



Government of Western Australia
Department of Water and Environmental Regulation

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



Salinity and land use impacts series report no. 66
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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 km² 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 (Petroni 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 km², 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.

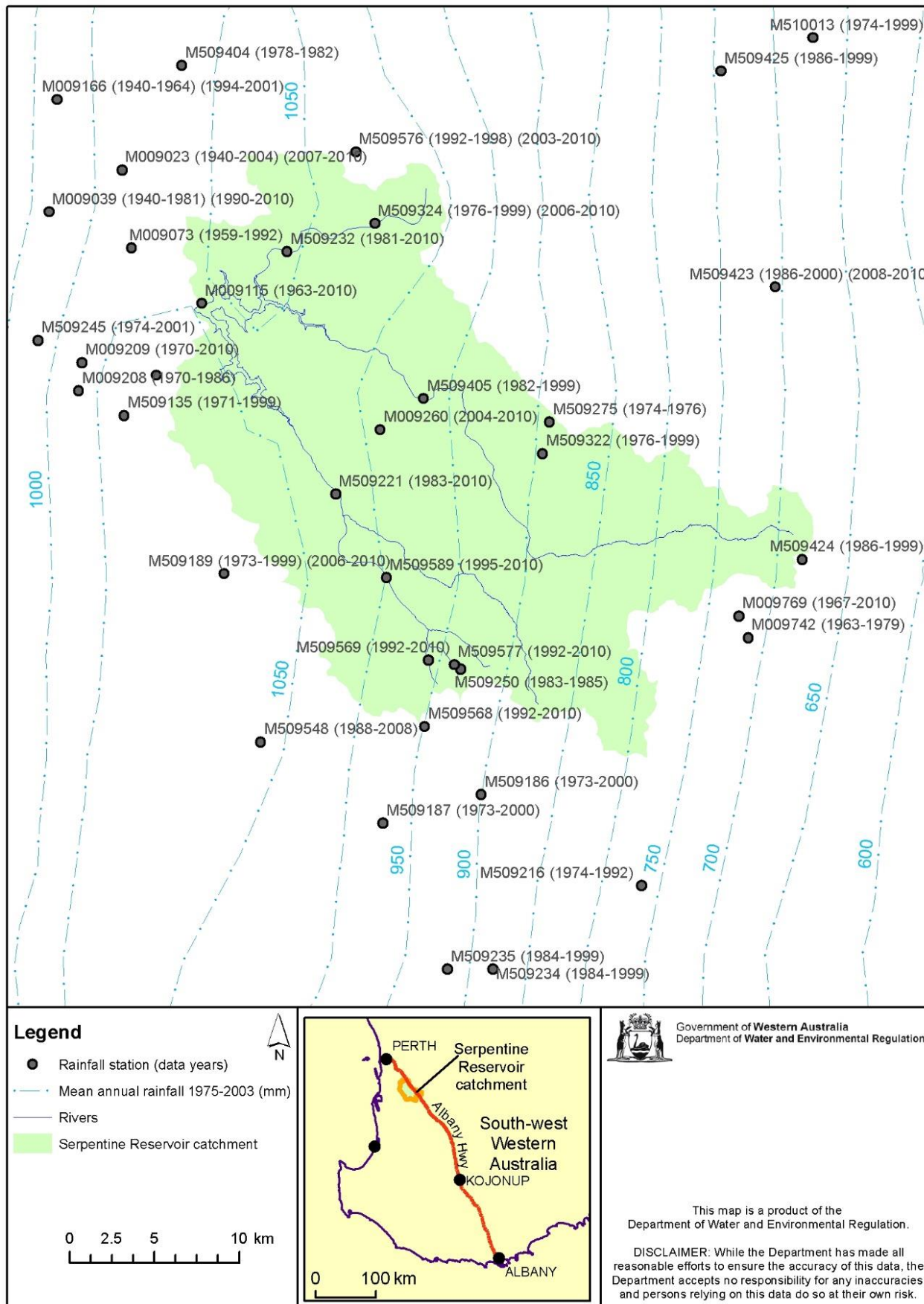


Figure 1 Location and rainfall of the Upper Serpentine catchment

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).

