrocarbon spill during refuelling to occur outside of sealed floors. • POSSIBLE for hydrocarbon leak in fuel reticulation from fuel farm or drainage reticulation to oily water treatment system. • RARE for leaks through sealed floor into soils.	Detailed site investigation and (if required) remediation at decommissioning of mine facilities.

CSM ref	Barrier	Description and function	Example	Potential barrier failures	Barrier fail-safes, performance evidence and residual likelihood of failure	How performance may be further improved, or uncertainties addressed
						
3	Vehicle washbays (existing)	Mine facilities heavy and light vehicle washbays service haul trucks, other wheeled heavy vehicles and light vehicles. Washbays include sealed floors to contain oily washwater and sediment,	**Heavy vehicle washbay at McCoy mine facilities** 	1. Washwater spray occurs outside of sealed washbay floors. 2. Overflow of washbay floor during heavy rainfall.	**Fail safes:** • Floors drain to the oily water treatment system. • Vehicle washing undertaken during periods when there is no heavy rainfall. **Performance evidence:** Site monitoring of existing Huntly Mine drainage systems demonstrate that hydrocarbons are collected by the oily water system. **Likelihood:** • POSSIBLE for washwater to overflow into adjacent unsealed ground. • RARE for leaks through sealed floor into soils.	Detailed site investigation and (if required) remediation at decommissioning of mine facilities.

CSM ref	Barrier	Description and function	Example	Potential barrier failures	Barrier fail-safes, performance evidence and residual likelihood of failure	How performance may be further improved, or uncertainties addressed
4	Fuel farm (existing)	Fuel farm comprising above ground diesel and oil tanks with fuel tanker delivery bay. Tanker delivery bay is sealed to capture spills during delivery operations.	**Diesel fuel and oil storage tanks at Myara mine facilities**  **Fuel tanker delivery bay at Myara mine facilities** 	1. Leaks due to vehicle collision damage or corrosion. 2. Leaks/spills during tank refuelling	**Fail safes:** • Double walled tanks. • Bollards to prevent vehicle collisions / damage. • Regular inspection of tanks. • Delivery bay floors drain to the oily water treatment system. • Spill response kits. **Performance evidence:** Site monitoring of existing Huntly Mine drainage systems demonstrate that hydrocarbons are collected by the oily water system. **Likelihood:** • POSSIBLE for hydrocarbon spill to occur outside of sealed floors. • POSSIBLE for hydrocarbon leak in fuel reticulation from delivery bay or drainage reticulation to oily water treatment system. • RARE for undetected leaks to occur into soils.	Detailed site investigation and (if required) remediation at decommissioning of mine facilities.
5	Vehicle maintenance workshops (existing)	McCoy mine facilities maintenance workshops provide planned maintenance for haul trucks, other wheeled heavy vehicles and light vehicles. Workshops include: • Roofs to prevent ingress of rainfall. • Sealed floors to contain spills and leaks.	**Heavy vehicle maintenance workshops, McCoy mine facilities**  **Waste oil storage tanks, McCoy mine facilities**	1. Leaks during in-field planned maintenance for excavators, heavy equipment and unplanned breakdowns. 2. Leaks due to vehicle collision damage or corrosion. 3. Accumulation of hydrocarbons in sediments within drainage infrastructure.	**Fail safes:** • Hazardous materials and wastes will be stored at designated construction compounds or other storage facilities in accordance with Road Transport Reform (Dangerous Goods) Regulations 1997 as application to the specific materials. Storage will take into consideration the requirements of WQPN 56[3], Inland Waters commitment 8-23, and Terrestrial Environmental Quality commitment 7-17. All hazardous chemicals stored in lockers and bunded pallets. • Bulk oils and waste oils stored in double walled above ground tanks. • Regular inspection of storage	Detailed site investigation and (if required) remediation at decommissioning of mine facilities.

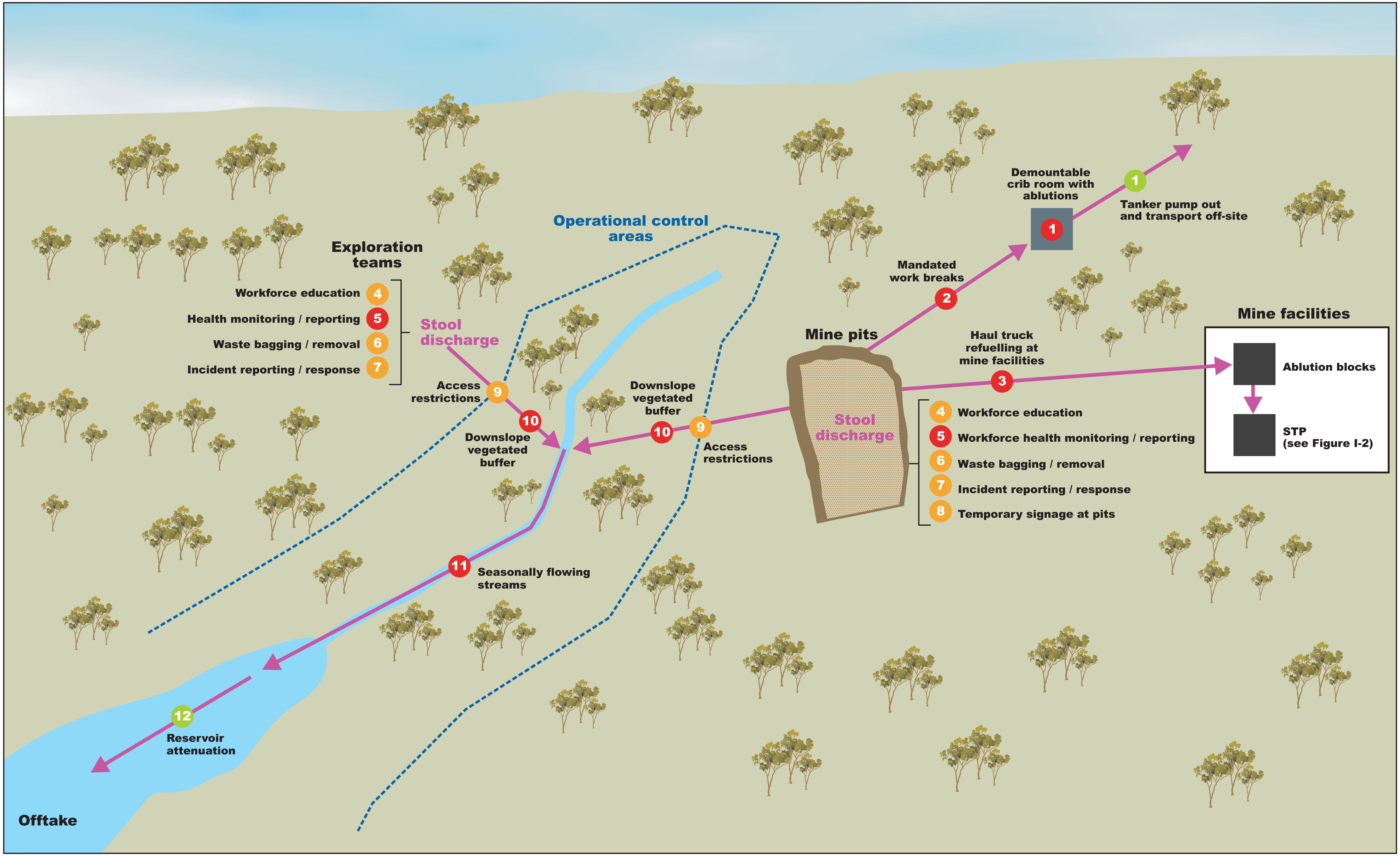
[3] Water Quality Protection Note 56, Department of Water and Environment Regulation (2018)

CSM ref	Barrier	Description and function	Example	Potential barrier failures	Barrier fail-safes, performance evidence and residual likelihood of failure	How performance may be further improved, or uncertainties addressed
					areas. • Spill response kits (item 7) **Performance evidence:** Site monitoring of existing Huntly Mine drainage systems demonstrate that are collected by the oily water system. **Likelihood:** • POSSIBLE for hydrocarbon spill to occur during maintenance outside of workshops. • POSSIBLE for undetected leaks to occur into soils. • RARE for leaks through sealed floor into soils.	
6	Fuel transport limits over river crossings (existing)	15,000 litre diesel fuel capacity limit over major river crossings.	**Signage installed at Big Brook Crossing, Myara mine region** 	1. Signage deterioration over time and subsequent crossing of higher volume fuel capacity 2. Disregard of limits by fuel truck drivers	**Fail safes:** • Fuel delivery tankers to mine facilities use mine access roads that do not cross major rivers. • Mobile fuel tanker that supplies excavators and other heavy equipment has a capacity less than 15,000 litres. • Haul trucks, other heavy and light vehicles have fuel tanks well below 15,000 litres. • Mine vehicle collision warning system. • Mine vehicle driver training and induction. **Performance evidence:** n/a **Likelihood:** • RARE for fuel capacity limits to be exceeded	n/a
7	Spill response (existing)	All hydrocarbon spills identified at mine facilities (outside of oily water system) or in the field responded to. All captured spill material is disposed off site at licensed facilities. All soil at spill site identified as contaminated is excavated and disposed off site at licensed facilities. All hydrocarbon spills are reported internally.	**Fire truck and spill response trailer, McCoy mine facilities** 	1. Spills during heavy rainfall discharge with runoff off site prior to spill response. 2. Spills occur during fire or other hazardous circumstance that prevents or slows spill responses, discharging off site. 3. Undetected leaks/spills.	**Fail safes:** • Compacted haul road surface and ongoing haul road maintenance, preventing spills on haul roads from infiltrating to subsurface. • Haul road berms direct fuel spills into haul road sumps. **Performance evidence:** n/a **Likelihood:** • POSSIBLE for large spills to occur during heavy rainfall or hazardous events. • UNLIKELY for large spills to be undetected. • LIKELY for small spills or leaks to be undetected.	n/a

CSM ref	Barrier	Description and function	Example	Potential barrier failures	Barrier fail-safes, performance evidence and residual likelihood of failure	How performance may be further improved, or uncertainties addressed
8	Stormwater drainage system (existing)	All paved areas at mine facilities and all haul roads drain to interception sumps. Paved areas upstream of major rivers (e.g. Big Brook) drain to triple interceptor sumps. All sumps are designed to retain rainfall from major storm events.	**Triple interceptor sumps at Big Brook, Myara mine region**  **Haul road sumps at Myara mine region** 	1. Sump overflow due to inadequate capacity to meet catchment runoff or groundwater conditions. 2. Leaks through base of unlined sumps. 3. Leaks through lining of lined sumps due to construction defects/lack of maintenance. 4. Accumulation of contaminated sediments in sumps acting as secondary source of contamination	**Fail safes:** • Lining of sumps upstream of major river crossings. • Sump pump out, sediment removal and repair. **Performance evidence:** Alcoa has recorded sump overflows each year at the Huntly Mine. **Likelihood:** • LIKELY for sump overflows. • POSSIBLE for undetected leaks to occur into soils.	Risk based mine drainage controls in accordance with Alcoa Drainage Management Manual
9	Oily water drainage system (existing)	Fuelbays, washbays and other potentially contaminated catchment drain to a network of open drains and underground drains and lined sumps. All sumps are designed to retain rainfall from major storm events.		1. Sump overflow due to inadequate capacity to meet rainfall or groundwater conditions. 2. Leaks through lining of lined sumps due to construction defects/lack of maintenance. 3. Accumulation of contaminated sediments in sumps acting as secondary source of contamination.	**Fail safes:** • Sump pump out, sediment removal and repair. **Performance evidence:** Site monitoring of existing Huntly Mine drainage systems demonstrate that are collected by the oily water system. **Likelihood:** • POSSIBLE for sump overflows. • POSSIBLE for undetected leaks to occur into soils.	n/a
10	Oily water treatment system (existing)	Oily water collected from fuelbays, washbays and other potentially contaminated catchments is treated at a Dissolved Air Flotation (DAF) plant. Treated water is stored in lined ponds and tested for oils, surfactants and metals prior to	**DAF Oily Water Treatment Plant at McCoy mine facilities**	1. Treatment system failure resulting in elevated oil content in treated water. 2. Overflow of ponds during heavy rainfall event. 3. Leak in pond liner due to construction defects/lack of maintenance	**Fail safes:** • Testing of treated water prior to reuse. • Pond freeboard to accommodate major storm rainfall and wave action. **Performance evidence:** Treated water test records.	n/a

CSM ref	Barrier	Description and function	Example	Potential barrier failures	Barrier fail-safes, performance evidence and residual likelihood of failure	How performance may be further improved, or uncertainties addressed
		reuse for dust suppression at the Huntly Mine. The DAF plant and treated water discharge are managed and reported under Environmental Licence L6210/1991/10 under Part V of the EP Act.	 **DAF Oily Water Treatment Plant ponds at McCoy mine facilities** 		**Likelihood:** • UNLIKELY for treatment system failure combined with pond overflow or leakage.	
11	Overland flow attenuation (existing)	In the event of failure in barriers 2 to 10, hydrocarbons will travel via overland flow downslope of the spill, leak or overflow discharge area. Hydrocarbons will attenuate during overland flow due to filtration in Jarrah forest understorey vegetation and litter layer. Overland flow is unlikely to reach streams unless there is heavy rainfall / wet catchment conditions.	**Jarrah forest vegetation with an intact understorey and litter layer** 	1. Overland flow transitions to shallow channels with preferential flow that short-circuits filtration by vegetation and litter. 2. Jarrah forest understorey has a patchy surface coverage amongst a varying litter layer. 3. Litter layer is consumed by bushfire and thereafter recovers over a period of several years.	**Fail safes:** n/a **Performance evidence:** n/a **Likelihood:** • LIKELY for overland flow to occur if spill or overflow is occurring during a major storm event. • POSSIBLE for limited filtration to occur	Washbays, fuelbays, fuel and oil storage tanks, workshops and oily water treatment system will be located at least 100 m from nearest stream, and located to maximise the travel distance to drinking water reservoirs, as far as is practicable.
12	Subsurface flow attenuation (existing)	In the event of failure of barriers 2 to 10, hydrocarbons may be transported with infiltration through the unsaturated zone and then transported downslope with groundwater. Diesel and oil based	n/a	1. Downslope seepage faces where groundwater expresses during winter/spring, causing overland flow. 2. Presence of granite outcrops downslope, causing overland flow.	**Fail safes:** n/a **Performance evidence:** n/a **Likelihood:** • UNLIKELY for limited attenuation to occur	Washbays, fuelbays, fuel and oil storage tanks, workshops and oily water treatment system will be located at least 100 m from nearest stream, and located to maximise the travel distance to drinking water reservoirs, as far as is practicable.

CSM ref	Barrier	Description and function	Example	Potential barrier failures	Barrier fail-safes, performance evidence and residual likelihood of failure	How performance may be further improved, or uncertainties addressed
		hydrocarbons are expected to substantially adsorb in soils with subsurface flow is expected to be attenuated.				
13	Reservoir attenuation (existing)	Serpentine Dam is the downstream reservoir for the Myara and Myara North mine facilities. South Dandalup Dam is the downstream reservoir for the Holyoake mine facilities. Dilution of hydrocarbons and settling of contaminated sediment due to natural mixing and retention processes in the reservoir.	**Serpentine Dam reservoir viewed from the dam wall** 	1. Thermal stratification during summer. 2. Low reservoir levels following a sequence of low rainfall years.	**Fail safes:** n/a **Performance evidence:** Hydrodynamic modelling with conservative assumptions (low reservoir water levels, summer discharge). **Likelihood:** • **RARE** for hydrocarbon overflows transported overland or subsurface into reservoirs to result in exceedance of drinking water criteria.	n/a



LEGEND

Contaminant pathway

BARRIER RESIDUAL LIKELIHOOD OF FAILURE

- Likely
- Possible
- Unlikely
- Rare

Conceptual diagram only - not to scale

Alcoa of Australia Pty Ltd
Huntly Mine Expansion

Job Number 12520591
Revision 0
Date 7 Jan 2022

Preventative barriers to pathogen discharge and transport - workforce in the field - conceptual model

Figure I-1

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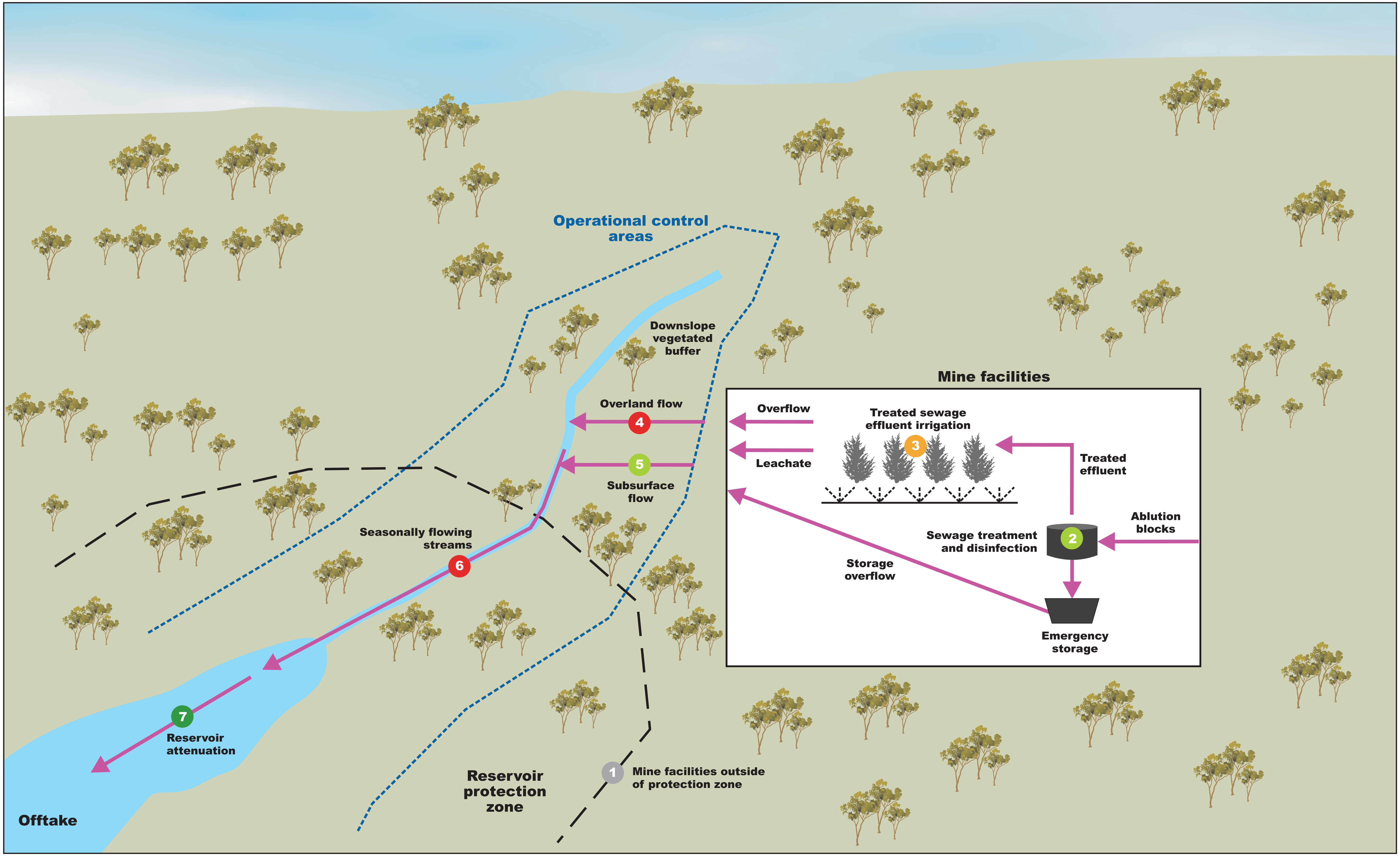

LEGEND

Contaminant pathway

BARRIER RESIDUAL LIKELIHOOD OF FAILURE

- Likely
- Possible
- Unlikely
- Rare

Conceptual diagram only - not to scale

GHD

Alcoa of Australia Pty Ltd
Drinking Water Risk Assessment
Serpentine, Serpentine Pipehead, South Dandalup and Wungong Brook Catchments

Job Number 12520591
Revision 0
Date 7 Jan 2022

Preventative barriers to pathogen discharge and transport - workforce at mine facilities - conceptual model

Figure I-2

GHD\Launceston\Projects\Admin\Graphics\12\520591\12520591_LST_04.cdr

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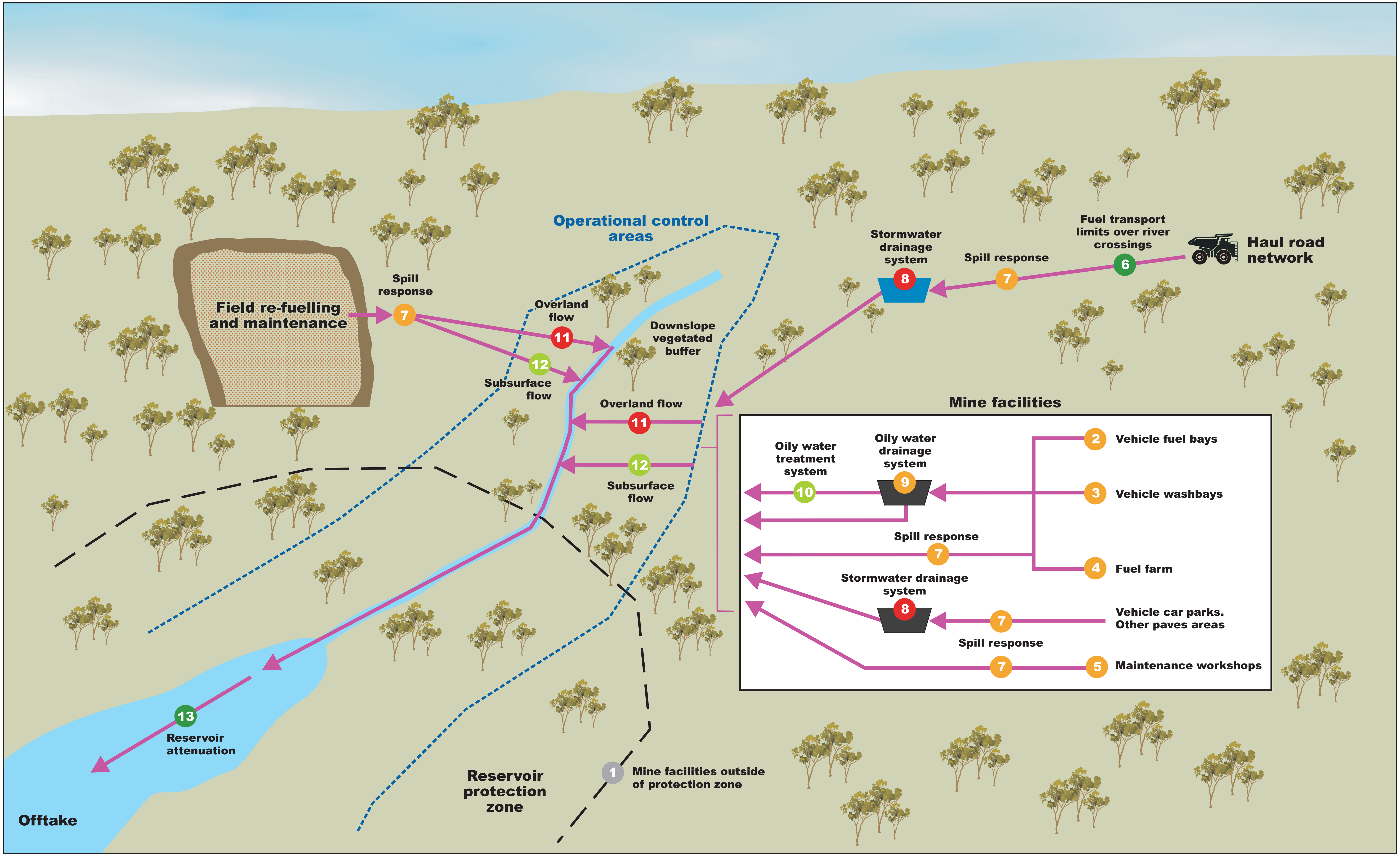

LEGEND

Contaminant pathway

BARRIER RESIDUAL LIKELIHOOD OF FAILURE

- Likely
- Possible
- Unlikely
- Rare

Conceptual diagram only - not to scale

GHD

Alcoa of Australia Pty Ltd
Drinking Water Risk Assessment
Serpentine, Serpentine Pipehead, South Dandalup and Wungong Brook Catchments

Job Number 12520591
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Date 7 Jan 2022

Preventative barriers to hydrocarbon discharge and transport - conceptual model

Figure I-4

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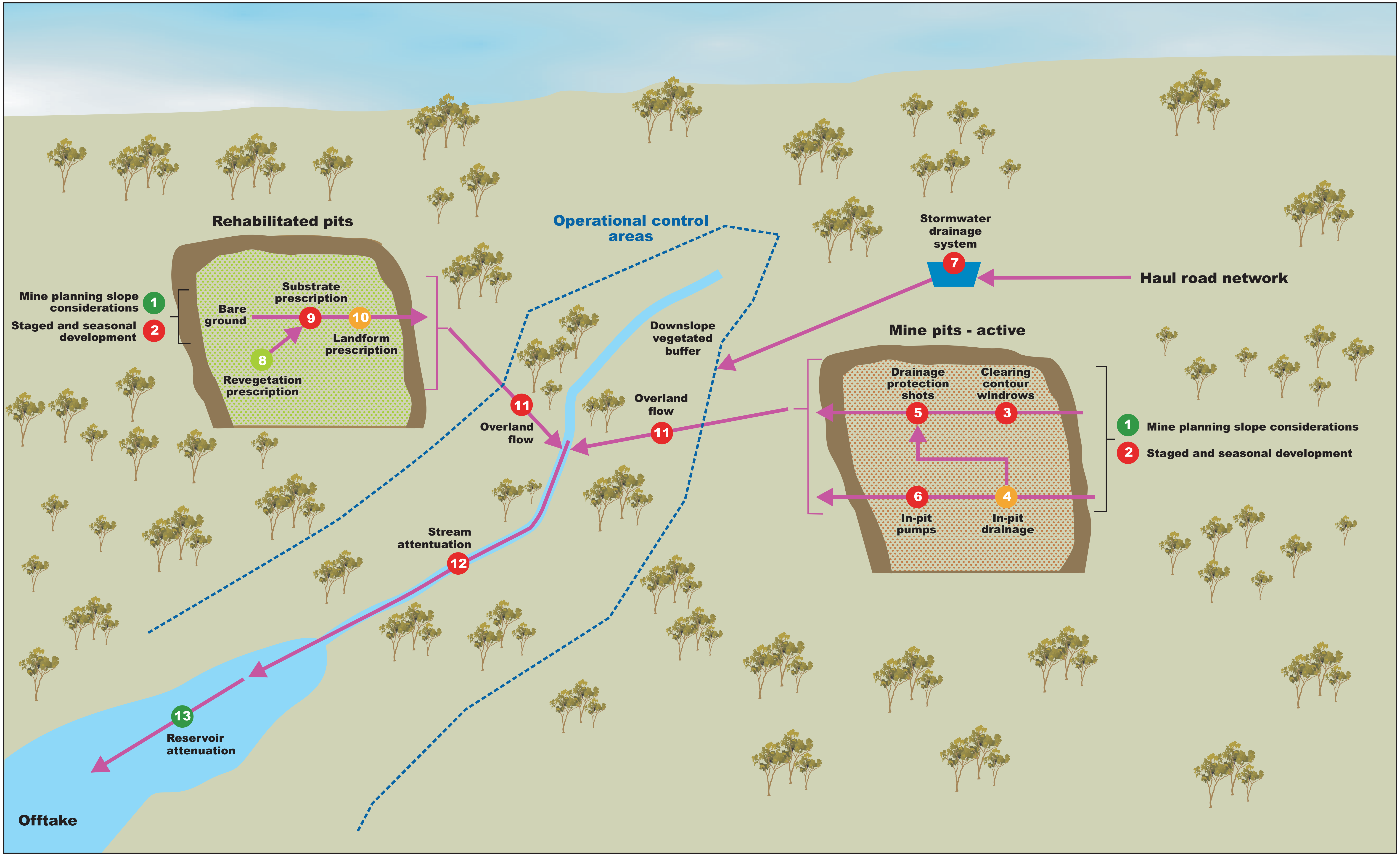

LEGEND

Contaminant pathway

BARRIER RESIDUAL LIKELIHOOD OF FAILURE

- Likely
- Possible
- Unlikely
- Rare

Conceptual diagram only - not to scale

Alcoa of Australia Pty Ltd
Drinking Water Risk Assessment
Serpentine, Serpentine Pipehead, South Dandalup and Wungong Brook Catchments

Job Number 12520591
Revision 0
Date 7 Jan 2022

Preventative barriers to sediment discharge and transport - conceptual model

Figure I-3

GHD\Launceston\Projects\Admin\Graphics\12\520591\12520591_LST_06.cdr

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Appendix J

RUSLE tool

Turbidity risk using RUSLE approach

A tool has been developed for Alcoa to estimate the raw (unmitigated) turbidity risk for a given catchment. The tool is based on the widely used Revised Universal Soil Loss Equation (RUSLE) to estimate annual sediment loads as a representation of turbid runoff.

Sensitivity analysis

A sensitivity analysis of the factors has been undertaken to understand the relative contribution of the variable to annual soil loss estimate. For each variable, the 10^{th}, 50^{th} (median) and 90^{th} percentile of the variable has been calculated for the Huntly mine region. Table J.1 lists the impact of adopting the 90^{th} percentile variable against the median value of the other variables. More information on the derivation of the variables is described in extracts from the tool in subsequent pages. Parameter P was not varied and represents the median combination of all parameters as a baseline.

Table J.1 Soil loss parameter sensitivity

Sensitivity factor	Median value	90^{th} percentile value	Estimated annual average soil loss at 90^{th} percentile, A (t/ha/yr)	Annual soil loss relative to median
Rainfall-runoff erosivity, *R*	3106	3382	40.2	8.9%
Soil erodibility, *K*	0.028	0.0375	50.4	36%
Length-Slope, *LS*	1.060	3.11	108.4	193%
Ground cover management, *C*	0.340	0.37	40.2	8.8%
Soil conservation practice, *P*	1.2	1.2	36.9	-

As can be seen from the sensitivity analysis:

– The range of length-slope factors, *LS* at Huntly is highly variable and causes the greatest increase in potential soil loss and turbidity, 193 per cent higher than the baseline. This indicates that *LS* is a high risk factor for consideration in planning and design of barriers.

– The range of ground cover management factors, *C* and rainfall runoff erosivity, *R* at Huntly is the least variable and causes the lowest increase in potential soil loss and turbidity, 8.8 per cent and 8.9 per cent higher than the baseline, respectively. This indicated that both *C* and *R* are of low risk and has little impact on the planning and design of barriers.

Relative risk ratings

Annual soil loss has been calculated for the range of variables measured across the Huntly mine region. A histogram of risk ratings has been derived for Huntly, assuming that:

– Mining can occur anywhere in the region.

– Soil erodibility for cleared areas represents the worst case soils, where the regolith is exposed, and that the regolith of future mined areas is similar to what is observed in the historically mined regions.

– Variables *R* and *LS* are spatially variable and known prior to any mining activity.

– Variable *C* is temporally variable depending on whether the cleared area is being mined or rehabilitated.

– No barriers are in place.

– Other minor assumptions as detailed throughout the tool.

By dividing the range of possible combinations into equal portions, the tool provides a relative risk rating to guide selection and implementation of barriers.

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Hydrological response to bauxite mining and rehabilitation in the jarrah forest in south west Australia

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Climate change
Groundwater discharge area
Shallow subsurface flow

ABSTRACT

Study region: Jarrah forest in south west Australia.
Study focus: The hydrological response to bauxite mining in the jarrah forest could differ from other land uses such as timber harvesting or clearing for agriculture, since mining involves excavation of the upper regolith in addition to changes in forest cover due to clearing and subsequent rehabilitation. Three catchments, one subject to mining, a second subject to an intensive forest thinning treatment and an untreated control were monitored for streamflow, rainfall, groundwater and leaf area index over a 36-year period.
New hydrological insights for the region: Mining caused a peak streamflow response of 225 mm or 18% of rainfall, before returning to pre-disturbance levels 11 years after mining commenced. Streamflow changes were closely associated with changes in a groundwater discharge area in the valley floor. Changes in groundwater level, in turn, were related to rainfall and leaf area index, and these effects did not differ between mine rehabilitation and unmined catchment areas. The streamflow response to mining could not be distinguished from the intensive thinning treatment in this study, or from clearfelling or clearing for agriculture reported elsewhere in the jarrah forest. The results indicate that shallow subsurface flow processes, considered to dominate streamflow generation in jarrah forest catchments, do not extend beyond the valley floor and immediately adjacent slopes which were not disturbed by mining.

1. Introduction

The deep highly weathered lateritic profiles that support jarrah (*Eucalyptus marginata*) forests in south-west Western Australia are capable of storing a large proportion of annual rainfall (Schofield et al., 1989). The store of soil water is exploited by the extensive rooting system of jarrah to depths of 40 m or more (Dell et al., 1983) and evapotranspiration forms the major loss component of the jarrah forest water balance, estimated in catchment studies to exceed 90% of annual rainfall (Ruprecht and Stoneman, 1993). Hence, manipulation of forest cover has long been proposed as one option to influence catchment yields (Stoneman and Schofield, 1989) and numerous studies have been undertaken to determine catchment responses to forest harvesting activities (Ruprecht et al., 1991; Stoneman, 1993; Bari et al., 1996; Robinson et al., 1997; Kinal and Stoneman, 2011). In reviewing the impacts of land use practices in 27 catchment studies across the south-west of Western Australia, Bari and Ruprecht (2003) reported that clearing for agriculture led to permanent increases in yield of about 30% of annual rainfall in high rainfall (> 1100 mm) areas. Forest thinning in higher rainfall areas resulted in maximum streamflow increases of 8–18% of rainfall, depending on the degree of treatment. Streamflows returned to pre-treatment level after 12–15 years, matching vegetation recovery, or longer if regeneration is limited.

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The lateritic profiles also support extensive but discontinuous and shallow (3–5m) surface deposits of bauxite, which have been mined since the 1960′s (Hickman et al., 1992). Expansion of mining in the 1970′s raised concerns over its effects on the hydrology of the jarrah forest (Steering Committee, 1978) and a small number of empirical catchment studies investigating the effect of mining have been reported. Ruprecht and Stoneman (1993) found that mining of 16% of Del Park catchment in 1975–79 resulted in a peak yield increase of 8% of rainfall, followed by a return to pre-mine levels 12 years after the commencement of mining. Bari and Ruprecht (2003) reported larger peak responses in the Seldom Seen and More Seldom Seen catchments of 23% and 21% of rainfall, respectively, noting a good correlation between the increase in streamflow and the proportion of the catchment cleared for mining but not yet rehabilitated. Croton and Reed (2007) found peak increases of 200–250 mm/year, representing responses of 14–17% of rainfall, in a further two mined catchments. In all cases, a consistent pattern of an initial increase in flow followed by a return to, or below, pre-mining levels was observed. These patterns show similarities to the responses observed for other land use practices, however, short (1–3 year) pre-mining calibration periods or difficulties with suitable controls detracted from some of these studies and none went beyond a consideration of annual flow responses. Furthermore, Croton et al. (2005) claimed that a higher water use in young mine rehabilitation was necessary to obtain an acceptable match to streamflow in modelling studies. There remains, therefore, a need to understand in greater detail the effects of bauxite mining on hydrological processes than has been reported to date.

Concurrent with the effects of land use practices on streamflows in the jarrah forest has been the effect of a drying climate. The south-west of Australia has experienced a 15–20% decline in annual rainfall since the 1970′s and a growing number of once perennial streams in the higher rainfall parts of the forest are now seasonal (Petrone et al., 2010). Streamflow decline is observed as a step change in response to the occurrence of years of very low rainfall, reflecting a strong correlation between runoff as a proportion of rainfall and groundwater storage (Hughes et al., 2012). Catchment groundwater storage increases when rainfall exceeds a certain threshold but decreases in years when rainfall is below the threshold. Kinal and Stoneman (2012) reported a particularly dramatic drop in streamflow when groundwater declined below or 'disconnected' from the valley floor, highlighting an 'amplifying' role of groundwater in streamflow generation. When groundwater levels are well below the valley floor, even intensive forest thinning within a catchment can have no effect on streamflows (Kinal and Stoneman, 2011).

The aims of this study were to determine the hydrological response to bauxite mining and subsequent rehabilitation in the jarrah forest, and to compare the response to mining with the response to other land use practices. The study utilised three small jarrah forest headwater catchments over a combined experimental period of 36 years. One catchment experienced a 5-year period of mining and associated rehabilitation, a second was subject to an intensive thinning treatment, and a third acted as an untreated control. Comparisons were made between the mined catchment and the untreated control to determine the effects of mining independent of changes due to climate, while the intensively thinned catchment provided a comparison between a mining disturbance and an alternative land use practice that reduced catchment forest cover to an extent similar to the mined catchment but without excavation of the upper regolith. Detailed measurements of rainfall, groundwater, streamflow and changes in forest leaf area index (LAI), a key determinant of vegetation water use (Waring, 1983), were collected and are reported here.

2. Materials and methods

2.1. Geomorphology, climate and bauxite mining in the jarrah forest

The northern jarrah forest region of Western Australia occurs on the Darling Plateau, an elevated undulating landform developed predominantly on coarse-grained granites and granitic gneisses (Churchward and Dimmock, 1989). The basement rock has been weathered *in situ* to form deep (> 30m) lateritic profiles, the upper parts of which are enriched in sesquioxides of iron and aluminium. The surface horizon consists typically of gravels, sands and loams including a discontinuous indurated layer or duricrust, mostly in mid- to upper-slope positions, merging with the underlying mottled and pallid clay zones. The sandy gravels of the upper slopes become finer downslope, forming deep sands adjacent to the valley floor which in turn are typically dominated by loams and clay loams (Churchward and Dimmock, 1989). Root channels of lower bulk density extending vertically through fissures and discontinuities in the indurated layer and deep into the mottled and pallid clay zones (Dell et al., 1983) are a feature of the lateritic profiles, forming preferred flow paths for infiltrated rainfall and permitting rapid recharge of permanent groundwaters (Johnston, 1987).

The climate of the region is Mediterranean with winter-dominant rainfall (May to October) and a summer drought. Rainfall is greatest on the western margin of the jarrah forest and declines with distance inland. Historical annual average rainfall ranged from 1300 to 600 mm (Gentilli, 1989), however, the region has experienced a 15–20% rainfall reduction since the 1970′s and drought years are now more frequent (Petrone et al., 2010).

The alumina-rich duricrust and mottled zone materials constitute the bauxite ore removed by mining (Hickman et al., 1992). Alcoa of Australia (Alcoa) has been mining for bauxite in the northern jarrah forest since 1963 and presently clears and rehabilitates approximately 550 ha annually (Koch, 2007a). Alcoa's operations comprise a mosaic of shallow pits averaging 4 m in depth and around 20 ha in size distributed across a mining region and linked to a centrally-located crusher by a radiating network of haulroads. A detailed description of the mining process and rehabilitation prescriptions is provided in Koch (2007a). Briefly, the process involves harvesting and clearing of the native forest, stripping of topsoil and subsoil layers to expose any lateritic duricrust layer present, followed by blasting and extraction of the duricrust and underlying friable bauxite. Once ore has been removed, the pit is landscaped to form an undulating terrain while ensuring that surface water does not discharge from the pit into adjacent unmined areas. Ripping using a winged tine to an approximate depth of 1.5 m is undertaken to relieve compaction of the pit floor, the subsoil and topsoil are returned, and the surface ripped for a second time to approximately 0.8 m depth along the contour. This aids infiltration, reduces the

Table 1
Selected characteristics of the three catchments.