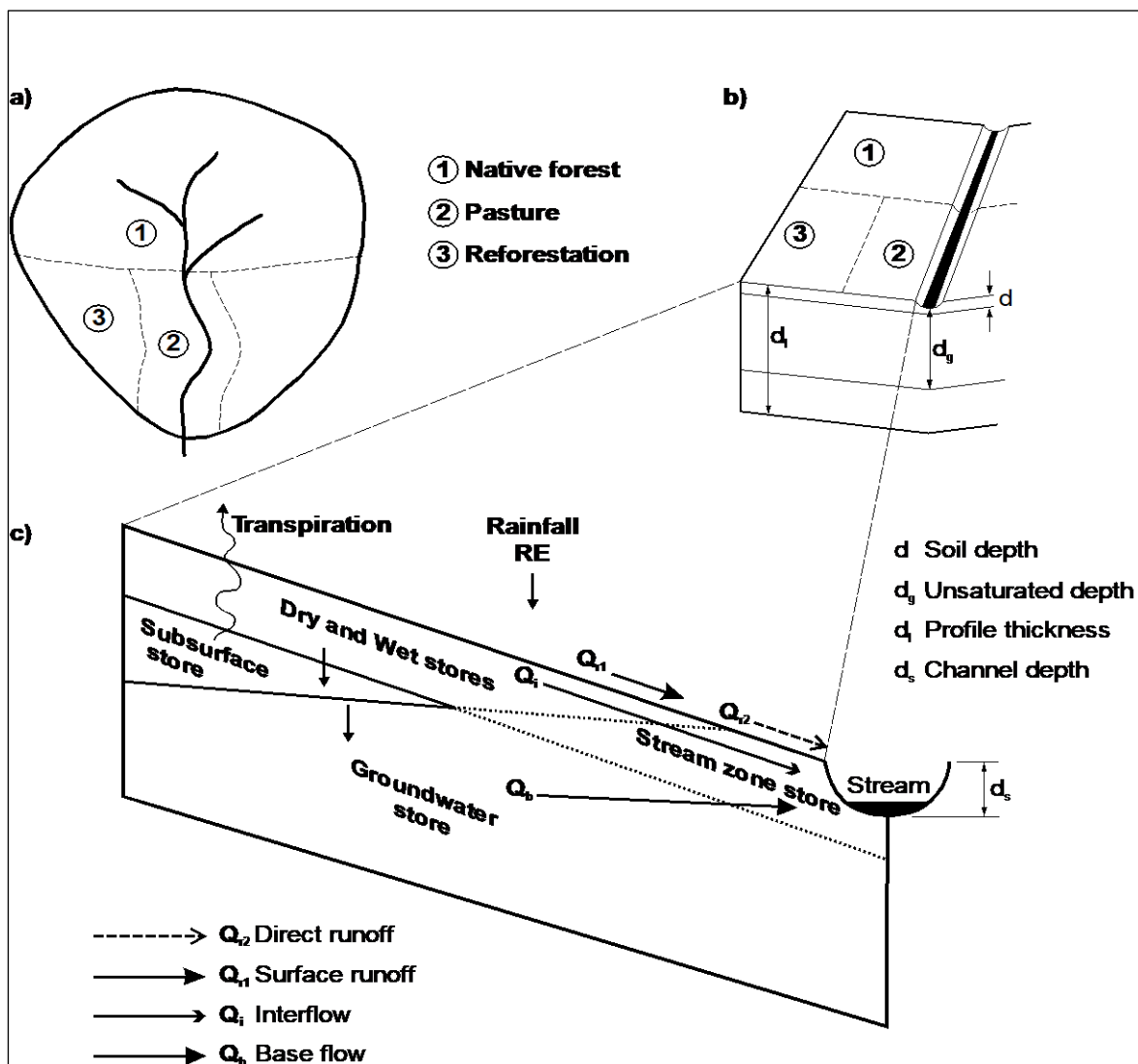


Figure 2 Schematic of the LUCICAT model showing a) a response unit or sub-catchment, b) 'open book' representation, and c) hydrological processes and sources of streamflow

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 km² (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.