Characteristic	Lewis	Hansen	Bates
Treatment	Mining	Intensive thinning	Control
Area (ha)	186	76	230
Weir elevation (m AHD)	277	256	255
Max. slope (°)	7	11	10
Max. relief (m)	80	70	70
Previous silvicultural treatments	Selective logging 1940s–1950s	Selective logging 1940s–1950s	Logging 1920s, 1980–83 (60% of area), burns 1984 and 2001
Flow record	1978–2013	1978–1998	1989–2013

potential for erosion and provides a tilled seedbed for subsequent seed application. Seed mixtures of 73–113 tree and understorey species are broadcast onto the ripped ground in the summer and autumn, and additional nursery-raised seedlings are planted by hand in the first winter. No further trafficking of the rehabilitated surface takes place and the vegetation is allowed to develop. The objective of rehabilitation is to restore a functioning jarrah forest ecosystem containing the dominant overstorey species of jarrah and marri (*Corymbia callophylla*) and a diverse mix of understorey plants (Koch and Samsa, 2007; Koch, 2007b).

2.2. Experimental catchments

Three catchments were examined in this study (Table 1). Lewis was subjected to standard mining operations and Bates acted as an untreated control. Hansen catchment had been intensively thinned in an earlier experiment and results have been previously reported (Ruprecht et al., 1991; Robinson et al., 1997). This catchment was used in the present study as a comparison between mining and non-mining disturbances with similar reductions in catchment forest cover, with analysis in the present study extending the previously reported results to include an examination of the dynamics of the groundwater discharge area and changes in catchment leaf area index. Lewis has a long streamflow record commencing in 1978, acting initially as a control for comparison with Hansen catchment (Ruprecht et al., 1991), before being mined in the late 1990′s. Bates catchment was established in the late 1980′s as a new control for comparison with Lewis in the present study.

All three catchments are located in the higher rainfall area of the northern jarrah forest approximately 100 km SE of Perth (32°38′S, 116°06′E), 10 km to the north of the town of Dwellingup and within a distance of 2 km of each other (Fig. 1). The long-term average rainfall for the area containing the catchments was approximately 1300 mm, while the long-term mean annual pan evaporation was 1600 mm (Ruprecht et al., 1991; Robinson et al., 1997). Lewis catchment supported an open forest dominated by jarrah and marri on the mid and upper slopes with bullich (*Eucalyptus megacarpa*) and swamp heath in the riparian zone primarily at the junctions of the two secondary stream branches. A mid-storey of bull banksia (*Banksia grandis)* was variably present along with grasstrees (*Xanthorrhoea preissii)* and a range of schlerophyllous shrubs and ground layer species (Bell and Heddle, 1989). Mining disturbance in Lewis commenced with clearing for haulroads and pit development in October 1996, after the main winter rainfalls. Additional areas were progressively cleared and mined through to February 2000 (Fig. 1). Rehabilitation of mined pits commenced in 1998 as mined out areas became available, continued in 1999 and all areas were completed by May 2001. There were no areas rehabilitated in the year 2000. A total of 51% of the catchment area was disturbed, with mine pits located on mid slope and upper slope positions. None of the riparian areas were disturbed (Fig. 1). In 2003, a fuel-reduction burn affected unmined portions of the catchment but none of the areas of young rehabilitation.

Bates catchment contained jarrah and marri forest regenerating from harvest activities in the 1920′s and most recently in the early 1980′s (Table 1), with blackbutt (*Eucalyptus patens*) in the valley floor. A mid-storey was largely absent while zamia (*Macrozamia riedlei)* and *Trymalium ledifolium* were common in the ground layer. Species indicative of wetter conditions including *Taxandria linearifolia*, *Astartea fascicularis* and *Melaleuca preissiana* were prevalent along the main watercourse. A post-harvest burn occurred in 1984 (prior to the commencement of stream records) and a fuel-reduction burn across the catchment was undertaken in 2001.

Hansen catchment was described in detail by Ruprecht et al. (1991). Briefly, the catchment was initially covered by open forest of jarrah and marri with a patchy sclerophyll understorey generally less than 1 m tall. A swamp occupied the lower central part of the catchment. In the summer of 1985–1986, a uniform and intensive thinning treatment was applied across the catchment, excluding the swamp and a 50 m buffer, reducing tree basal area from 27–35 m^2/ha down to 7 m^2/ha (Ruprecht et al., 1991; Robinson et al., 1997).

2.3. Instrumentation and measurement

Hydrological measurements in the three catchments encompassed streamflow, rainfall and groundwater. Streamflow was measured using sharp-crested V-notch weirs (90° in Lewis, 90° in Hansen from 1978 to 1994 and 60° from 1994 to 1998, 120° in Bates) with deep (2 m) cut-off walls. Rainfall was measured by a pluviometer located in a forest clearing either at the outlet (Lewis, Hansen) or higher in the catchment (Bates) (Fig. 1). Streamflow and rainfall were recorded in Lewis and Hansen from late 1977 while streamflow recording in Bates commenced in mid 1988. Monitoring in Hansen was discontinued in early 1999, while monitoring continued in Lewis and Bates through to the end of 2013. Rainfall measurement in Bates commenced in May 1992 and annual rainfall for the period 1989–1992 was estimated from a regression with annual rainfall in Lewis. The earliest full year common to the mined

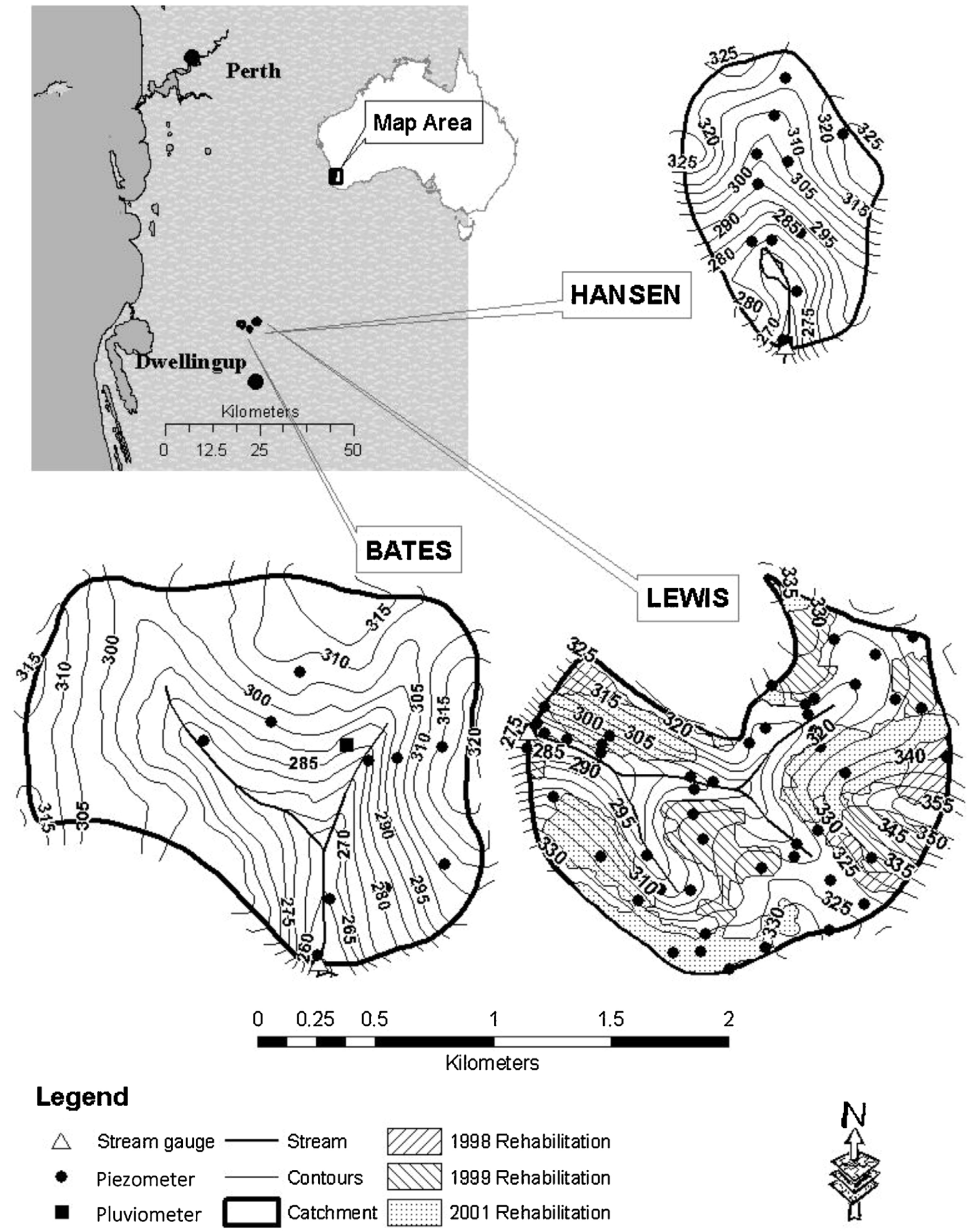

Fig. 1. Location of the three experimental catchments in the study region and topography of each catchment showing location of mining and rehabilitated areas in Lewis, stream gauging stations, pluviometers and groundwater monitoring piezometers.

(Lewis) and control (Bates) catchments for which streamflow data were available was 1989.

Groundwater monitoring commenced in Lewis in late 1988. Measurement of depth to the permanent groundwater was typically monthly. Small gaps in measurements were infilled by linear interpolation, however, where more than half the annual cycle was missing, or the piezometer was dry for more than half the year, the record was not used in subsequent calculations. The number of deep piezometers available in each individual year varied between 7 and 41 over the study period, and a total of 55 over the study period. The number increased from 26 to 41 in 2000–2001 as piezometers were installed in previously mined and rehabilitated areas. For the period 1989–1992 when only seven piezometers were available, groundwater depths for an additional 12 locations were estimated as follows. For the period 1993, when new piezometers were constructed, to the end of 1996 when clearing for mining commenced, correlations between the seven original piezometers and the piezometers constructed in 1993 were generated. The best regression models, with correlation coefficients ranging from 0.88 to 0.98, were then applied using measurements from the original seven piezometers for the earlier period. In Bates catchment, records from a total of 12 deep piezometers were available commencing in late 1988, although two of these became dry within the first five years due to falling groundwater levels. A third piezometer became permanently dry from 2010. A total of 13 deep piezometers were established across Hansen in April 1984 (Ruprecht et al., 1991). For this study, a total of 11 piezometers with approximately monthly readings from April 1985 to early 1999 were used.

An annual time series of spatially averaged catchment LAI was calculated (i) for each catchment, (ii) for individual areas of rehabilitation within Lewis catchment excluding pixels that overlapped rehabilitation boundaries, and (iii) for defined zones associated with individual piezometers in Lewis and Bates catchments (see below). Data were derived from mapping of combined canopy and understorey leaf area index generated for the northern jarrah forest using a series of standardised and calibrated Landsat imagery developed and described by Macfarlane et al. (2017).

2.4. Data analysis

2.4.1. Streamflow response

A linear regression of annual streamflow was established between Lewis and Bates catchments for the pre-mining period. The regression was then applied to the flow data for Bates in the post-mining period to predict flow in Lewis as if there had been no mining.

2.4.2. Groundwater

The response of the deep groundwater to mining in Lewis catchment was estimated as the difference in annual average depth to water compared to a suitable control piezometer in Bates catchment. For piezometers in unmined mid- to upper-slope locations, an average of three control piezometers in Bates was used to reduce the potential for error. One of these bores became dry after 2010 and an average of two bores was used for the final three years of record. For lower slope and streamzone positions, only a single control piezometer was used due to limited availability of piezometers in Bates in comparable locations. In addition, there were too few water level readings in Bates during 1998 to calculate an average depth to water, and a linearly interpolated value from adjacent years was used instead. Differences between each piezometer in Lewis and respective controls in Bates were then normalised by substracting the average difference for all available pre-mining years up to and including 1996. For piezometers established in rehabilitated locations after mining where there were no pre-mining level data, differences between Lewis and Bates were normalised by subtracting the difference recorded in the year that a peak was either observed or, in a small number of cases, estimated.

An analysis of year-on-year changes in annual average groundwater level at the piezometer scale in Lewis and Bates catchments was undertaken to investigate whether groundwater levels responded differently between mined and unmined locations. A generalized linear modelling approach was implemented in Minitab 17 (Minitab Inc., Pennsylvania, USA) using the average of the current and preceding years' rainfall and LAI as main effects. LAI was estimated as the average for a 100 m wide strip extending from the individual piezometer perpendicular to the contour upslope to the closest ridgeline. For piezometers close to the catchment divide, a circle of radius 50 m was used. Piezometers located in valley floor or streamzone positions were excluded from the analysis, giving a total final dataset of 497 records. The location of the piezometer in either Bates or Lewis, and for Lewis in either an unmined or mined and rehabilitated part of the catchment, was included as a random factor in the model. Subsequently, interaction terms and main effects were dropped in a backwards stepwise elimination with an $\alpha = 0.05$ to remove until only significant terms remained in the model (Sokal and Rohlf, 1995).

Streamflow responses to catchment disturbance in the jarrah forest have been closely linked to the size of a groundwater discharge area within the valley floor (Ruprecht and Schofield, 1989; Silberstein et al., 2003). Therefore, estimates of the extent of such zones were made in the present study for each year of available groundwater records using the following approaches. In Bates and Hansen, an annual average depth to water below the ground surface was calculated for each piezometer using all available measurements for the year. There were insufficient piezometers in either catchment to generate a reliable interpolated piezometric surface from these data alone. Instead, mean annual depth to groundwater for each piezometer was regressed against values of UPNESS at each piezometer. UPNESS is a topographic index variable within the model FLAG (Roberts et al., 1997) that describes a position within the landscape in terms of the size of the contributing area, calculated from the number of gridcells connected by a monotonic continuous uphill path. An asymptotic regression model of the form $y = a - b*exp(-c*x)$ was fitted to the annual depth to water and UPNESS data for each catchment, and maps of annual depth to groundwater were generated by applying the predicted depth of water to a 50 m grid of UPNESS values constructed over each catchment. Maps were generated within Surfer 8.0®, using the default linear variogram and point kriging options. In a small number of years, regressions could not be performed due to insufficient piezometer readings, and regression coefficients were estimated by interpolating between adjacent years. In Lewis, a different approach was required as forest cover across the catchment was not uniform as a consequence of mining, and groundwater depth could not reliably be estimated from UPNESS alone. In this catchment, the larger number of piezometers enabled the generation of contour maps of depth to groundwater directly from the piezometric dataset. For all catchments, the extent of groundwater discharge areas was delineated where mean annual groundwater level was within 2 m of the topographic surface, which is conservatively indicative of groundwater 'connection' in the riparian zone (Hughes et al., 2012). In these catchments with intact riparian vegetation, groundwater rarely intersects the surface all year round (Kinal and Stoneman, 2012).

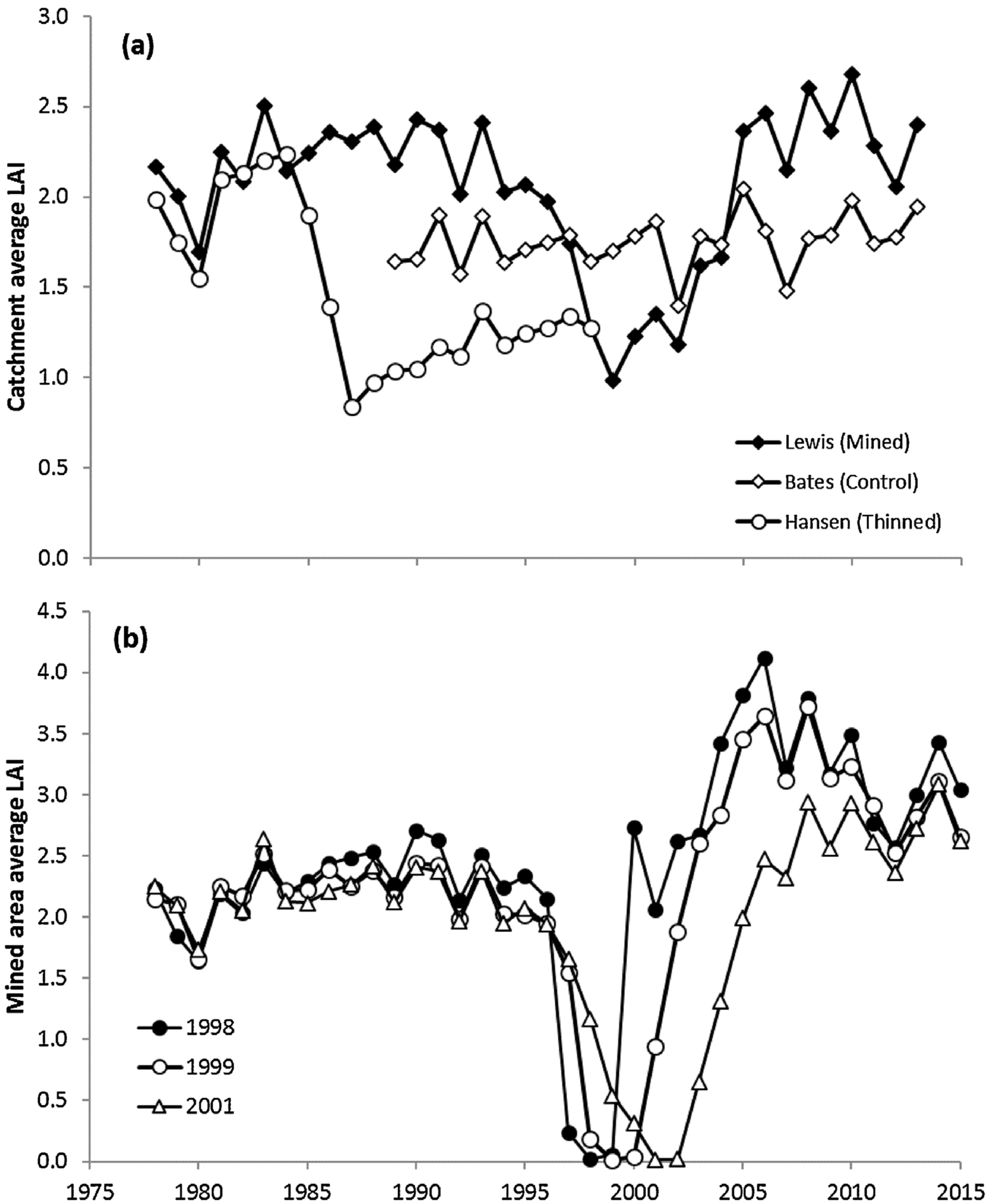

Fig. 2. Changes in (a) catchment average LAI in the three catchments over the periods monitored for streamflow, and (b) mean LAI within areas of Lewis catchment that were mined and subsequently rehabilitated in three different years.

3. Results

3.1. Rainfall

In Lewis catchment, annual average rainfall for the pre-mining period 1989–1996 was 1209 mm, 5% above the long-term annual average (1155 mm), but in the post-mining period 1997–2013 was 1075 mm or 7% below the long-term annual average. Substantially drier years were observed in 2001 (771 mm), 2006 (841 mm) and 2010 (605 mm), representing reductions of 33%, 27% and 48%, respectively, compared to the long-term average. Similar patterns were evident for Bates catchment which had an average annual rainfall of 1192 mm in the period 1989–1996, and 1049 mm in the period 1997–2013. Reduced annual rainfall in the post-mining period was associated with lower rainfall in the months of May, June and July. In Hansen, annual average rainfall for the pre-treatment period 1978–1985 was 1214 mm, and 1217 mm for the post-treatment period 1986–1998.