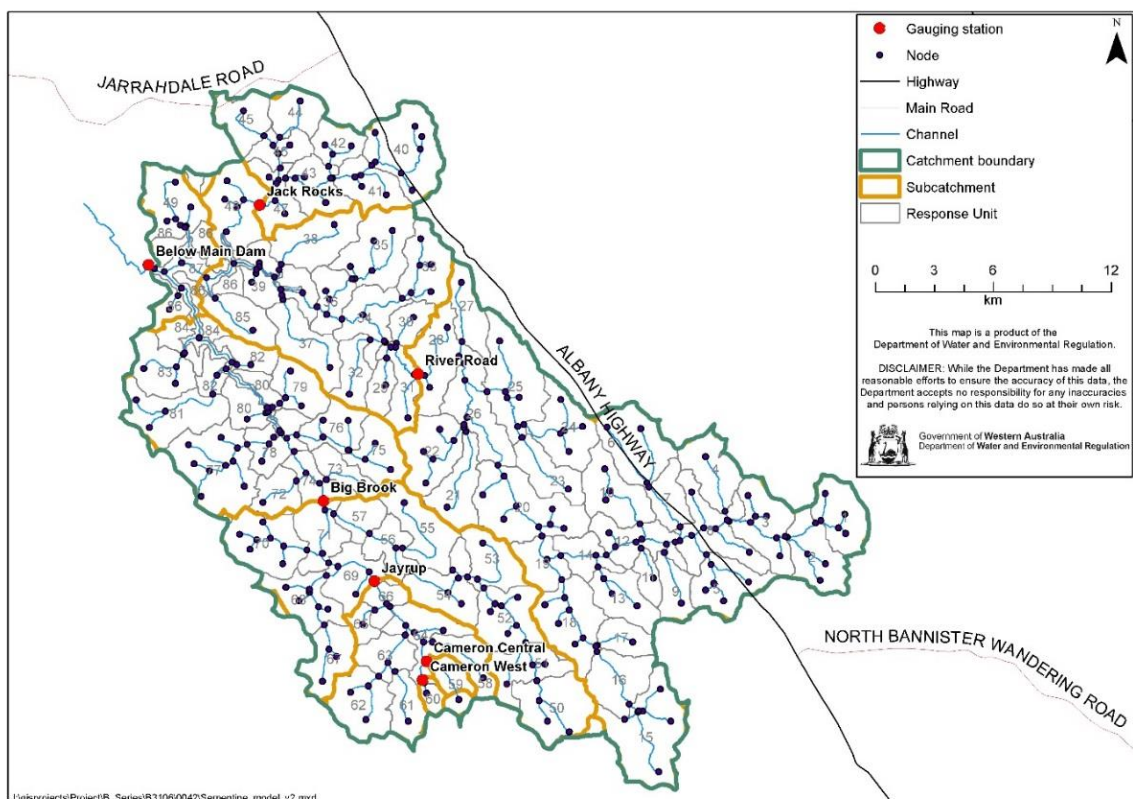


Figure 3 Response units and channels used in the LUCICAT model. Sub-catchments within the Upper Serpentine defined by gauging stations, termed reporting nodes, are also shown

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.

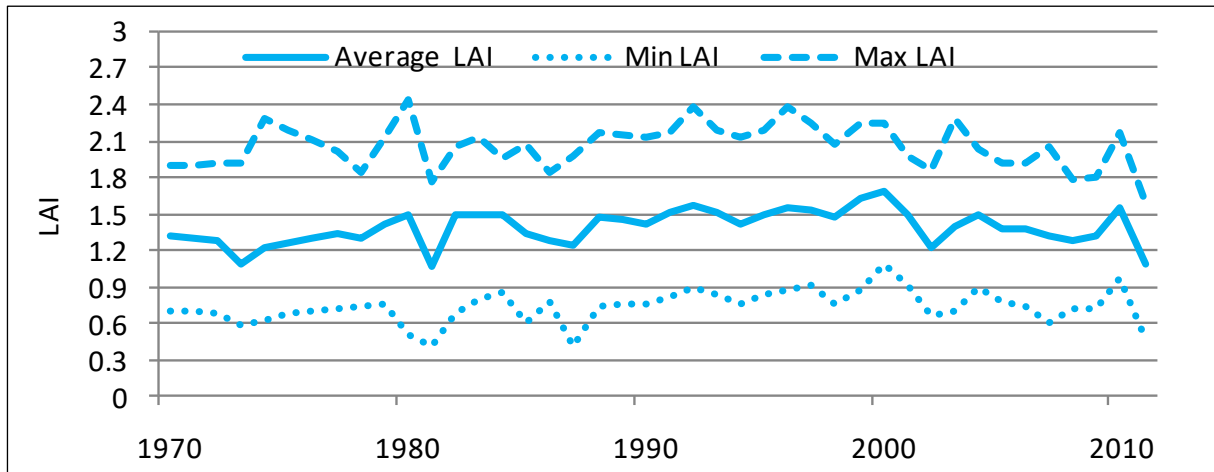


Figure 4 Average, minimum and maximum LAI of all Response Units in the Upper Serpentine catchment (1970–2011)

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 (km ²)
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):

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

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:

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

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 $< \pm 25\%$
- 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 (Figure 7b) 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.