3.2. Changes in catchment and mined area LAI

Catchment average LAI in Lewis was more than halved from approximately 2.2 prior to mining to a minimum of 1.0 in 1999 (Fig. 2a) when most clearing had been completed and areas of young rehabilitation supported minimal vegetation cover. Recovery in LAI was rapid from 2002 when all mining and rehabilitation activities had been completed, and stabilised at a catchment average LAI of 2.4 from approximately 2005. Catchment average LAI in Bates showed a slight upward trend throughout the period of records, rising from 1.6 to approximately 1.9 between 1989 and 2013 (Fig. 2a). The marked reduction in catchment average LAI in Hansen to a minimum LAI of 0.8 in 1987 due to the intense thinning in 1985–1986 is also evident (Fig. 2a). The magnitude of the reduction in Hansen is comparable to the peak reduction in LAI in Lewis due to mining, while in contrast to Lewis, recovery was much slower.

In Lewis, all areas that were subject to mining supported forest with an average LAI of 2.2 over the period 1978–1996 (Fig. 2b). Recovery in LAI was rapid in the second year after rehabilitation establishment, attaining pre-mine levels within approximately six years, and attaining an equilibrium average LAI of 3.0 shortly thereafter (Fig. 2b). Routine monitoring undertaken in all rehabilitated pits one year after establishment indicated that pits in Lewis rehabilitated in 1998 and 1999 contained an average combined stocking of jarrah and marri of 3200 trees/ha (Alcoa, unpublished data), and a lower average of 2000 trees/ha for 2001 rehabilitation. Understorey densities were also high, averaging close to 5 plants/m^2 for 1998 and 1999 rehabilitation and 2.5 plants/m^2 in 2001 rehabilitation. Results of a single plot measurement in 2008 (unpublished data) of rehabilitation established in 1999 contained 2100 trees/ha with a basal area (over bark) of 28 m^2/ha (LAI 1.5) and a tall dense understorey dominated by *Bossiea aquifolium* with a notably high LAI of 1.4.

3.3. Groundwater

Groundwater hydrographs for mid-slope upper catchment, mid-catchment valley and catchment outlet locations in unmined portions of Lewis, and comparative locations in Bates, are shown in Fig. 3(a–c). While there is a break in the record at the upper location in Lewis due to access restrictions, a rise in groundwater due to mining immediately upslope from 1997 and a minimum depth to water in or before 2000 are clearly visible (Fig. 3a). Over the same period, there is a relatively steady decline in groundwater levels in Bates, representing a total decline of 8.92 m at an average rate of 0.42 m/year. In the mid-catchment valley locations, groundwater depth minima are apparent in 2000, 2002 and 2003, although not in the dry year of 2001 (Fig. 3b). These years are also associated with a reduction in the seasonal amplitude of the hydrograph. Step declines of similar magnitude in Lewis and the control catchment Bates coinciding with drought years in 2006 and particularly 2010 are evident. At the catchment outlet, seasonal fluctuations and the effects of the dry years in 2001 and 2006 are more muted than higher in the catchment (Fig. 3c). However, the effect of the 2010 drought in both Lewis and Bates is clearly recognisable, characterised by significant declines in average groundwater levels and a marked increase in the amplitude of the seasonal cycle thereafter.

Changes in groundwater level in the catchment before, during and after the period of mining are shown relative to equivalent unmined groundwater levels in Fig. 4(a–c). All time traces showed a consistent pattern, rising rapidly after clearing to a peak before returning to pre-mine levels, or slightly below pre-mine levels. In mid-slope locations, peak rises of 2.5–5 m occurred within the period 1999–2003 (Fig. 4a), while slightly higher peaks of 2.8–5.5 m were observed in lower slope and valley edge locations, typically around 2003 (Fig. 4b). Peaks were much smaller in streamzone locations or near the catchment outlet, in the range 0.5–1.5 m (Fig. 4c). In all three sets of locations, groundwater levels in nearly all cases had returned to, or declined slightly below, pre-mining levels relative to the unmined state by 2008, approximately 11 years after initial mining disturbance. For piezometers established in mine pits after final rehabilitation, peaks in groundwater levels were typically observed in 2002–3 with subsequent declines of 2.5–5.5 m (Fig. 4d). While levels in a number of piezometers appeared to equilibrate from about 2008, several others continued a declining trend relative to the control.

Both rainfall and LAI were highly significant ($P < 0.001$) in predicting the year-on-year change in mean annual depth to groundwater, with the model explaining 53% of the variation. Piezometer location in Bates or Lewis, or in mined or unmined parts of either catchment, had no significant effect, and there were no significant interactions. The effect of rainfall was particularly strong (Fig. 5): two-year average rainfalls in excess of 1200 mm were almost always associated with reductions in the depth to groundwater (ie. groundwater rise), while conversely, two-year average rainfalls less than 1100 mm resulted in groundwater falls, except where LAI was low. More generally, LAI was inversely related with change in depth to groundwater.

In Bates, the maximum extent of the groundwater discharge area occurred in 1992 followed by an almost unbroken decline throughout the rest of the record (Fig. 6a). Step declines were apparent around the dry years 2001 and 2010, and after the latter only a very small groundwater discharge area remained at the catchment outlet. In Lewis, a peak in the size of the groundwater discharge area was also evident in 1992, followed by an expansion after mining entry in 1997 to a maximum extent of 8% of the catchment area in 2000 (Fig. 6b). The discharge area contracted in 2001 and further again in 2002, recovered to some extent in 2003 but declined thereafter. There was no groundwater discharge area in the catchment on an average annual basis from 2010 onwards, although transient connection in the lowest parts of the catchment was observed for several weeks in the winter and spring of 2010–2013. In Hansen, the groundwater discharge area expanded rapidly in 1987 following thinning treatment in 1985–86, peaking at an average 12.4% in the period 1989–1992 and then declining to the end of records in 1998 (Fig. 6c).

3.4. Streamflow

Annual streamflow and runoff coefficient in Bates catchment exhibited a declining trend throughout the study period from a peak

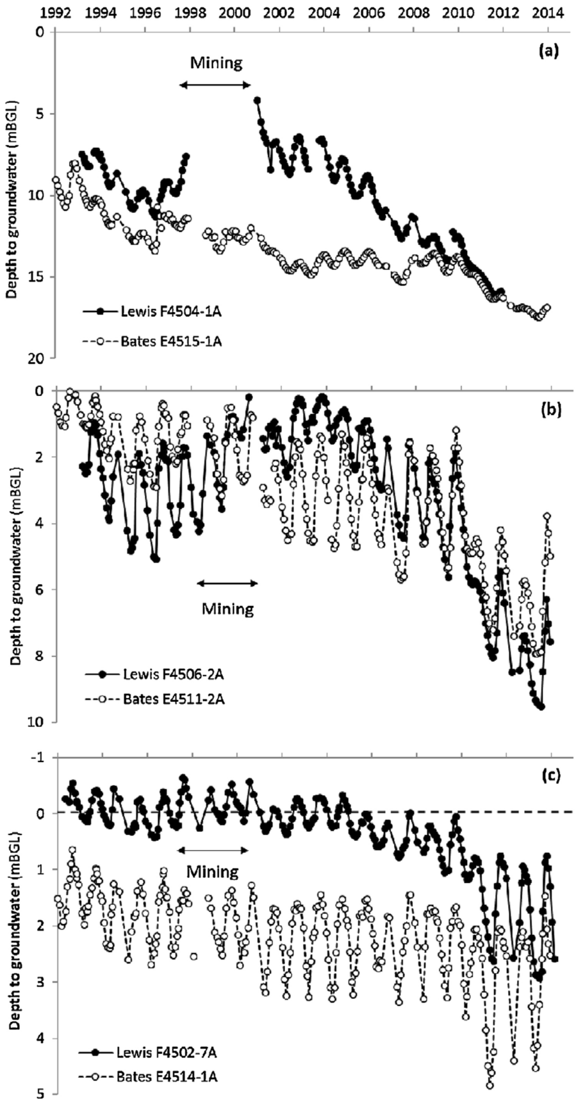

Fig. 3. Groundwater level hydrographs for selected piezometers in (a) upper catchment mid-slope, (b) mid-catchment valley and (c) catchment outlet locations in Lewis (mined) and comparable piezometers in Bates (Control). The periods of mining from clearing to final rehabilitation in areas upslope of each piezometer in Lewis are indicated.

of 325 mm or 27% of rainfall as runoff in 1992 to a low of 28.8 mm or 2.6% of rainfall in 2011 (Fig. 6a) following the record dry year of 2010. This catchment changed from perennial to seasonal flow after 2010, with flows in the last three years 2011–2013 limited to the months of June through December. In Lewis catchment, the runoff coefficient was initially low before a peak following well above average rainfall in 1991, followed by a higher peak of 307 mm or 19% of rainfall in 2000 (Fig. 6b) a year after the lowest average catchment LAI (Fig. 4a). Flow fell sharply in 2001 corresponding with an exceptionally dry year, recovered slightly in the subsequent two years but then declined for the remainder of the study period (Fig. 6b). Zero-flow days during the study period were observed in autumn 2008 (17 days) and increased in frequency thereafter (2009, 110 days; 2010, 209 days; 2011, 220 days; 2012 298 days; 2013, 285 days). Streamflow in Hansen increased after thinning to a peak of 438 mm or 33% of rainfall in 1992 (Fig. 6c). Annual flows declined in each subsequent year to the end of record in 1998 except for the relatively wetter year of 1996. Consistent across all three catchments, there is a close match throughout the periods of record between the runoff coefficient and the size of the groundwater discharge area.

Annual streamflows in Lewis and Bates catchments were closely related during the pre-mining period 1989–1996, with the exception of the years 1989 and 1990 which have been excluded in the fitted regression (Fig. 7). In the two years prior to 1988, Lewis catchment exhibited runoff coefficients of approximately 0.04 and days of zero-flow. Additionally, inspection of the hydrographs for daily flow revealed that during 1989 and 1990, streamflow in Lewis did not respond to rain events early in the winter rainfall season, remaining low until July. Later in the season, both catchments responded in a similar pattern (data not shown). In Fig. 7, annual flows from 1997 to 2007 in Lewis lie above the regression line, while annual flows from 2008 to 2013 (except 2009) form a continuation of

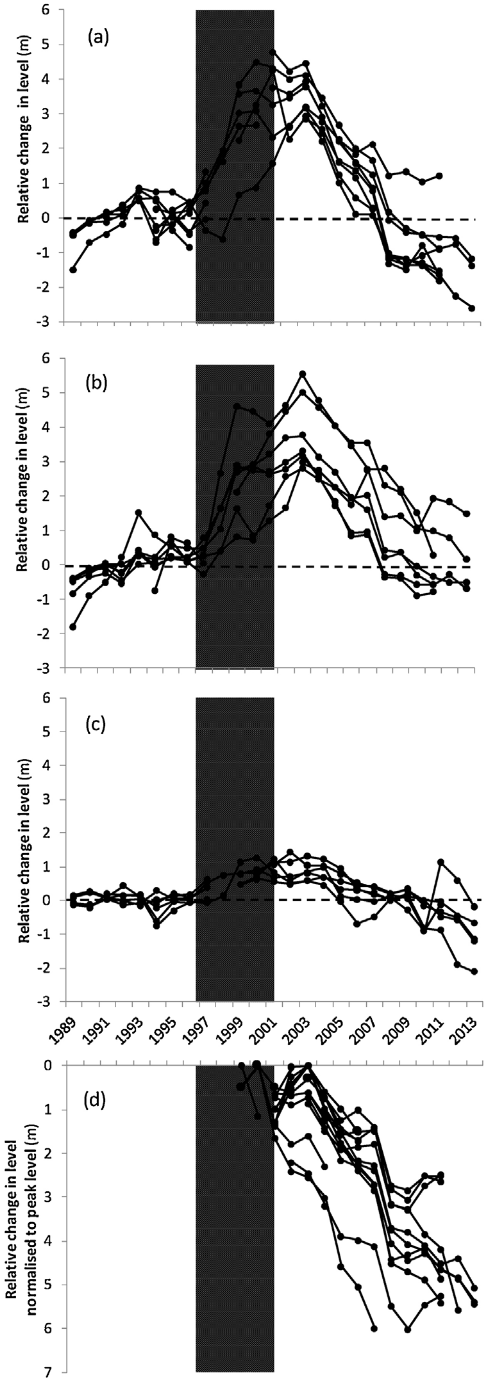

Fig. 4. Mean annual groundwater level relative to an unmined control for piezometers in Lewis in (a) mid-slope, (b) lower slope and valley edge, (c) streamzone locations. Note that in (d) rehabilitated areas, groundwater levels have been normalised to the observed or estimated minimum depth to water in each piezometer, since no pre-mine record exists. The shaded interval indicates the period of mining from clearing to final rehabilitation.

the pre-mining relationship, with both catchments displaying lower flows than during the pre-mining period.

The fitted regression shown in Fig. 7 was given by (Eq. (1)):s

$$Q_L = 0.74 * Q_B - 31 \ (R^2 = 0.99, P < 0.01) \tag{1}$$

where Q_L is the Lewis catchment streamflow (mm) and Q_B is annual flow in Bates (mm). This linear relationship predicts negative flows in Lewis catchment for annual flows in Bates less than 42 mm which occurred from 2010 onwards, therefore estimates of flow response in Lewis using Eq. (1) (Table 2) will be an overestimate. The true relationship between the two catchments at these low

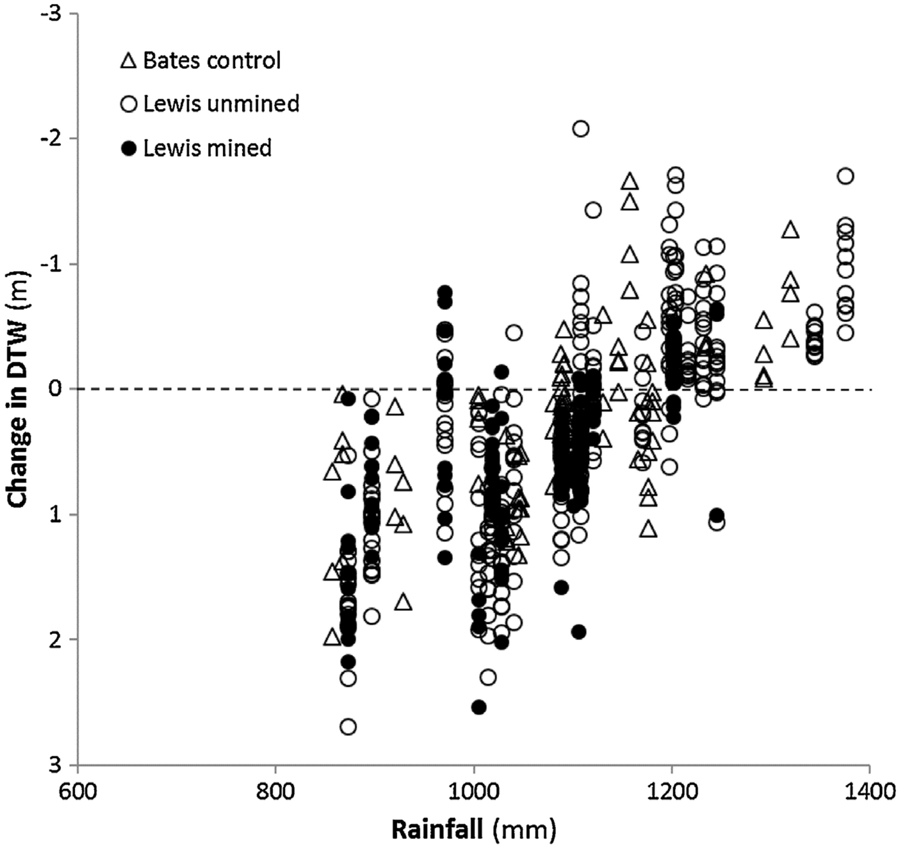

Fig. 5. Change in annual average depth to groundwater in relation to two-year averaged annual rainfall for piezometers in Bates and in mined or unmined parts of Lewis catchment. The dotted line divides occurrences of groundwater rise (negative values) from occurrences of groundwater fall (positive values).

flows, in the absence of any disturbance, cannot be determined. However, a more conservative estimate of the flow response to mining was calculated based on the slope and intercept at the lower end of the 95% confidence interval from the original regression (Eq. (2)):

$$Q_L = 0.66 * Q_B - 12.7 \tag{2}$$

For either set of estimates, there was minimal response in the first full year of mining in 1997, but the response increased steeply from 1998 (Table 2). Using Eq. (2), the estimated peak response to mining was approximately 225 mm or 18% of rainfall in the year 2000 (Table 2), with minimal further mining response from around 2008.

Annual streamflow response to mining in Lewis using the more conservative estimate from Eq. (2) (Table 2) was closely and linearly associated with the size of the groundwater discharge area (Fig. 8a). A similar linear relationship was also observed between the response to thinning treatment in Hansen, as estimated by Robinson et al. (1997), and the size of the groundwater discharge area each year estimated in the current study. Results from two further studies undertaken in jarrah forest catchments, one completely cleared for pasture development (Ruprecht and Schofield, 1989) and the second subject to a clearfell treatment (Bari et al., 1996), indicate a general pattern consistent across all of these land use types (Fig. 8a). Streamflow response to mining also showed a linear but inverse relationship with catchment average LAI (Fig. 8b). The pattern of response again could not be distinguished from the response to thinning in Hansen catchment.

4. Discussion

The response to mining in this study involved an initial increase in streamflow, peaking approximately four years after mining entry into the catchment, followed by a return to pre-mine flows after about 11 years. The peak response was estimated to be approximately 225 mm or 18% of rainfall, which was comparable to the peak response in Hansen of approximately 300 mm or 23% of rainfall reported by Robinson et al. (1997). The response in Lewis is toward the upper end of the range of responses reported for other mined catchments of 8–23% (Bari and Ruprecht, 2003; Croton and Reed, 2007; Ruprecht and Stoneman, 1993), and similar to responses to forest thinning (8–18% of rainfall: Bari and Ruprecht, 2003), but lower than the peak of 32% of rainfall in response to complete clearing (Ruprecht and Schofield, 1989). The duration of response of about 11 years in this study is also comparable to catchment logging and thinning studies in the jarrah forest, which show a return to pre-treatment flows after 12–15 years depending

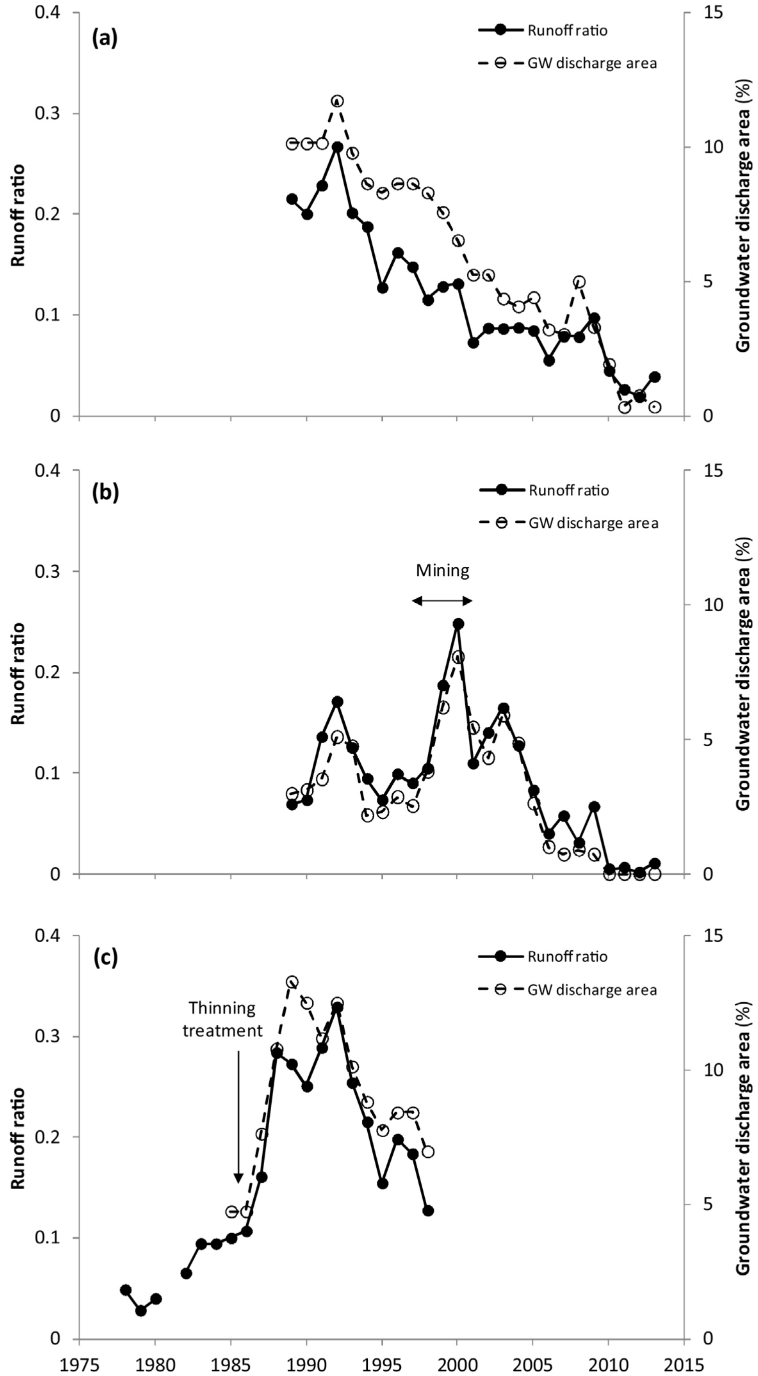

Fig. 6. Annual rainfall runoff coefficient, and estimated groundwater discharge area expressed as a percentage of the catchment area, for (a) Bates (control), (b) Lewis (mined) and (c) Hansen (thinned) catchments.

on the rate of vegetation regrowth (Bari and Ruprecht, 2003; Ruprecht and Stoneman, 1993).