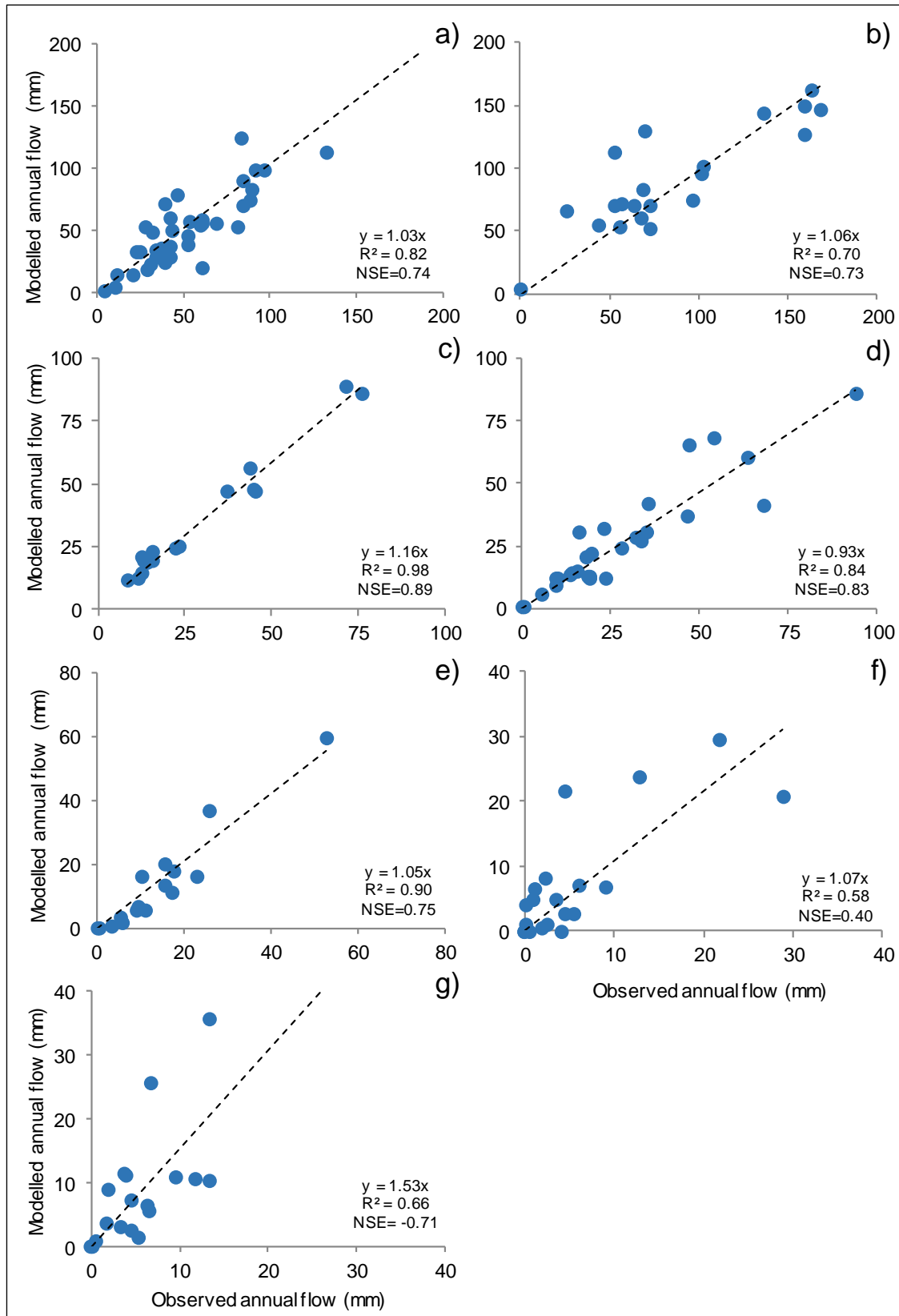


Figure 5 Regression plots and objective function statistics for comparisons of observed and LUCICAT-modelled annual flows for a) Serpentine reservoir, b) Jack Rocks, c) River Road, d) Big Brook, e) Jayrup, f) Cameron West and g) Cameron Central gauging stations

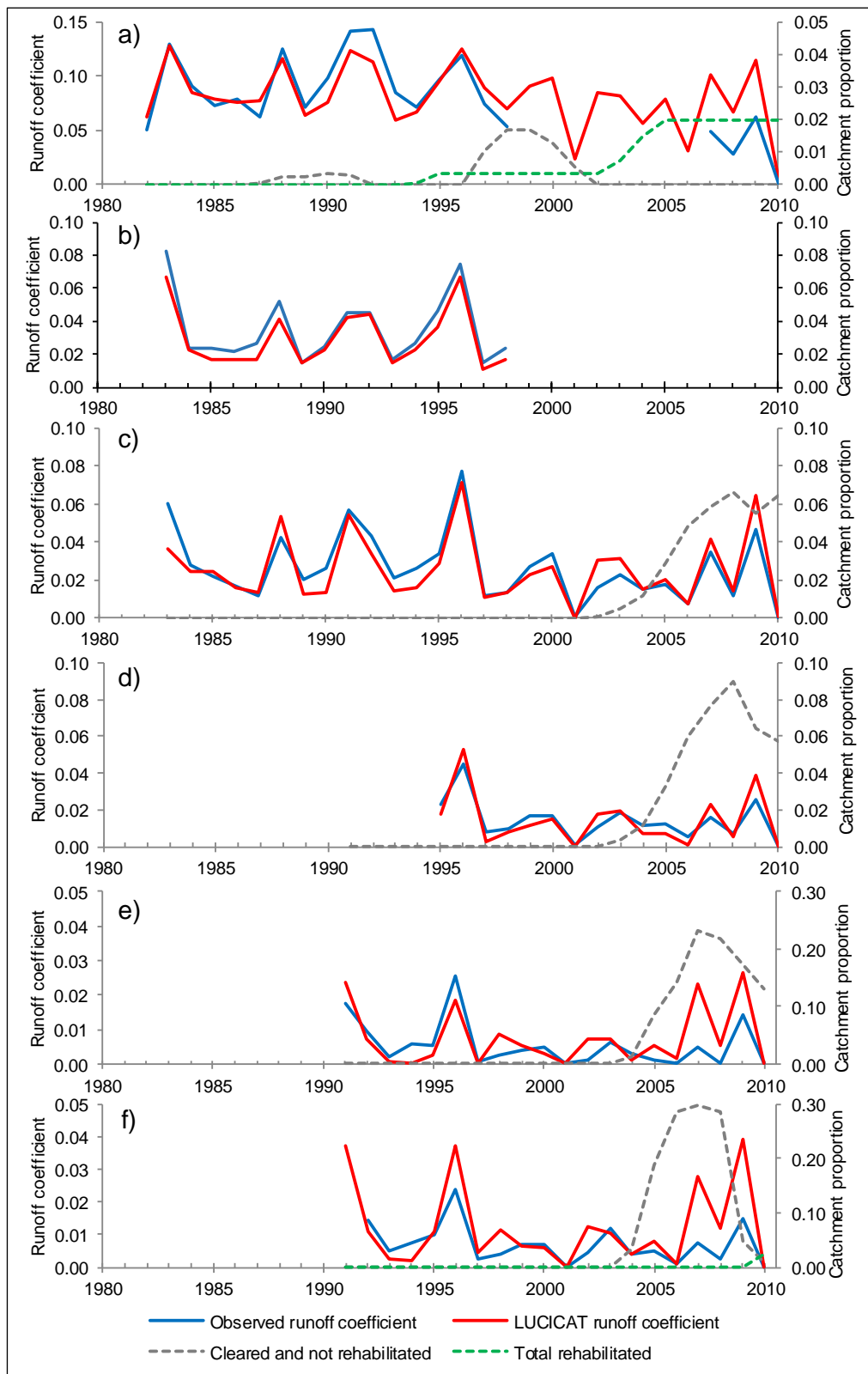


Figure 6 Comparison of LUCICAT-modelled and observed runoff coefficients at a) Jack Rocks, b) River Road, c) Big Brook, d) Jayrup, e) Cameron West and f) Cameron Central. Also shown is the proportion of the catchment affected by clearing for mining and not yet rehabilitated and the proportion of the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

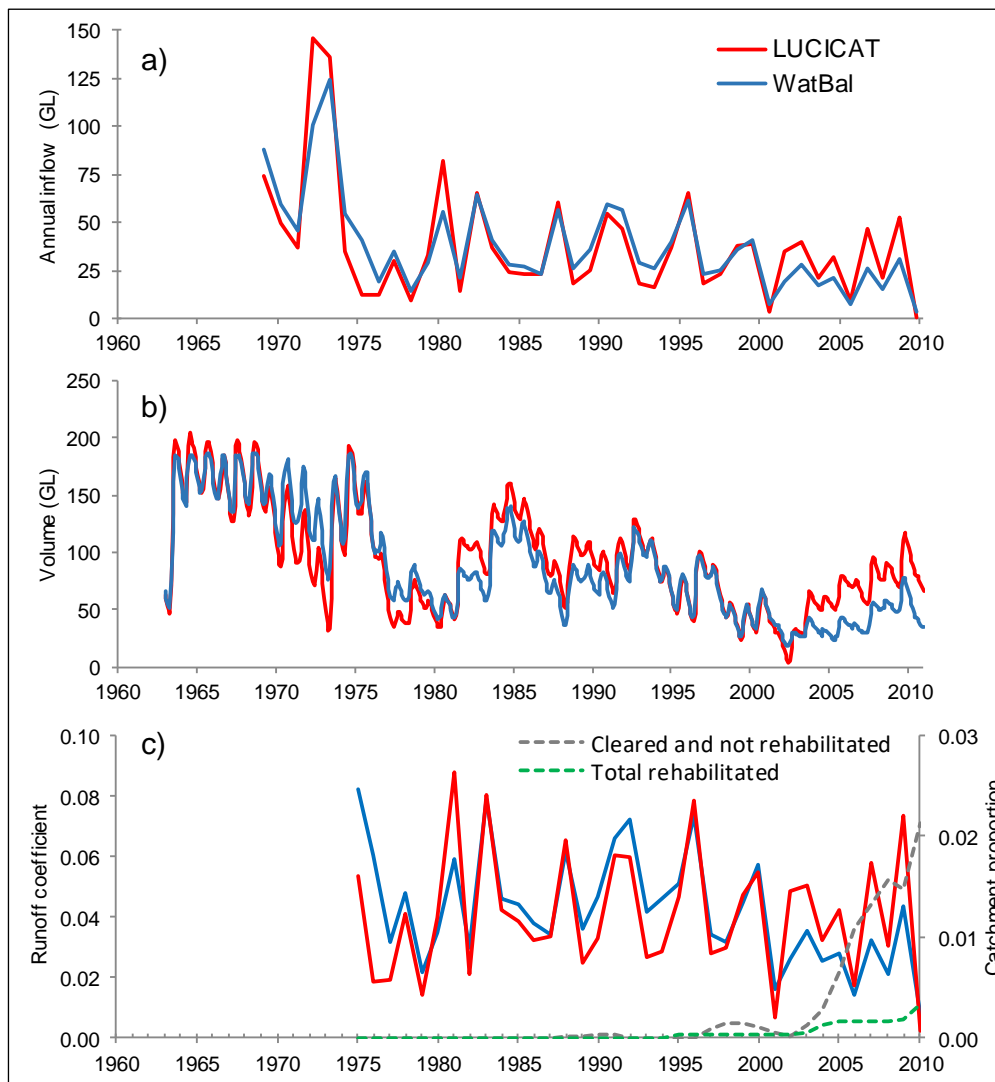


Figure 7 Comparison of a) annual inflows, b) monthly storage volumes and c) runoff coefficients from LUCICAT modelling and a dam water balance model estimate (WatBal) for the Serpentine Reservoir. Also shown in c) is the proportion of the catchment affected by clearing for mining and the proportion of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