Both the streamflow response to mining and the annual runoff ratio in Lewis were very closely related to the size of the groundwater discharge area (Figs. 6, 8). The same behaviour was evident for Hansen catchment in which forest LAI was reduced to levels comparable to Lewis (Fig. 2) but without the disruption to the upper regolith. In addition, the relationship between the annual runoff ratio and the groundwater discharge area from these two treated catchments was similar to the control catchment Bates (Fig. 6). More broadly, the responses to mining and intensive thinning reported in this study are indistinguishable from jarrah forest catchments subject to complete clearing, or clearfelling and regeneration (Fig. 8a). These results confirm the earlier conclusion of Ruprecht and Schofield (1989) that the 'permanent groundwater system is instrumental in controlling streamflow response' and are

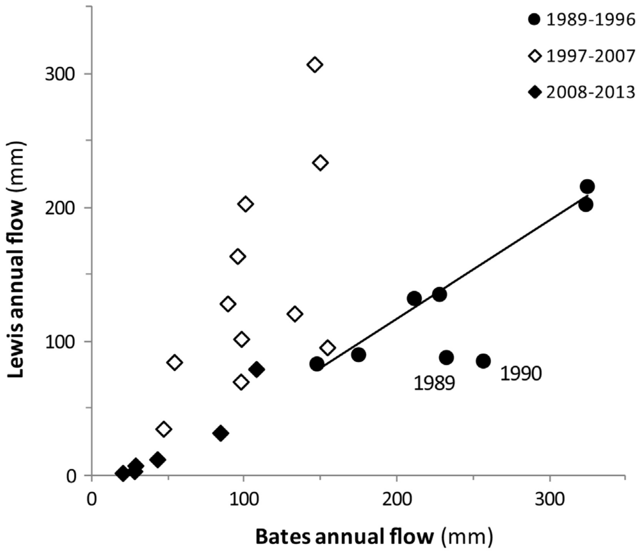

Fig. 7. Relationship of annual streamflow between Lewis (mined) and Bates (control) catchments in the pre-mining period (1989–1996), in the mining and early post-mining phase (1997–2007) and later post-mining phase (2008–2013). Details of the fitted regression (Eq. (1)) are given in Section 3.4; the two years of 1989 and 1990 not used in the regression are indicated.

consistent with more recent research that has reaffirmed the key role that groundwater storage plays in streamflow generation in jarrah forest catchments (Hughes et al., 2012; Kinal and Stoneman, 2012).

Groundwater responded to the combined but opposing influences of rainfall and forest LAI. At the local scale in this study, changes in the annual average depth to groundwater were positively related to rainfall. A threshold rainfall (on a two-year averaged annual basis) at which groundwater levels were maintained was found to be 1100–1200 mm. This is within the range of threshold rainfalls of 1050–1400 mm estimated for whole catchments by Hughes et al. (2012), who also postulated that differences in the threshold between catchments was likely related to forest management and forest density. Conversely, reductions in LAI led to increased recharge, as a result of decreases in transpiration and interception losses (Ruprecht and Schofield, 1989). Importantly, there was no significant effect of mining in the groundwater model developed here, indicating that neither disruption of the upper regolith nor the post-mining vegetation that was re-established altered the fundamental factors influencing the amount of recharge. Similarly,

Table 2
Streamflow response in Lewis catchment due to mining and rehabilitation, estimated using Equation (1) and Equation (2) (see Section 3.4).

Year	Rainfall (mm)	Measured flow (mm)	Eq. (1)		Eq. (2)	
			Predicted flow (mm)	Measured − predicted flow (% rainfall)	Predicted flow (mm)	Measured − predicted flow (% rainfall)
1991	1488	202	209	−0.5	201	0.0
1992	1261	215	210	0.5	202	1.1
1993	1078	135	138	−0.3	138	−0.3
1994	950	90	99	−0.9	103	−1.4
1995	1130	83	78	0.4	85	−0.2
1996	1333	132	126	0.5	127	0.3
1997	1061	95	83	1.1	89	0.6
1998	1154	121	67	4.6	75	4.0
1999	1252	234	80	12.3	86	11.8
2000	1238	307	77	18.6	84	18.0
2001	771	84	9.0	9.8	23	7.9
2002	1169	164	40	10.6	50	9.7
2003	1234	203	43	12.9	54	12.1
2004	1010	128	35	9.2	46	8.1
2005	1229	102	42	4.9	52	4.0
2006	871	35	3.8	3.5	18	1.9
2007	1214	70	41	2.3	52	1.5
2008	1027	32	31	0.02	43	−1.1
2009	1188	79	49	2.6	59	1.7
2010	605	2.9	−10	2.2	6	−0.5
2011	1140	7.1	−10	1.5	6	0.1
2012	1076	1.5	−16	1.6	1	0.1
2013	1130	11.7	1	1.0	16	−0.4

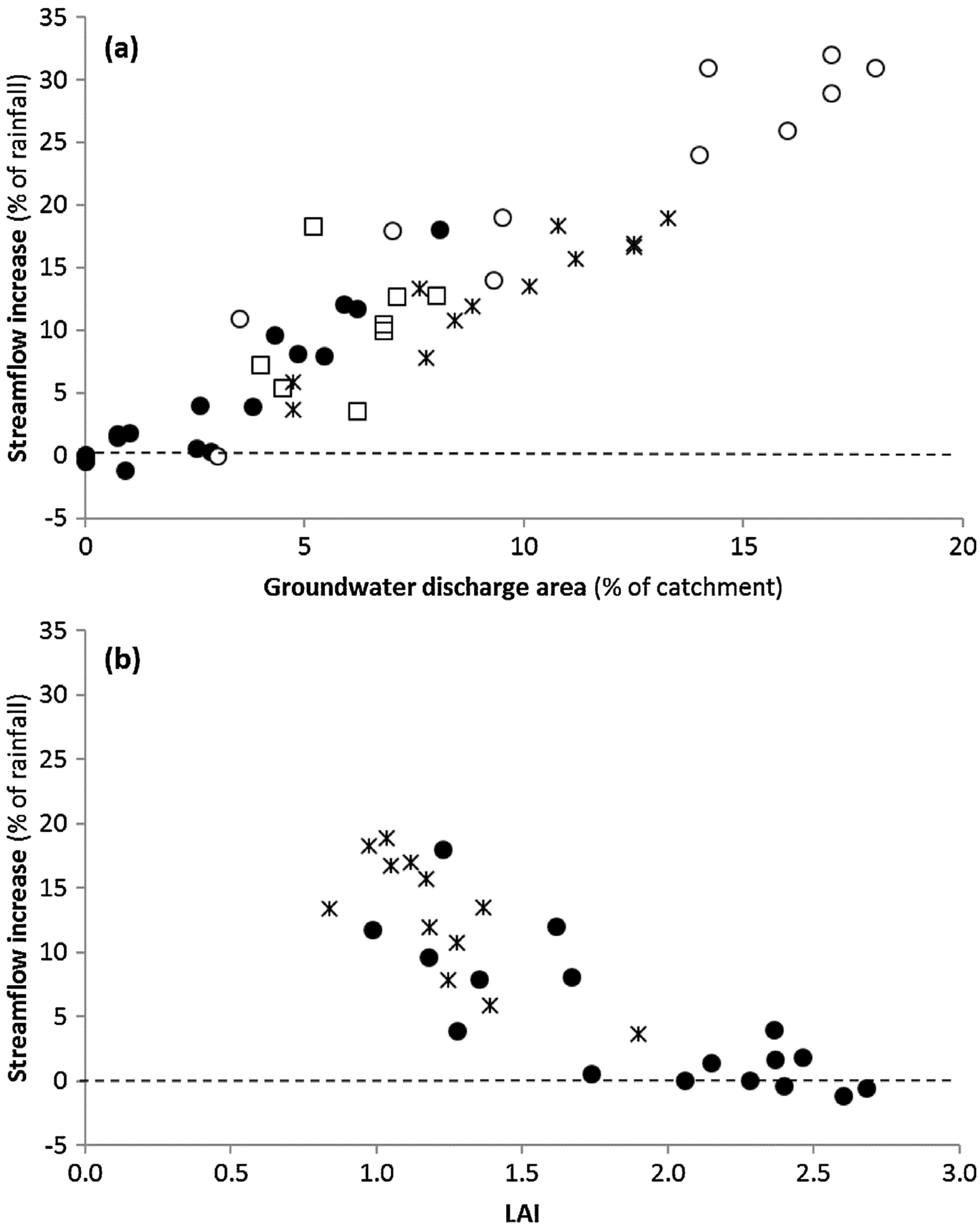

Fig. 8. Estimated streamflow response to mining in Lewis using Eq. (2) (●) and thinning in Hansen (*) (Robinson et al., 1997) in relation to (a) the size of the groundwater discharge area and (b) catchment average LAI. Also shown in (a) are streamflow responses reported for two other catchment studies in the jarrah forest: March Rd (□) (Bari et al., 1996) and Wights (○) (Ruprecht and Schofield, 1989).

Hughes (2012) who investigated the time delay between individual rain events and groundwater recharge for piezometers in mined and unmined jarrah forest catchments, found that only depth-to-water was a significant predictor.

Bauxite extraction clearly disturbs the upper regolith and eliminates any indurated layer present. If there was a permanent change to streamflow generation, then it should have been detectable in Lewis where more than half of the catchment (encompassing almost all upland areas) was mined and rehabilitated (Fig. 1). To the contrary, this study found no discernible difference in the streamflow response in Lewis compared to other land use types which cause little disturbance to the regolith. These findings contradict the notion that shallow sub-surface flow or throughflow is the dominant mechanism for the transfer of rainfall to streams in these catchments, whereby infiltrating rainfall 'perches on the clay B horizon and flows downslope to discharge to streams' (Bari and Ruprecht, 2003). Such a shallow sub-surface pathway would be expected to be disrupted by the mining process and be revealed as a departure in streamflow response when compared with other land use types, but this was not the case. Observations of ephemeral saturation above a duricrust or in fine-textured soils are put forward in support of this view (Ruprecht and Stoneman, 1993), but perching may not be as extensive across the landscape as implied. Robinson et al. (1997), for example, report true perching in only two of a total of 23 shallow piezometers across four catchments, and other studies highlight significant vertical fluxes to depth explained by the presence of preferred flow channels (McFarlane and Williamson, 2002; Turner et al., 1987a). The magnitude of lateral movement of infiltrated rainfall, or interflow, will be determined by the hydraulic conductivities of the upper and impeding layers, topographic gradient and the thickness of the saturated lens (Jackson et al., 2014; McFarlane and Williamson, 2002). Application of the formula provided by Jackson et al. (2014) using typical values for jarrah forest surface soils and subsoils (Sharma et al., 1987) suggests maximum interflow distances to be in the order of tens of metres. Jackson et al. (2014) extend their analysis to conclude that a catchment may be divided into zones, with significant interflow likely to be limited to the valley floor and immediate surrounds. None of these areas were directly impacted by mining in Lewis (Fig. 1), as is typically the case for bauxite mining across the jarrah forest (Koch, 2007a).

The notion of downslope interflow as a dominant process may have arisen from earlier research that showed that contributions to streamflow in these catchments are dominated by shallow throughflow, and that deep groundwater contributions are relatively small (Stokes and Loh, 1982; Turner et al., 1987b). A drying climate in the south west of Australia, however, has challenged this notion by placing greater emphasis on the role of deep groundwater (Hughes et al., 2012; Kinal and Stoneman, 2012; Hughes and Vaze, 2015). The present study expands upon our understanding by indicating that the facilitated shallow throughflow component is likely to be largely confined to the valley floor and immediately adjacent lower slopes. The role of the remainder of the catchment in a hydrological sense is in controlling recharge and hence overall catchment storage. Additional recharge within and downslope of cleared mine pits is clearly visible (Figs. 3 and 4) and groundwater beneath rehabilitated pits responds to rainfall and LAI in the same way as unmined forest areas, from which it is concluded that mining does not fundamentally alter the processes leading to streamflow generation in this environment.

Ongoing declines in groundwater storage in both Lewis and Bates catchments can be expected if the lower-than-average rainfall conditions experienced in the post-mining period persist. Since groundwater storage is negatively associated with forest LAI, declines are likely to be more rapid under mined and rehabilitated areas where the post-mining LAI has plateaued at a higher level than the pre-mine forest (Fig. 2). There are early indications that this may have already occurred in mid-slope and valley locations (Fig. 4). In the case of Lewis catchment, this is unlikely to significantly influence streamflows in the short term as groundwater disconnection is well advanced and streamflows are already small. However, a slower return to a groundwater connected state and associated higher flows relative to the unmined alternative may be anticipated should a wetter rainfall regime return in the future. The relatively higher total overstorey and understorey LAI in rehabilitated parts of this catchment are comparable to other published estimates in bauxite mine rehabilitation of a similar establishment era (Macfarlane et al., 2010) and are due to both higher tree densities than unmined forest and a substantial understorey component. This reflects tree and understorey seeding protocols of the time which were notably higher than current seeding rates. Tree and leguminous understorey seeding rates were substantially decreased from 2000 (Alcoa, unpublished data), and this is evident in the slower recovery in LAI in 2001 rehabilitated areas when compared with 1998/1999 rehabilitation areas (Fig. 2b). For existing stands such as in Lewis, silvicultural treatment such as thinning and fuel-reduction burning may be considered in managing the longer-term development of rehabilitated areas (Grigg and Grant, 2009) and associated hydrological effects.

Declines in groundwater levels and runoff coefficients occurred across both mined and control catchments over the course of the study (Fig. 3) and in Lewis, groundwater at the catchment outlet showed increasing 'disconnection' from the valley floor after the record drought year in 2010 (Fig. 6). Kinal and Stoneman (2012) also reported the abrupt and substantial drop in runoff coefficient associated with such a change in catchment hydrological state. This provides a possible explanation for the anomalous years of 1989 and 1990 in the comparison of streamflows in Lewis and Bates in the pre-mine period (Fig. 7). Streamflow characteristics in Lewis in the two years prior suggest that connectivity was weak, consistent with relatively lower rainfall and high catchment LAI at the time. In contrast, the groundwater discharge area in Bates is likely to have been comparatively larger during the same period, giving rise to contrasting hydrological states in the two catchments. Robinson et al. (1997) encountered a similar issue when comparing Lewis with Hansen in their study, describing Lewis as an unstable control and presenting estimates of treatment response by both a paired catchment approach (which is reported here) and by changes to the rainfall-runoff relationship in Hansen alone. This highlights the difficulties and potential problems of the paired catchment approach in this environment. For the present study, the relationship between Lewis and Bates was affected only when flows in both catchments were small and the error in prediction correspondingly small. However, any future investigation into the longer-term effects of mining in Lewis catchment will be unable to use the same paired catchment approach. More generally, drying conditions and further decreases in streamflow are likely in the south west of Western Australia (Silberstein et al., 2012) and future catchment studies in the jarrah forest will need to closely consider the efficacy of the paired catchment approach in the light of progressive groundwater disconnection.

5. Conclusions

Mining for bauxite in the jarrah forest caused a peak response in catchment streamflow of 225 mm or 18% of rainfall before returning to pre-mine levels 11 years after mining commenced. Changes in streamflow were closely associated with an expansion and subsequent contraction of the groundwater discharge area in the valley floor, which in turn was primarily driven by changes in LAI and rainfall. The response to mining could not be distinguished from responses to other catchment disturbances which do not disrupt the regolith including forest thinning and clearing, indicating that shallow subsurface flow processes, considered to dominate streamflow generation in jarrah forest catchments, do not extend beyond the valley floor and immediately adjacent slopes. The effects of climate and especially very dry years were evident in streamflow declines in both mined and control catchments during the period of records. In Lewis catchment where LAI of rehabilitated areas has risen above pre-mine levels, silvicultural treatment such as thinning and fuel-reduction burning may be considered in managing vegetation development and associated longer-term hydrological effects of mining.

Acknowledgements

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The impact of land use change on sediment mobilisation and stream turbidity: a review

Prepared for Alcoa

By Hydrological and Environmental Scientific Solutions Pty Ltd

The impact of land use change on sediment mobilisation and stream turbidity: a review:
Prepared for Alcoa,

by Richard Silberstein.

Frontispiece: Stream flow gauge on stream in the Darling Range and erosion monitoring pins

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Executive Summary

This report was compiled for Alcoa, to consider the potential impact of mining of bauxite on:

- catchment and stream bank erosion,
- possible increase in stream flow that may lead to bank erosion,
- sediment transport and
- turbidity in streams.

Other land uses in addition to mining have been included to ensure that, as much as possible, any studies that may inform discussion on the impact on sediment mobilisation and turbidity be included. This material has been collated from published scientific literature, departmental and industry reports, and unpublished data and internal reports in commercial, academic and government departments.

Key points:

- The focus of this review is confined to stream bank erosion and sediment mobilisation, resulting from increased stream or stream zone flows that may occur accompanying mining activities.
- This source presents a lower risk than the potential turbidity impact directly from the mining disturbance area.
- The mechanisms leading to stream bank erosion and sediment mobilisation, which could indirectly occur as result of mining activity, are well understood. However, there is limited data available from south-west WA on land uses and in-stream turbidity generation and by bauxite mining in particular.
- The mitigating effect of riparian zone buffers, bank revegetation and stream channel vegetation on erosion and turbidity is well documented.
- While the relative risk is recognised to be low, limited information is available to conclude the likely impact from bauxite mining.
- The report concludes with recommendations for follow on work. In particular, further analysis of the data from the experiments undertaken over the last few decades to determine likelihood of increased flow under future conditions. This should include analysis of whether reports of increased rainfall intensities have occurred or are likely to eventuate.
- A risk analysis considering extent of mining within water supply catchments should identify locations of concern.

This report summarises the findings in the literature sources and highlights material particularly relevant to jarrah forest catchment clearing induced streamflow and any associated stream bank erosion and turbidity above natural trends.

The report concludes with recommendations for follow on work to better address several issues that are insufficiently clear. A significant uncertainty is the likelihood of increased rainfall intensity within the projected climate future. It is not clear whether, despite the general reduction in rainfall throughout the region over the last 50 years, there has been a measurable increase in rainfall intensity in short duration events, as has been discussed in the media and other fora. Predictions are that, under continuing climate change, despite a reduction in rainfall there may be an increase in intense events that may result in increased peak flows, against an overall decline in mean flows. This climatic dichotomy somewhat reduces confidence in predictions.