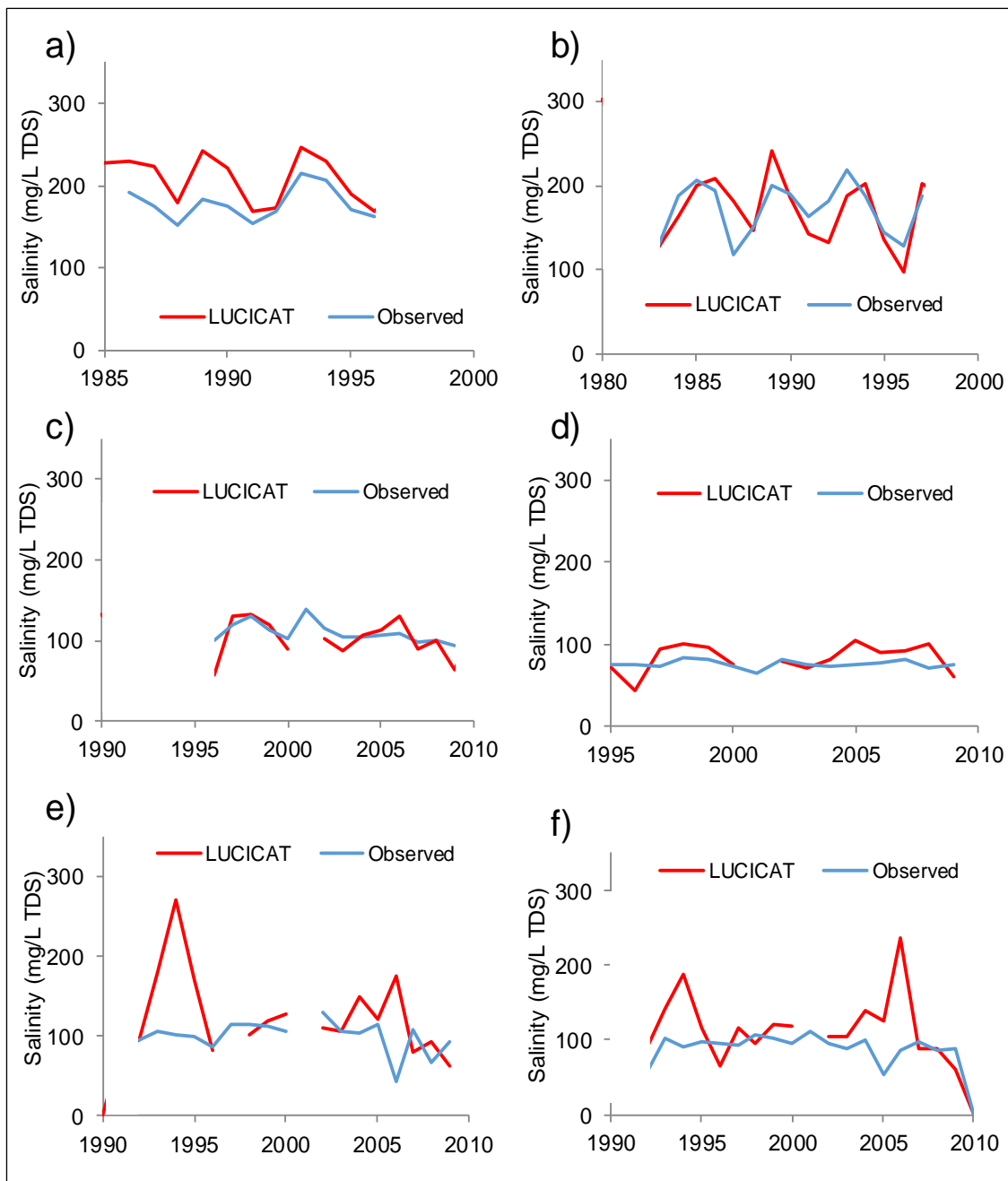


Figure 8 Annual salinity comparisons for a) Jack Rocks, b) River Road, c) Big Brook, d) Jayrup, e) Cameron West and f) Cameron Central