The report covers references giving observations and techniques, mathematical representations of the bank erosion processes, and presents several models that may prove useful in application in the Western Australian environment. Unfortunately, there are not many publications giving detailed data on conditions in south-west WA. Apart from some references in agricultural settings, none have been found documenting stream bank erosion in south-west W.A.

Observations from forestry and mining studies have found these disturbances resulted in annual increases in flow of 20 to 30% above the expected level, based on comparison with Control catchments, and increases in peak flows of two to four times the level expected in the absence of disturbance. In some cases these increased flows were the highest levels recorded in those streams, but it is still uncertain whether these flow rates would be found in the current climate with the declined groundwater levels and reduced average rainfall. The paucity of observations would suggest that, even though major erosion may be unlikely, especially given the decline in rainfall and stream flow over the last few decades, a program of monitoring and analysis should be undertaken to better quantify the likelihood of bank erosion and to develop robust methods of predicting the conditions under which this would occur in the region.

There is limited availability of data from the south-west of Western Australia on sediment mobilisation and turbidity in streams indirectly resulting from land use changes relative to land use change direct source of sediment and turbidity. Evidence to date indicates that sediment loads from disturbed areas and turbidity usually settle back to pre-disturbance levels much quicker than stream flow rates. Also, while total catchment yields have usually returned to similar undisturbed levels within a few years, peak flows often seem to remain higher than the undisturbed levels for much longer, this is higher than they would if undisturbed, and higher than they had before disturbance. Impact of this peak flow persistence on bank erosion has not been quantified.

The review identifies the processes that lead to bank erosion and lists several models that could be used to predict where and under what circumstances erosion may occur. To some extent this is out of human control, as unpredictable high intensity rainfall events can lead to bank erosion downstream once the stream power reaches a critical level. Of concern is whether Alcoa's operations may lead to these flows being enhanced.

While it is clear that high stream flow rates can destabilise banks, some authors found that peak turbidity is often more related to the number of days with low flow between events than peak discharge.

There is ample evidence that the retention of undisturbed stream buffers, or the introduction of vegetation into bare stream banks, will reduce sediment reaching the stream and reduce erosion of the bank itself. Even a moderate grass cover could prevent bank erosion.

The influence of groundwater on erosion was primarily by increasing unsaturated pore-water pressures and decreasing soil shear strength in surface runoff, and the increased moisture content in stream banks may result in increased erosion during flow events even if they are not greater than would be in the absence of the extra discharge. This probably could be investigated in drainages downslope of mine clearings.

By retaining multiple barriers to sediment transport, through stream buffers, mine-site controls, and preservation of appropriate stream bed conditions and retention pools, the risk to reservoirs should be reduced.

Contents

1. Background

When Alcoa began bauxite mining in the mid 1960s prescriptions for operations and post-mining rehabilitation were partly founded on the concerns at the time that there may be significant negative impact of the operations and their aftermath on public water supply reservoir water quality. The issues of greatest concern were that there may be increased stream salinity, reduction in reservoir yield, spread of the dieback disease and, to a lesser extent, erosion and turbidity. Experience has shown that, with few exceptions, stream salinity has not risen and the mine evolution has gradually extended to higher rainfall regions with steeper land forms. In concert with these developments, the drying climate over the last 50 years has resulted in significantly reduced inflow to dams and the greater dependence on groundwater and desalinated seawater for metropolitan water supply. Some of the desalinated water is stored in hills dams prior to consumer delivery. As a consequence, especially given the cost of generating the desalinated water, concern has increased over the risk of erosion and delivery of increased turbidity and sediment into streams that discharge to the Perth water supply dams.

The risk of erosion with turbidity and sediment transport exists within forested catchments. Under natural conditions stream flow interacts with stream banks and there are circumstances that can lead to natural process of erosion and deposition. It is reasonable to consider the risk is low given the typical vegetated extent of streams. However, it is known that infrastructure, in particular tracks, roads and firebreaks around powerlines, in forests are associated with increased erosion and sediment mobilisation. Bauxite mining increases the risk due to forest clearing and relatively short duration exposed mine surfaces until rehabilitation achieves restored forest system. It is reasonable to consider the exposed mining surfaces within the mining envelope present the greater risk potential for erosion and delivery of increased turbidity and sediment into catchment streams over any other potential source of erosion. However, this risk is expected to be managed on-site under normal operating procedures and is not considered further in this review.

It should be noted that there is uncertainty around likely flow regimes and the occurrence of erosion generating flows since average rainfall has fallen significantly in the region over the last 50 years, and since many of the relevant studies were undertaken. However, there is also the suggestion that despite a reduction in total rainfall there may be an increase in intensity of rare events.

1.1 Purpose of this review

The issue of interest within this review is confined to stream bank erosion and sediment mobilisation resulting from increased stream or stream zone flows that may occur accompanying mining activities. As a result, Alcoa has commissioned a short study to ascertain what is known about the issue, to assess the likelihood of an impact from their activities, explore what methods may be available to predict locations of concern and frequency of occurrence, and anticipate what actions should be taken to, firstly, reduce the likelihood of occurrence and, secondly, to assist design of remedial actions in the event of incidents.

This report documents a summary of published findings relevant to land use activities that may impact on stream erosion and turbidity levels. The focus has been on publications that contain quantifications of impacts of land use changes that may affect stream flow and hence bank erosion, if not direct measurements of banks erosion itself. The Water and Rivers Commission (2000a; 2000b; 2002) published a series of reports aimed at capturing the processes of river restoration. However, while containing much useful guidance, there are few, if any, detailed studies presented that can be used to estimate the likely changes to bank erosion in the bauxite mining context. There is a step by step process to assess river channels for likelihood of exceedance of bankfull status and assistance in designing river management to minimise erosion, but this is, perhaps, a step further than this review needs to go (Water and Rivers Commission, 2000a).

There are relatively few published reports from the mining industry with relevant data and quantification of the issue, hence the literature search has included other, non-mining, activities which may result in similar downstream or off-site impacts, such as, in particular, forestry logging and roading activities, and, to a lesser extent, agriculture related activities.

A survey of the following sources has been undertaken:

i. Web of Science
ii. Google Scholar
iii. Scopus

The following agencies have also been contacted and their web sites searched for any studies they may have, whether published or otherwise, relevant to this topic:

i. In WA - DWER, DBCA, DPIRD
ii. Water Corporation
iii. CSIRO Floreat and Canberra
iv. NSW Forests and Vic Forests
v. Trawl USDA Forests Service

2. Bank erosion and turbidity generation

The process of mining bauxite in the Darling Range involves clearing of surface vegetation, including harvesting of commercial material, the removal and storage of overburden, extraction of bauxite, rehabilitation of mine pits, replacement of the stored overburden and topsoil, reseeding and replanting of native species. These processes can result in periods of enhanced surface runoff and groundwater recharge which can result in, usually temporary, increases in stream flow. While increase in stream flow is not, of itself, a concern, on the contrary, in the context of declining rainfall and reservoir inflows, may be seen as an advantage, there is concern that this increased flow may result in increased erosion of stream banks above a natural rate and this may lead to enhanced turbidity in water supply reservoirs.

Increases in stream flow can result from several mechanisms:

i. With the removal of forest and understorey there is less interception of rainfall, and hence more rainfall reaching the ground surface;
ii. There is also less surface roughness, from plants and litter, inhibiting flow, and thus the enhanced water at the surface may flow more rapidly down slope;
iii. Compaction due to the machinery operating over the surface may reduce infiltration capacity, and hence enhance runoff;
iv. Increased recharge will raise watertables which, if they get close to the surface, particularly in lower slope positions,
   - will reduce infiltration and enhance runoff, and
   - may discharge at the surface, increasing stream flow

2.1 Stream banks erosion – observations

Lawler (1993) presented a detailed review of techniques used for the measurement of river bank erosion and channel change from 1863 to 1988, which he classified in terms of time scales involved, namely long, intermediate and short timescales, and discussed the accuracy and, perhaps more importantly, repeatability of each technique. Interestingly, perhaps, of the 150 studies he examined, only six were undertaken in Australia, and all of these in the east.

Prosser et al. (2000) examined a new technique to monitor stream bank erosion in an upland stream in Tasmania. They found that erosion was controlled by aeration processes that loosen bank material, flows were unable to dislodge firm cohesive clays and erosion was limited to the presence of loosened material, commensurate with the conceptual model presented by Lawler (1995). In some situations, largely dependent on soil characteristics, there may be significant hysteresis in turbidity during events and that the peak turbidity is often more related to the number of days with low flow between events than peak discharge. They also found that even a moderate grass cover could prevent bank erosion. Olley and Wasson (2003) analysed changes sediment flux in the Upper Murrumbidgee catchment since European settlement. In this case, it was mainly gully erosion, largely due to clearing and animal grazing, and the modifications to the riparian zone of many of the tributaries. It seems that gully erosion is much more significant in the eastern states than in the south-west.

Rockwell (2002) analysed the relationship between groundwater depth and bank erosion and found that erosion rates did not correlate well with surface hydraulic flow conditions, and that erosion began well before the full soil depth was saturated. The influence of groundwater on erosion was primarily by increasing unsaturated pore-water pressures and decreasing soil shear strength in surface runoff. Similarly, Fox *et al.* (2005; 2007) investigated the importance of subsurface processes leading to bank erosion and showed the links between different phases of bank moisture content, presence of a shallow watertable and regimes of erosion onset.

Smith and Dragovich (2007) measured sediment flux in a small headwater sub-catchment to ascertain its impact on sediment load downstream. They found that the major supply of fine sediment came from channel walls, with slopes largely decoupled from channels; this would further be enhanced with on-site amelioration techniques, such as those required in active mine pits and forestry operations. They concluded on the need for channel restoration in small upland headwater catchments to reduce local sediment supply to the larger downstream rivers.

Fox and Felice (2014) discussed the importance of groundwater seepage in generating bank instability and consequent erosion. This adds an extra influence on top of the risen watertables generating increased stream flow, the increased moisture content in stream banks may result in increased erosion during flow events even if they are not greater than would be in the absence of the extra discharge.

2.2 Sediment yield and mining

Loh *et al.* (1984) examined the effects of bauxite mining on hydrology in south-west W.A. They observed increased runoff generation on haul roads and associated drain works leading to increased storm flow, but they comment that these were "observations not measurements", citing TAG (1978). There was an increase in stream yield of 20-30% and an increase in peak flows of 2-3 times. The increased water yield was due to increased lateral subsurface flow rather than increased surface runoff or groundwater discharge. The authors noted that in a comparable study looking at the hydrological effects of clearing for agriculture, clearing for pasture in the Wights catchment had increased peak flows 10 to 20 times. Of course, the clearing in Wights was of virtually 100% of the forest and was accomplished within a single year, which is quite different from that undertaken in the mining activities.

Goodman (1992) looked at the hydrological effects of mining in the low rainfall (<900 mm) zone. Rainfall during the period of the study was very low (<700mm), but the observations were that groundwater rose substantially in the vicinity of the mining (only 10 % of the catchment). The catchments yielded 0.65 mm, or 0.1 % of rainfall prior to mining and this rose by about 0.01 mm (6%) in a low rainfall year (690 mm) and by 0.2 mm (90% increase and 0.02% of rainfall) in a high rainfall year (900 mm). There was an apparent reduction in the rainfall required to initiate flow, by about 80 mm, but, in the report, the maximum flow reported prior to mining was 150 m^3/day, with a peak of 6 L/s, and following mining, a maximum daily flow of 800 m^3 with a peak flow rate of 4 L/s. Goodman also analysed salinity changes and mentioned that samples were analysed for suspended sediment but no results of these sediment measurements are reported. These data would still be available at the department and could warrant further analysis.

Croton *et al.* (2005), using a model, and Davies *et al.* (1995) reviewed the impact of land disturbances on the hydrology of the Seldom Seen and More Seldom Seen catchments subject to bauxite mining. These reports presented the impact on groundwater and stream flow but did not consider turbidity nor sediment mobilisation. However, the continued data collection from these catchments and their Control, Waterfall Gully, present an opportunity to re-examine the data for possible emergent principles. Following mining and rehabilitation, total flow increased by 23% or precipitation in Seldom Seen and 21% in More Seldom Seen, and base flow increased by about twice the increase in surface flow. The daily maximum flow rose by 4-5 mm/day in both catchments, which is a two-fold increase over the pre-mining values. Observed flow returned to pre-mining levels within 10-12 years, although in modelling study by Croton *et al.* it took at least a decade longer. The authors state that during mining in 1980, peak flow in both of the Seldom Seen catchments exceeded that in the Control, as did the annual totals, in significant contrast to the situation prior to mining.

Mauger *et al.* (1998) reviewed research on hydrological effects of bauxite mining undertaken to 1997. However, this review does not mention the words "turbidity" or "erosion", except in citing a reference to a technical report on minimising erosion on mine pits and gives no specific data relevant to this review.

Bari and Ruprecht (2003) reviewed the effects of land use changes on hydrology in the catchments of the Darling Plateau, citing a large number of studies. They found the effects of bauxite mining and rehabilitation on water yield were transient with water yields from three study catchments rising by 8% before returning to their pre-treatment levels once rehabilitation was complete. However, they noted that data at the time (2003) were insufficient to make conclusive statements on the longer term (> 20 years) effects of bauxite mining and rehabilitation on water yield and salinity.

Croton and Reed (2007) presented a synopsis of the interactions between bauxite mining and hydrology in the Darling Range. They described the control of turbidity in water leaving the mine pits through control of erosion in a series of sediment trap ponds used to process water from active mine areas prior to its release. At that time, after mining, a containment pond with a size equal to the one in 20-year rainfall event was worked into the post-mine landscape as part of the rehabilitation (Croton and Tierney, 1985). If properly implemented, these measures, along with the characteristics of soils in the bauxitic areas of the Darling Range and the low intensities of rainfall in the region (one in 100 year, 1-hour event of 45 mm/hr— Institution of Engineers (1987)), resulted in low incidence of erosion and turbidity. Throughout the mining and rehabilitation area stream turbidity was monitored with a continuous sampling network placed on tributaries flowing from the mine envelope, thus a significant database of data is available for analysis to inform this discussion. Such analysis is currently underway (Brad Smith, Alcoa, personal communication). Reporting limits had been agreed with the Water Corporation at an event exceeding 25 Nephelometric Turbidity Units (NTU) for two hours or more is reported as an environmental incident and is investigated and actions implemented to avoid a recurrence. For the whole of Alcoa's operations on the Darling Plateau, there were just four reportable events for the period 2003–2006, inclusive (Croton and Tierney, 1985). However, neither Croton and Reed (2007) nor, the supporting technical report (Croton et al., 2005), considered suspended sediment or turbidity as a result of downstream processes.

Mengler and Gilkes (2006) analysed trigger conditions that enable erosion gullies to develop across mine areas in the Darling Range. Mengler (2008) developed a conceptual model for gully erosion onset that depends on slope steepness with certain triggers and threshold effects operating under different site conditions that govern gully erosion occurrence and severity. Steeper slopes and longer slope lengths intensified the severity of erosion where they combined with one or more major or additional minor erosion triggers. Most gully erosion initiated at the upper parts of rehabilitated hillslopes, either at the base of a shoulder or on backslopes. Many pre-existing triggers that predispose critical parts of a landscape to gully erosion activate only under threshold-excess conditions. While specific relationships varied with location, and presumably soil characteristics, area-slope relationships show that no gullies, or only small ones, occur at slopes from 0 to 14° where catchment area contributing to a given point is less than 0.4 ha. Above 0.6 ha contributing area, and steeper than 10° slope, large gullies can occur but not in all cases. With slopes less than 10°, even at relatively large areas of catchment draining through a point (>1 ha contributing area) gullies are usually small. These results are represented in Figure 1.

In concert with their field investigations, Mengler *et al.* (2007) tested two established models to simulate the development of gully erosion in the mined areas. The empirical Revised Universal Soil Loss Equation (Renard et al., 1996) or RUSLE model was used to determine an annual rate of potential soil loss for each surveyed site. RUSLE was found to be reliable to empirically predict erosion risk and estimate the magnitude of expected annual soil loss for a given site. A more sophisticated simulation model known as SIBERIA (Willgoose, 2002) was calibrated and its simulated outputs were compared to known locations of gully erosion on a steep, rehabilitated pit from the Willowdale mine. At a resolution of one metre, SIBERIA was able to simulate gullies whose form was similar in length, width and depth to that of the real gullies but the exact location of individual gully heads was not simulated.

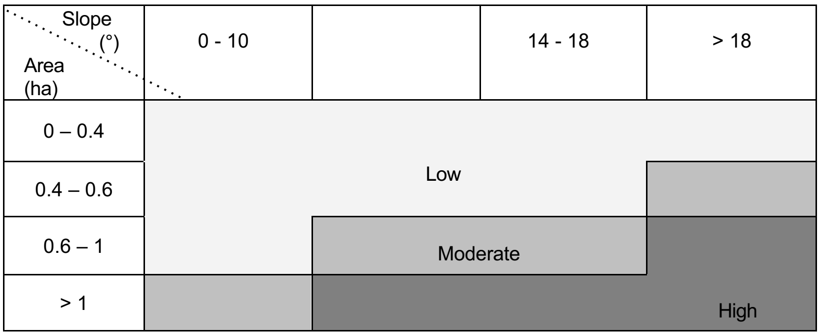

Figure 1. General gully risk categories based on pre-mining slope (°) and contributing area (ha) for rehabilitated Darling Range bauxite mines (taken from Mengler et al., 2007).

Grigg (2017) presented an extensive summary of a long-term data set analysing the hydrological impacts of bauxite mining. Using data from catchments collected over up to 35 years, he found a significant increase in annual yields from mined and rehabilitated catchments, peaking at 18% of rainfall (relative to the Control) about 4 years after clearing. Grigg did not consider erosion nor stream turbidity in this analysis, and did not appear to consider instantaneous peak flows, but these instantaneous flow data would be available in the dataset analysed and there may be some turbidity data also.

2.3 Sediment yield and forestry

Clinnick (1985) presented a review of the implementation of riparian buffer strips in forestry operations to minimise sediment delivery to streams and reduce incidence of turbidity. He made the observation that strips were often designed at 30 m wide but that the width should vary according to soil, slope and operating conditions. His concern was that often the width appears to simply follow a fixed specification, rather than be designed in a site specific manner. Borg *et al.* (1988) examined the impact of reduction in stream buffers from 100 m down to 50 m, and a single trial removing the buffers altogether. They found the reduction in area had no impact on the stream, while a buffer was retained, and complete removal resulted in "*minor changes in stream channel profile and algal blooms, … however … no impact on suspended sediment concentration in the stream*".

Borg *et al.* (1987a; 1987b) undertook one of the most comprehensive studies of the impact of logging on stream flow and water quality in south-west WA. They found that during the period of logging, and for up to 4 years thereafter, groundwater rose and stream flow increased substantially in the higher rainfall catchments. In these catchments the minimum watertable level rose by around 2 m relative to the Control catchments, which remained more or less stable over the period. Stream turbidity and sediment load increased but only in catchments that did not have a 30-100 m riparian stream buffer and were harvested in winter and the increased concentration lasted only 2 to 4 years. Years with the maximum increase in flow yielded around 2 to 2½ times the flow that would have been expected without logging. In 1984, the year of highest flow in most catchments, yield rose from about 140 mm to around 300 mm. They also found that peak daily flow rates in the disturbed catchments increased in all years in all disturbed catchments of the experiment, by between 50 and 1200% over the expected rate if the catchments had been undisturbed. While apparently very high, it should be noted that the maximum proportional increases were in years of low rainfall and very low flow; the quantum of increase was between double and three times the undisturbed maximum rates. The reports give instantaneous peak flow rates and highest daily flow totals, which did not usually occur in the same year. The highest flow rates were generally recorded in 1985, and were equivalent to 30 to 60 mm/day (these are the units quoted in the report), which were 2½ to 4½ times the expected value if there were no logging. These data are presumably stored in the DWER database and further analysis would be possible. The Steering Committee for Research on Land Use and Water Supply (WAWA, 1987) summarised the findings of Borg *et al.* (1987a; 1987b) and several others, noting that the experiments occurred during a decade of significantly lower than average rainfall, in the high and intermediate rainfall zones (>900 mm) stream flow increase peaked in the year with least forest cover, that is at the peak of clearing before regrowth commenced, at about double the undisturbed rate, about

10% of rainfall, and in the low rainfall zone, a similar proportional increase in flow occurred but was only about 4% of rainfall. It was expected that the streams would return to pre-disturbance levels of flow by about 10-12 years in the high and intermediate rainfall zone and about 7 years in the low rainfall zone. There was no increase in sediment load in catchments that had riparian buffers and were harvested in summer, but they could not separate the independent effects of logging in summer and the riparian buffer. WAWA (1987) made several recommendations on refinements to logging practice to limit impact on stream turbidity, however, these are not really relevant to this review and are not discussed further.

Moulds *et al.* (1994) presented the results from thinning Yarragil 4L by 80% of cover. Watertables rose by 4-6 m relative to the control, Yarragil 4X, in which the watertable fell about 3 m over the same period. Streamflow increased, peaking around 9 years after treatment at 10% of rainfall, with a mean flow rate after treatment of 4.5 % of rainfall, representing a 9-fold increase in proportion of rainfall, from around 0.5% prior to treatment. Prior to treatment, mean annual flow in the Control, 4X, was 11.9 mm, about 2½ times that from 4L; in the period after treatment mean annual flow from 4L was 49.4 mm, three times that of 4X at 15.5 mm. It should be noted that the rainfall in the 7 years prior to treatment averaged 860 mm and in the 9 years after treatment was 1000 mm, thus the increase in runoff coefficient will be partly influenced by the increased rainfall.

Kinal and Stoneman (2011) performed a similar experiment to that of Borg *et al.* (1987a; 1987b), although in a more northern jarrah forest setting, and more recently when the rainfall has declined somewhat. While finding a small rise in groundwater levels in response to forest thinning they found only minor changes to stream flow, thus raising the question of whether the drying climate in southern Western Australia may result in continued significant decline in stream flows and the previously observed increases in flow following mining and forest harvesting may no longer manifest.

Campbell and Doeg (1989) were concerned about the impact of stream water sediment on instream biota. They reviewed a large number of studies covering impact of forest disturbance on stream quality. While they did not consider bank erosion, as our interest here, they made the observation that the majority of sediment transport occurs in streams during periods of high flow, and "*many studies fail to sample intensively through such events, and … produce such gross underestimates of sediment load as to be almost worthless*." They also remarked that results were often inconclusive and, for example, Cornish (1980; 1981; 1983) investigated turbidity levels in a number of streams draining catchments from which the timber was harvested in New South Wales. In each of his studies, he recorded higher maximum turbidity from streams with logged catchments than for similar streams with unlogged catchments, and in all but one study the mean turbidity were higher in the logged than the unlogged streams. Nevertheless, he concluded that "*in general, forest operations do not have an adverse impact on stream turbidity levels*", which seems a little odd, given his results, but I think, means the major problem was from tracks and roads and not the harvest area itself.

Harper and Lacey (1997) reviewed the Yambulla catchment experiments examining the impact of logging and wildfire on stream flow quantity and quality in the wood-chipping area of forests in southern NSW. The soils of these forests had been classified as highly erodible. They found that, following the most intensive impact, being the combination of pre-and post-wildfire logging, stream flow rose, and peak flows, in particular, for up to 10 years but that without the post-fire logging, the return to pre-treatment levels occurred in four years. The findings suggested that sediment mobilisation was mainly confined to the near vicinity of the stream. Turbidity increased dramatically during storm events following the disturbance, but ground cover recruitment brought this back below pre-disturbance levels within five years. Citing Chalmers (1979), Harper and Lacey (1997) stated there was "qualitative" evidence that the main impact on stream turbidity was from logging roads and snig tracks to a much greater extent than the disturbance during normal logging operations. While vegetation recovery reduced sediment load over five years, there was some suggestion, but no evidence presented, that the increased peak flows, which persisted beyond this, may result in bank erosion (Cornish and Binns, 1987; Harper and Lacey, 1997).

More recently, Croke and Hairsine (2006) reviewed published studies linking harvesting, forest removal, road construction, and off-site water quality. They provide an extensive literature list, however, their review focussed only on the sediment delivery to the stream from forest disturbance. They emphasise the importance of reducing runoff generation and consequent sediment mobilisation but conclude that the major problem derives from the track and road networks associated with forest harvesting. This was also the conclusion by Loh *et al.* (1984) examining the effects of bauxite mining on hydrology in south-west W.A. None of these studies explicitly considered bank erosion impacts that may derive from increased stream flow from disturbed areas.

Bathurst and Iroumé (2014) looked for emergent principles governing sediment yield from 51 catchments around the world (though not in Australia) subject to forest logging and with 16 Control catchments. They found, in common with other authors (e.g. Bosch and Hewlett, 1982; Brown et al., 2005), that if less than 20 % of a catchment was treated there was no distinguishable response in streamflow. Often responses were greater on low flows than high flows, but this was by no means universal. Bathurst and Iroumé found that forest cover had little impact on long recurrence interval (>10 years) peak storm flows for sites in Chile. More particularly, they emphasised that impact of logging on sediment mobilisation was dependent on hillslope conditions, locations and conditions of roads and tracks, and logging practice and the unpredictable occurrence of a major rainfall event. Hence, they concluded, there is no apparent general relationship between sediment yield impact and the proportion of catchment logged; two thirds of logged catchments deliver their maximum post-logging sediment yield in the first 2 years after logging, and there is no obvious quantitative generalization concerning the time for recovery to pre-logging conditions. However, on this last point, it was noted that their datasets, in the main, ran to only about 6 years post-disturbance.

Rachels *et al.* (2020) showed the value in characterising sediments at source in order to demonstrate the origin of in-stream mobilised sediment. They quantified the proportional contributions of suspended sediment from hillslopes, roads, and stream banks. The primary source of suspended sediment in both harvested and control catchments was stream bank, with lesser amounts from hillslopes and roads.

Pennifold and Pinder (2011) provide a large amount of data on invertebrate biodiversity, physical and chemical properties of streams in jarrah and karri forest as part of the monitoring required by the Forest Management Plan. Interestingly, a simple analysis of their data show a reduction in turbidity, and an increase in invertebrate biodiversity, with increasing stream flow velocity (Figure 2). In this case, their measures of stream flow were designed to indicate the size of the stream and variability along reaches; they were not monitoring temporal variability in flows. Their monitoring was aimed at tracking landscape scale impacts of logging, and it may be more relevant to assess the results of local scale studies they cite (Growns and Davis, 1991; Horwitz, 1997; Trayler and Davis, 1998) rather than their results themselves.

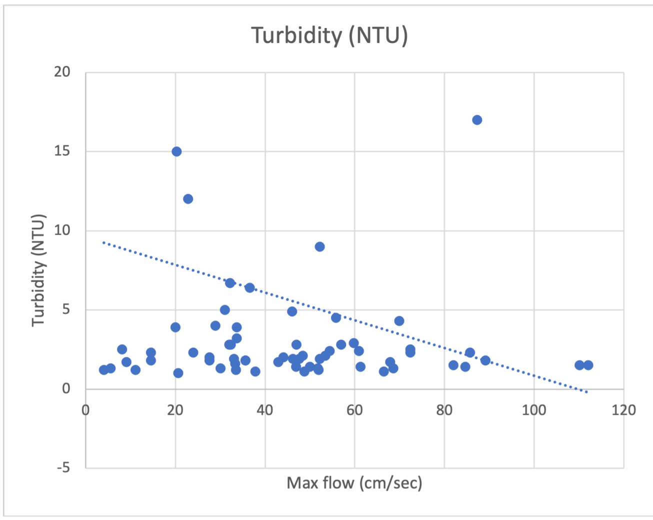

Figure 2. Turbidity against maximum stream velocity in rivers assessed by Pennifold and Pinder (2011). This figure is for illustration, and does not show a robust causal relationship but is indicative the complexities that may exist in the interconnections between different stream condition indicators.

2.4 Sediment yield and agriculture

The benefits of riparian buffer strips to protect streams discharging from agricultural land are now well documented. McKergow *et al.* (2003) demonstrated, using data from a ten year study near Albany, W.A., that there was a reduction of suspended sediment to a tenth of pre-treatment levels, although there was little impact on nutrients, although both P and N changed species mix as a result of the riparian changes.

When the Collie Catchment clearing experiment was undertaken in the 1970s and 1980s, though designed to chronicle the development of salinisation associated with the clearing for agriculture, there were also observations of turbidity and sediment transport associated with the clearing. Abawi and Stokes (1982) tracked turbidity and sediment mobilisation of the Wights catchment, that had been almost completely cleared and seeded to pasture. They found that, after the initial disturbance had settled, the highest sediment delivery occurred during summer storm events. They also found that 7% of annual runoff delivered 60% of the sediment to the stream, maximum suspended sediment concentrations of over 1,000 mg L^{-1} and total sediment load of about 1.5-2 t/ha/yr. Bed load may greatly exceed suspended sediment, citing sediment traps in the woodchip licence area that collected substantial amounts of sediment. They also found, as do many other studies, that there is a significant hysteresis in sediment mobilisation, and that concentrations are much higher on the rising limbs of events, than during the falling phase. However, there was insufficient data from storm events to confidently develop a suspended sediment rating curve.

Silberstein *et al.* (2003) analysed the impact of clearing for agriculture on stream flow statistics for the five cleared and two re-afforested Collie catchments, and found substantial increases in peak flows. Average runoff coefficient rose by a factor of 5 in the high rainfall catchments, about 10 in the intermediate rainfall catchments and virtually infinitely in the low rainfall catchments, as the mean flow of natural catchments is so low. However, peak flows, specifically 99th percentile, increased by a factor of about 2 in the high rainfall catchment and in the intermediate rainfall zone, prior to the watertable reaching the surface and doubled again once the watertable reached the surface.

2.5 Stream bank erosion modelling

There have been substantial recent advances in modelling the onset of erosion gullies and bank instability, that could be deployed in the Darling Range context, if sufficient and adequate site characteristics data can be assembled. In analysing sediment loads from the Wights catchment following clearing, Abawi and Stokes (1982) set out a simple model determining the trajectory of concentration of suspended sediment in a stream as dependent on time between samples, flow at given sample times, antecedent flow, and a "flood intensity index". This may be a basis for future modelling investigations but does require the flow records. They observed that higher sediment concentrations occurred in summer when the surfaces of slopes lost sediment to the stream channel.

Lawler (1995) presented a relatively simple conceptual model (DOCPROBE: DOwnstream Change in PRocesses Of Bank Erosion) that predicts the effect of scale on stream bank erosion processes and demonstrates that in small upland catchments, sub-aerial processes are most significant in facilitating bank erosion, because the stream power is rarely adequate in the upper reaches to dislodge material. Stream power becomes more significant in the middle reaches of catchments. A brief description of the first component of this model is given in the Appendix.

Fox and Wilson (2010) provided an extensive review of subsurface flow processes leading to stream bank erosion, with a detailed physical analysis and mathematical representation of the dynamics involved. They derived relationships based on laboratory tank tests and field observations. Subsurface flow affects erosion directly by seepage and pipe flow processes and indirectly by the relationship of soil properties with soil water pressure. Seepage contributes to erosion through interrelated mechanisms: hydraulic gradient forces that reduce the resistance of the particle to dislodging from the soil matrix and particle mobilization when soil particles become entrained in exfiltrating water. These authors conclude that current geotechnical models based on invariant hydrostatic vertical pressure distribution are underestimating the effects of subsurface flow mechanisms on bank stability. Recent advances in process-based modelling and improvements in data collection of critical erodibility and geotechnical parameters enable process-based approaches in the design of projects for control of bank erosion (Enlow et al., 2018; Klavon et al., 2017) .

The journal *Water* had a special issue in 2018 presenting recent advances in stream bank erosion modelling, monitoring and management (Castro-Bolinaga and Fox, 2018). The assemblage of articles in this issue demonstrated the need to better understand the non-linear relationship between erosion rates cohesive soil conditions and increasing boundary shear stress, to adapt computational procedures obtain erodibility parameters under these conditions and thence the need to incorporate process-based modelling of streambank erosion and failure in the design and assessment of stream restoration projects.

Karimov and Sheshukov (2017) monitored an ephemeral gully over two years to identify the main factors responsible for soil detachment and developed a critical shear stress function that accounts for changes in soil moisture content to give a more accurate prediction of erosion zones within ephemeral gullies.

The Bank Stability and Toe Erosion Model (BSTEM) is a process-based model used to predict stream bank retreat and volumes of sediment resulting from stream bank erosion (Langendoen et al., 2016; Simon and Collison, 2002; Simon et al., 2011; USDA, 2018). The model integrates two components which simulate hydraulic and geotechnical processes that influence mass failure (bank stability module) and fluvial scour (toe erosion module) in streambanks. Originally an Excel (Microsoft, WA) based model, BSTEM was recently incorporated into the Hydrologic Engineering Center's River Analysis System (HEC-RAS) model (CEIWR-HEC, 2015) to create a reach-scale bank erosion capability. BSTEM predicts bank failure based on a fundamental force balance, with a toe scour model that allows feedback between the hydraulic dynamics on the bank toe which could exacerbate failure risk (in the case of toe scour) or decrease failure risk (in the case of toe protection). It is purpose built to test the efficacy of stream bank stabilisation treatments (both revegetation and engineered toe protection). To set up and run this model requires, of course, the data needed by HEC-RAS, and then details of the bank geometry and layering, flow conditions, soil hydraulic conductivity and cohesion. BSTEM assumes simple channel cross section, and that stream bank and floodplain sediments are relatively uniform and can be characterised by simple flood plain processes. The BSTEM model is designed to predict stream bank erosion at a site scale. In systems where the bank morphology does not contain inset units and site-specific bank sedimentology and hydrological information is available it is an excellent tool for bank erosion prediction. Although a calibration process is often required to obtain a good match between modelled and observed data it would be worth considering.

Alluvium (2020) reviewed a selection of models of stream bank erosion looking at sediment discharge to the Great Barrier Reef. They reviewed the BANCS and BSTEM models as well as the Dynamic SedNet model as currently used within the GBR Source Catchment Modelling framework. Dynamic SedNet is a semi-distributed spatial daily time-stepping sediment budget model which is implemented within the Source integrated catchment modelling system (eWater, 2022). SedNet is comprised of multiple models, with each component modelling a specific process (i.e. stream bank erosion, floodplain deposition etc.). It simulates spatial patterns in primary erosion processes at a catchment scale using data relating to terrain, land use, riparian vegetation cover, soils and rainfall. It predicts runoff for each land use Functional Unit in each sub-catchment, and subsequently to predict daily flow and bankfull flow for each stream link (Wilkinson et al., 2014). Flow data is used in the subsequent modelling of daily fine sediment budgets for each link in the river network. It has been assessed on reaches of 14 km and found that for good model performance local measurements of bed slopes and bank full discharge were required (Bartley et al., 2008).

Within the SedNet model bankfull stream power is considered the dominate driver of bank erosion, but this is not universally accepted and Prosser (2018) argues this may be due to limits to statistical analysis such as the ranges of stream power under investigation relative to its variability in time and space across large regions. Stream power is still likely to be a significant driver of channel erosion in almost all river typologies, however the high variability in the characteristics and erodibility of the channel boundary material and riparian vegetation make finding reach scale correlations between stream power and channel erosion problematic.

The Bank Assessment of Non-point Source Consequence of Sediment (BANCS) (Bigham et al., 2018; Rosgen, 2001; Rosgen, 2009; Rosgen, 2011; Rosgen et al., 2019) approach is an empirical, process integrated model used to predict the rate and volume of stream bank erosion along river reaches in a specific hydrophysiographic region. BANCS is a reach-scale, rather than catchment-scale, bank erosion prediction model. However, the model can be used to predict erosion rates across a catchment for similar stream systems. The model integrates two bank erodibility estimation tools: the Bank Erosion Hazard Index (BEHI) and the Near Bank Stress (NBS) (Bigham et al., 2018). The BEHI and NBS data is then used to develop a relationship with annual bank erosion rate. Both indices (BEHI and NBS) are traditionally derived from field measurements although recent advancements in remote sensing data could replace some of the field assessments.

The BANCS approach is similar to the Dynamic SedNet stream bank equation, however, the BANCS approach requires significantly more local data to determine the susceptibility of the channel boundary to erosion. Furthermore, the model requires local erosion data for calibration. Given more local data is required to inform the model development the BANCS approach may significantly improve bank erosion prediction at the reach and sub-catchment scale.

3. Discussion

None of these studies explicitly considered bank erosion impacts that may derive from increased stream flow from disturbed areas. However, several of the studies from south-west WA indicate the likely existence of relevant data that may not have been directly analysed to assess the impact of mining or forestry operations on processes that may impact on downstream sediment mobilisation or bank erosion. In particular these are:

i. Increase in instantaneous stormflows that may result in mobilisation of increased amounts of sediment downstream, and
ii. measurements of turbidity and sediment concentration themselves.

Additionally, many studies were undertaken during a period of higher rainfall than current and hence the values of changes to flow regime that may have occurred may no longer persist, at least not as the same quantity. These observations suggest that the most relevant datasets be reanalysed to distil the most recent trends, and that where possible, data from more recent periods be analysed to assess whether increases in streamflow, particularly storm flows, are still likely, and if so, whether the risk of increased stream turbidity remains.

For example, Goodman (1992) analysed salinity changes and mentioned that samples were analysed for suspended sediment but no results of these sediment measurements are reported. These data would still be available at the department and could warrant further analysis.

The observations by Loh *et al.* (1984) of increased runoff generation on haul roads and associated drain works deserve further scrutiny, and if there are still insufficient measurements should be investigated explicitly as a potential cause of turbidity, independent of the mine pit activities themselves. The importance of tracks and roads as sources of sediment and turbidity were also discussed by many authors (Campbell and Doeg, 1989; Cornish, 1980; 1981; 1983; 2001; Croke and Hairsine, 2006; Harper and Lacey, 1997). Rachels *et al.* (2020) showed the value in characterising sediments at source in order to demonstrate the origin of in-stream mobilised sediment.

Also, the observation that increased water yield was due to increased lateral subsurface flow rather than increased surface runoff or groundwater discharge should be investigated further, in the context of the discussion on the influence of soil moisture and shallow watertable presented above (Fox and Felice, 2014; Fox et al., 2007; Rockwell, 2002).

Bari and Ruprecht (2003) commented regarding the shortness of the data series available at the time, prompting the suggestion that, twenty years later, a re-analysis of the data from the experimental catchments would probably answer questions that previous analysis was unable to.

The dataset provided by Pennifold and Pinder (2011) provide a large amount of data on invertebrate biodiversity, physical and chemical properties of streams in jarrah and karri forest. It may be useful to examine these data in combination with a more detailed flow regime analysis, and to include more recent surveys, which have presumably been undertaken.

The many studies reviewed include data on streamflow and changes that occurred due to forest management, clearing or mining. However, as noted, the values reported are often given with different baseline references, that is, changes may be given as a percentage change in flow, or as a change in proportion of rainfall.

Table 1. *An attempt to reconcile the quantities given, as far as possible from the information provided, against a common baseline in each case*

	Rain long-term ave	Rain study ave (mm)	GW rise (m) RTC	GW rise (m) (actual)	Max ann Q (mm)	Max ann Q (%rain)	Inc max annQ (mm)	Inc flow %	Peak flow (mm/day equiv)	Inc Peak flow %	Max Sediment conc (mg/L)	Inc sediment conc (mg/L)	
Borg *et al.* (1987a; 1987b)	1100	1000	2-3	2-3m	200-300	25%	170	200	40-60	200-400			
Moulds *et al.* (1994)		1000	4-6	1-3	100	10%	90	900	N/R	N/R			
Abawi and Stokes (1982)	1100	1100							3.6m^3/s		>1,000	>980	
Silberstein *et al.* (2003)	1100	1100											
Loh *et al.* (1984)								30		300			
Goodman (1992)	740	680	8	-2	9	1	0.2	90	150 m3/d, 6 L/s	uncertain	N/R	N/R	
Davies *et al.* (1995)	1250	1150	N/R	N/R	470	36	40	25	4.5	100	N/R	N/R	
Bari and Ruprecht (2003)	1100		4	4			260	500			38	33	
	700		20	20									
Bari *et al.* (1994)	1040	940	4.5		290	32	150	18	10	200			
Ruprecht and Schofield (1991)	750		15-20	15-20	38	5	30	4					
Ruprecht and Schofield (1989)	1200				561	50	359	31	6434 (.07m^3/s	7000			
Ruprecht *et al.* (1991)	1300	1200	3	3	423	27	304	260	N/R	N/R	N/R	N/R	

Table 2. More details on some individual studies (from Ruprecht and Schofield (1989) reproduced the table below, following WAWA (1987)

Summary of streamflow increases of research catchments following forest reduction (from Steering Committee for Research on Land Use and Water Supply, 1987)

Catchment	Long term rainfall (mm)	Treatment	Forest reduction	Post-treatment monitoring	Average annual streamflow increase since treatment			Max annual streamflow increase		Groundwater at surface
					mm	% rain	% flow	mm	% rain	
Wights	1200	Agricultural development	PCF 100–0	1976–86	239	23.9	272	359	32.5	Yes
Lemon	800	Agricultural development	PCF 100–46	1976–83	17	2.1	279	38	4.8	No
Dons	800	Agricultural block, strip and parkland clearing	PCF 100–62	1976–83	11	1.4	286	38	4.8	No
March Rd	1070	Clearfelling and regeneration	CC 65–0	1982–85	121	11.3	147	196	18.3	Yes
April Rd North	1070	Clearfelling leaving 100 m buffers and regeneration	CC 65–0 buffer 10% of area	1982–85	104	9.7	167	155	14.5	Yes
Lewin South	1220	Selection cut and regeneration	CC 70–11 BA 44–7	1982–85	116	9.5	81	178	14.6	Yes
Yerraminnup S.	850	Logging leaving 50 m buffer and regeneration	CC 70–10 buffer 12% of area BA 44–5	1982–85	20	2.3	83	38	4.5	No
Wellbucket	700	Selection cut and regeneration	CC 38–20 BA 16–11	1977–81	2	0.3	128	3	0.4	No
Yarragil 4L	1120	Thinning	CC 55–22 BA 35–11 LAI 1.9–0.6	1983–85	17	1.9	293	31	3.1	No

CC = crown cover (%), BA = basal area ($m^2 ha^{-1}$), PCF = percentage of catchment forested, LAI = leaf area index.

4. Conclusions

It is not news that land use changes can result in major changes in streamflow volume, frequency, and intensity, and in significant impact on water quality, in nutrient, chemicals and suspended sediment. The land uses that have the biggest impacts on hydrology and sediment mobilisation are forestry, mining and agriculture. Of these, mining potentially has the biggest impact, if we are concerned with the mine pits themselves, followed by forestry coupes and agriculture. However, off-site impacts, including the issue of interest here, are much more difficult to quantify.

Key points:

- The issue covered by this review is confined to stream bank erosion and sediment mobilisation, resulting from increased stream or stream zone flows that may occur accompanying mining activities.
- This presents a lower risk than the potential turbidity impact directly from the mining disturbance area.
- The mechanisms leading to stream bank erosion and sediment mobilisation, which could indirectly occur as result of mining activity, are well understood. However, there is limited data available from south-west WA on land uses and in-stream turbidity generation and by bauxite mining in particular.
- The mitigating effect of vegetated riparian zone buffers, bank revegetation and stream channel vegetation on erosion and turbidity is well documented. Therefore, while the relative risk is recognised to be low, limited information is available to conclude the likely impact from bauxite mining.
- It is recommended that further analysis be undertaken of the data from the experiments over the last few decades to determine likelihood of increased flow under future conditions. This should include analysis of whether reports of increased rainfall intensities have eventuated or are likely to.
- A risk analysis considering extent of mining within water supply catchments should identify locations of concern. This could include application of a one of several models that predict erosion.

Bauxite mining results in increased recharge of groundwater and runoff during the forest clearing and mining phases of the operation (Croton and Reed, 2007). Following surface rehabilitation with forest species enhanced recharge persists for some years which results in increased stream flows for up to 10 years (Grigg, 2017). Standard operations *should* control runoff and sediment mobilisation on operating and former mine pits, but the controls in place may occasionally fail, or may require adjustment or maintenance over time. Further, the extent to which persistent increased stream flow, beyond the period normally associated with rehabilitation, particularly short duration peak flow events, may result in increased stream bank erosion resulting in increased turbidity is uncertain. Soil characteristics, site slope and contributing surface catchment area also have a major controlling influence on whether erosion will manifest in a particular location.

The increase in near stream erosion and resultant turbidity may occur in a number of ways.

- Firstly, and perhaps most obviously, increased flow from disturbed and treated ground may increase sediment mobilisation and hence turbidity.
- Secondly, raised watertables may discharge directly to streams or may result in greater runoff generation on wetted areas, particularly in lower slope positions.
- These wetted areas are also likely to generate more sediment mobilisation by modification to the structure and stability of the near stream material.
- Studies have noted that peak discharges often increase much more, and for longer periods after rehabilitation, than mean discharges and it is the high flow events most likely to cause bank erosion and sediment delivery to streams.
- Finally, as discussed by Fox and Felice (2014) and Fox *et al.* (2010), the increased moisture content in stream bank soils, accompanying raised groundwater, can result in a reduction in bank

stability such that bank erosion may increase, even without an increase in the size of flow events over historical levels.
- The influence of groundwater on erosion was primarily by increasing unsaturated pore-water pressures and decreasing soil shear strength in surface runoff
- At least one study has found that peak turbidity is often more related to the number of days with low flow between events than peak discharge.

However, there is also ample evidence that the retention of undisturbed stream buffers, or the introduction of vegetation into bare stream banks, will reduce sediment reaching the stream and reduce erosion of the bank itself. Even a moderate grass cover could prevent bank erosion. By retaining multiple barriers to sediment transport, through stream buffers, mine-site controls, and preservation of appropriate stream bed conditions and retention pools, the risk to reservoirs can be reduced.

There is limited availability of data from the south-west of Western Australia on sediment mobilisation and turbidity in streams indirectly resulting from land use changes relative to land use change direct source of sediment and turbidity. Evidence to date indicates that sediment loads from disturbed areas and turbidity usually settle back to pre-disturbance levels much quicker than stream flow rates. Also, while total catchment yields have usually returned to similar undisturbed levels within a few years, peak flows often seem to remain higher than the undisturbed levels for much longer, this is higher than they would be if undisturbed, and, in some studies, higher than they were before disturbance, although this latter situation clearly depends on the occurrence of high rainfall events that may not have been measured prior to the disturbance. Impact of this peak flow persistence on bank erosion has not been quantified.

The most comprehensive study on the effect of forest harvesting for timber in the south-west of W.A., was that by Borg *et al.* (1987a; 1987b) who found annual stream flow increased, relative to values in the Control catchments, and stream turbidity and sediment load increased, but only in catchments that did not have a 30 m riparian stream buffer. Peak daily flow rates after disturbance were up to three or four times the peak rates recorded prior to disturbance. Clearly, flow rates elevated to this extent could have impacts on bank stability downstream. However, undertaking a similar experiment in the jarrah forest several decades later, Kinal and Stoneman (2011) observed only very minor increase in annual stream flow. The data would need to be further examined to determine if peak flow rates had increased in a manner similar to the other studies referred to above.

Loh *et al.* (1984) observed increased runoff generation on bauxite mine haul roads and associated drain works leading to increased storm flow. There was an increase in annual stream yield of 20-30% and an increase in peak flows of 2-3 times that in un-mined conditions. The increased water yield was due to increased lateral subsurface flow rather than increased surface runoff or groundwater discharge, and this, as discussed above, may have an impact on stream bank stability and, hence, bank erosion.

The lack of local observations would suggest that, even though major erosion may be unlikely, especially given the decline in rainfall and stream flow over the last few decades, a program of monitoring and analysis should be undertaken to better quantify the likelihood of bank erosion and to develop robust methods of predicting the conditions under which this would occur in the region.

Predictions are that, under continuing climate change, despite a reduction in total rainfall, there may be an increase in intense events that may result in increased peak flows, against an overall decline in mean flows. This climatic dichotomy somewhat reduces confidence in predictions and suggests that a comprehensive analysis of data available from State agencies as well as within Alcoa should proceed and be complemented by a monitoring and research programme, that specifically includes a model testing program in the local context.

Although not directly relevant to stream bank erosion, perhaps, conditions for the onset of gully erosion in the bauxite mining areas are encapsulated in the conceptual model developed by Mengler (2008). While specific relationships varied with location, hillslope convergence and curvature, and soil characteristics, Mengler found that virtually no gullies developed when catchment contributing area was less than 0.4 ha unless slopes were steeper than 14°, or 25%. Above 0.6 ha contributing area and where steeper than 10° slope, large gullies can occur but not in all cases. With slopes less than 10° (18%), even at relatively large areas of catchment draining through a point (>1 ha) gullies are usually small. These observations are summarised in the mnemonic in Figure 1.

Using data from the bauxite mining areas, Mengler *et al.* (2007) found, with a sufficiently fine resolution DEM, that the simulation model SIBERIA (Willgoose, 2002) could predict the onset of hill side erosion, although not necessarily its precise location.

There are several other erosion models reviewed by Alluvium (2020) that warrant examination in the W.A. context namely:

- Dynamic SedNet, available in the eWater Source platform (Wilkinson et al., 2004; 2006; 2009),
- Bank Assessment of Non-point Source Consequence of Sediment (BANCS) (Bigham et al., 2018; Rosgen, 2001; 2009; 2011; Rosgen et al., 2019), and the
- HEC-RAS version of Bank Stability and Toe Erosion Model (BSTEM) should also be tested.

These models are generally used for annual or longer-term erosion studies but have been used for site specific and event specific analysis and should be examined for their utility at shorter time scales.

5. Recommendations

1. A risk assessment of likelihood of off-site erosion

While this review has identified a number of approaches to investigate the likelihood of stream bank erosion, prediction of where and under what conditions it may occur, and the processes that may exacerbate it, at the outset it is suggested that Alcoa undertake a risk assessment of the likelihood of bank erosion within the catchments of concern. This assessment would examine the extent, that is the proportion, of mining within catchments, the proximity to stream beds, slopes and contributing areas. It should also include an examination of the likelihood of increased flow intensities, given what is known and projected about future rainfall trends. This latter activity would be undertaken in parallel with the historical stream flow analysis suggested below (item 5).

2. A baseline monitoring programme

The lack of local observations would suggest that, even though major erosion may be unlikely, especially given the decline in rainfall and stream flow over the last few decades, a program of monitoring and analysis should be undertaken to better quantify the likelihood of bank erosion and to develop robust methods of predicting the conditions under which this would occur in the region. This programme would establish a baseline dataset with which to compare future measurements. This should be accompanied with a sediment characterisation, as suggested by Rachels *et al.* (2020) so that sediment delivered downstream could be attributed to the appropriate source.

This study should include stream reaches that are assessed, *a priori*, as susceptible and not susceptible to bank erosion, along with suitable stream flow and water quality monitoring in order to make an assessment of whether there is an issue or not. These reaches should be measured and monitored for the appropriate parameters of the models reviewed here, and these models tested in order to make forward projections of potential risks.

The methods outlined by Walling *et al.* (Walling et al., 2001; Walling and Woodward, 1992) would be a useful reference point.

Complementing local studies reviewed here and elsewhere, it would be worth monitoring the moisture content in stream banks with the explicit aim of determining any connection with bank erosion rates, as discussed by Fox *et al.* (2007), as changed bank moisture content may result in increased erosion during flow events even if flow rates are not greater than would be in the absence of the extra discharge. This probably could be investigated in drainages downslope of mine clearings, that is, measure soil moistures above areas with watertable rise.

3. Examine high resolution remote sensing as a means to monitor bank erosion

As part of the baseline monitoring, high resolution remote sensing could be tested to see if bank erosion can be identified within the Darling Range and bauxite mining area, in particular. If this is successful it could provide a method of assessing historical erosion, and perhaps fast track an assessment of the impact of mining and other forest operations on downstream erosion. It would also provide a method of initial testing of the performance of models.

4. Examine turbidity and inflow data to reservoirs in small Water Supply catchments

The Water Corporation collects reservoir water turbidity on a routine basis, although, in the main, these samples are taken at the outlet and near the dam wall, and hence are not likely to be closely related to stream flow events. However, for the reservoirs in smaller catchments, such as Conjurunup, Churchman Brook Dam, Logue Brook Dam, Samson Brook Dam, and Victoria Dam have small enough reservoir volumes that there may be a useful record of turbidity that could be associated with individual storm flow events that could be analysed for any turbidity response to flow rates and hence, projected increases in flow due to mining and could be assessed for their risk. These data have been requested but have not yet been delivered.

5. Renewed analysis of existing datasets from experimental catchments

Grigg (2017) did not consider erosion nor stream turbidity in his analysis, and did not appear to consider instantaneous peak flows, but these instantaneous flow data would be available in the dataset analysed and there may be some turbidity data also. Many of the studies reviewed here include intensive measurements of flow and turbidity that may contain information not presented in the reports. In particular, examination of the occurrence of intense flow events, and their frequency may improve our understanding of the risk. It is recommended that further analysis of these data be included in the activity currently underway. These should be examined for useful learnings.

6. Examine literature and data on rainfall intensity and future trends.

The overall climate trend of the last 50 years, and projected to continue, is a reduction in mean rainfall. However, there are also reports of increased rainfall intensities in short duration events. It is suggested that a literature review be undertaken to expressly determine if this is a real likelihood. In the absence of sufficient reports, short duration rainfall data can be analysed to determine whether there has been a systematic change in high intensity events, against the overall reduction[1].

7. Examine existing erosion models for applicability here

This review has identified a number of models that attempt to predict the location and intensity of sediment mobilisation from different parts of a catchment and stream bank. It is recommended that a targeted review of these models assess their appropriateness for the bauxite mining area, assessing their data requirements, relevant scale of prediction, in both space and time, and their process representation.

It is suggested that the first step in any modelling exercise be to explore the conceptual model of Lawler (1995) which would give a rapid means of exploring the likely parameter space of sediment mobilisation in our region.

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A. Appendix – Outline of erosion conceptual model DOCPROBE: DOwnstream Change in PRocesses Of Bank Erosion

Lawler (1995) presented a relatively simple conceptual model (DOCPROBE: DOwnstream Change in PRocesses Of Bank Erosion) that predicts the effect of scale on stream bank erosion processes and demonstrates that in small upland catchments, sub-aerial processes are most significant in facilitating bank erosion, because the stream power is rarely adequate in the upper reaches to dislodge material.

A.1 Direct fluid entrainment processes

Entrainment of bank particles closely relates to the boundary shear stresses, which can be loosely approximated by stream power variations. Bankfull stream power, Ω(W m^{-2}), is:

$$\Omega = pgQS \qquad (1)$$

in which p is fluid density (1000 kg m^{-3}), g is gravitational acceleration (9.81 m s^{-2}), Q is bankfull discharge (m^3s^{-1}) and S is energy slope (m m^{-1}). If p and g are constant downstream, combining the functions for change in Q and S yields an equation for downstream change in Q. In the following numerical experiments, discharge is a power function of channel length, L (km) and:

$$Q = kL^m \qquad (2)$$

and slope is made a negative exponential function of L (Rana et al., 1973):

$$S = Soe^{-rL} \qquad (3)$$

in which S is channel slope and r is the coefficient of slope reduction. Multiplying gives:

$$QS = (kL^m)\ (S_oe^{-rL}) \qquad (4)$$

which, when differentiated, yields the downstream rate of change of the stream power index:

$$\delta(QS)/\ \delta L = (mkL^{m-1})(S_oe^{-rL}) + (kL^m)(-rS_oe^{-rL}) \qquad (5)$$

or:

$$\delta(QS)/\ \delta L = kL^m S_0e^{-rL}\ [(m/L) - r] \qquad (6)$$

Equation (4) describes an inverted "U", suggesting low stream power in headwater reaches, peaks in mid-basin and small values further downstream. We can also determine critical channel length, L_c, at which stream power peaks, where $\delta(QS)/\delta L = 0$. As only the bracketed expression in equation (6) can be zero, this is the only term set to zero. Thus:

$$L_c = m/r \qquad (7)$$

which is simply the ratio of the two rates of change of the component relations (equations (2) and (3)).

The result leads to the following general characteristic:

- in upstream reaches of low stream power and low banks, sub-aerial preparation processes are most effective;
- in the middle courses, stream power peaks and fluid entrainment prevails;
- in low reaches, bank heights achieve critical values and mass failure dominates.

B. Appendix - Research Catchments across south-west WA

B.1. Clearing for Agriculture

Catchment	Catchment area (km^2)	Mean annual rainfall (mm)	Treatment
Wights	0.94	1120	100% cleared
Salmon	0.82	1120	Control – Open jarrah forest
Ernies	2.70	820	Control – Open jarrah forest
Lemon	3.44	820	Lower 53% cleared, remaining 47% open jarrah forest
Dons	3.50	800	Parkland clearing 4%, strip clearing 20%, soil unit clearing 14%, remaining area open jarrah forest

B.2. Timber harvesting

Catchment	Catchment area (km^2)	Rainfall zone	Treatment
Lewin South	0.9	High	Heavy selection cut of jarrah/marri, karri gully clearfelled – no stream buffer
Lewin North	1.13	High	Control – jarrah/marri, and karri forest
April Road South	1.79	Intermediate	Control - Jarrah, marri and karri forest
April Road North	2.48	Intermediate	Jarrah, marri and karri forest clearfelled and then replanted with karri – stream buffer retained
March Road	2.61	Intermediate	Clearfelled and then replanted – no stream buffer retained
Yerraminnup South	1.83	Low	Heavy selection cut jarrah forest – stream buffer retained
Yerraminnup North	2.53	Low	Control – jarrah forest
Wellbucket	4.65	Low	Heavy selection cut of jarrah forest – stream buffer retained

B.3. Forest Thinning

Catchment	Catchment area (km^2)	Rainfall zone	Treatment
Hansen	0.78	High	Uniform thinning, reducing basal area from 35 to 7 m^2 ha^{-1}
Higgens	0.60	High	Uniform thinning, reducing basal area from 37 to 14 m^2 ha^{-1}
Jones	0.69	High	Operational thinning, reducing basal area from 43 to 17 m^2 ha^{-1}
Gordon	2.09	Intermediate	Control - Forest
Bates	2.70	High	Control
Yarragil 4L	1.28	Intermediate	Operational thinning
Yarragil 6C	4.58	Intermediate	Intensive treatment
Yarragil 4X	2.73	Intermediate	Operational thinning
Wuraming	4.4	Intermediate	Control - Forest
Lewis	2.01	High	Control, later mined for bauxite
Cobiac	3.64	Intermediate	66% of catchment thinned, reducing basal area from 26.4 to 15.7 m^2 ha^{-1}
Chandler Road	17.50	Intermediate	25% of catchment previously mined and rehabilitated 55% of catchment thinned (predominantly bauxite mining rehabilitation) resulting in reducing basal area from 26 to 16 m^2 ha^{-1}

B.4. Bauxite Mining

Catchment	Catchment area (km^2)	Rainfall zone	Treatment
Waterfall Gully	8.74	High	Control - Forest
Seldom Seen	7.53	High	Treated - Mined from 1969 to 1994
More Seldom Seen	3.2	High	Treated - Mined from 1969 to 1994
Del Park	1.31	High	Treated
Warren	0.87	High	Treated
Bennetts	0.88	High	Treated
Lewis	2.01	High	Treated
West Cameron	1.87	Intermediate	Treated – 33% cleared for mining
Central Cameron	4.73	Intermediate	Treated – 27% cleared for mining

Gordon	2.13	Intermediate	Control - Forest
Jayrup	45.8	Intermediate	Treated – 13% cleared for mining
Tunnel Road	2.07	Low	Treated
Bee Farm Road	1.81	Low	Control - Forest