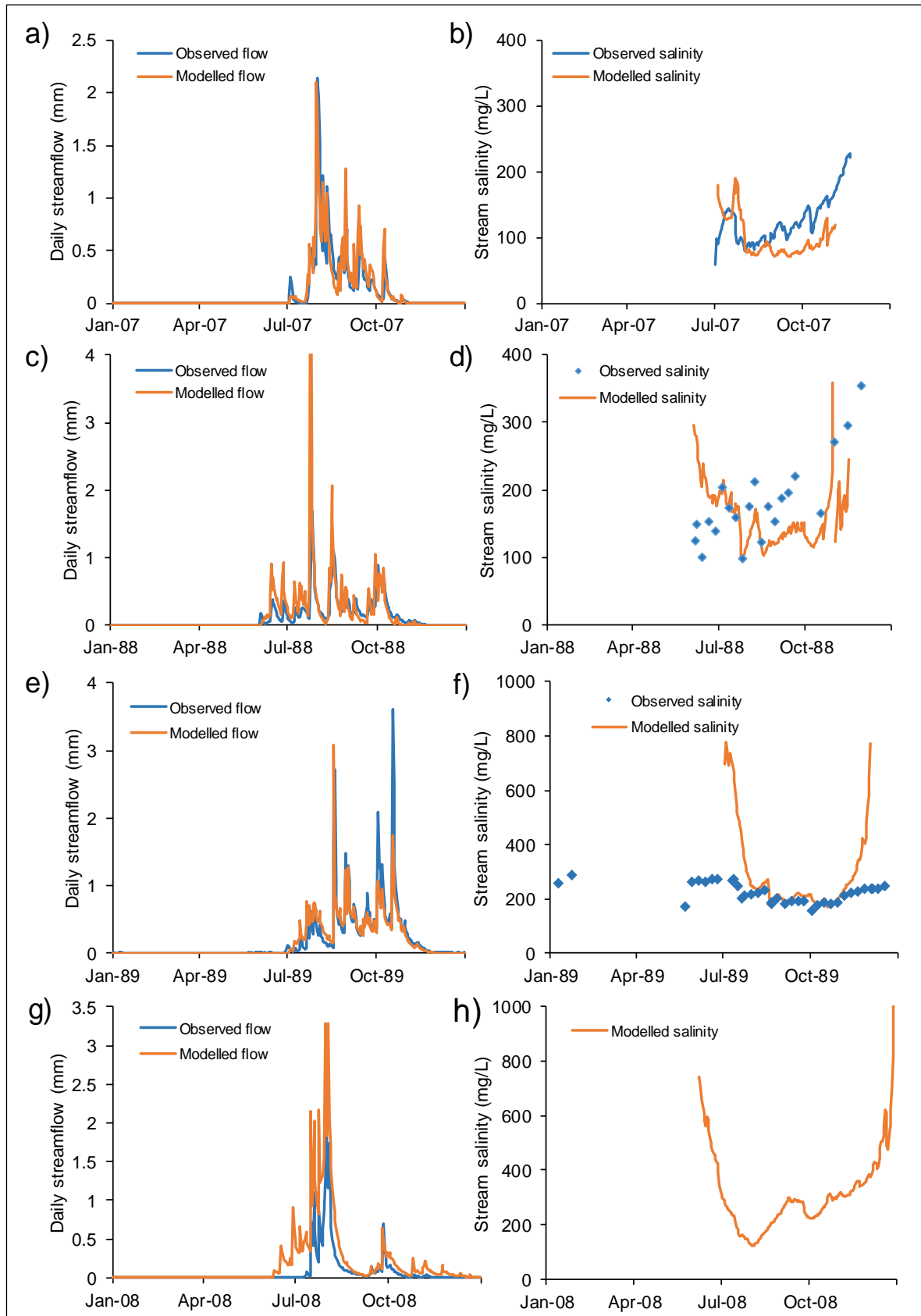


Figure 9 Daily flow and stream salinity hydrographs for (a, b) Big Brook in 2007, (c, d) River Road in 1988, (e, f) Jack Rocks in 1989 and (g, h) Jack Rocks in 2008

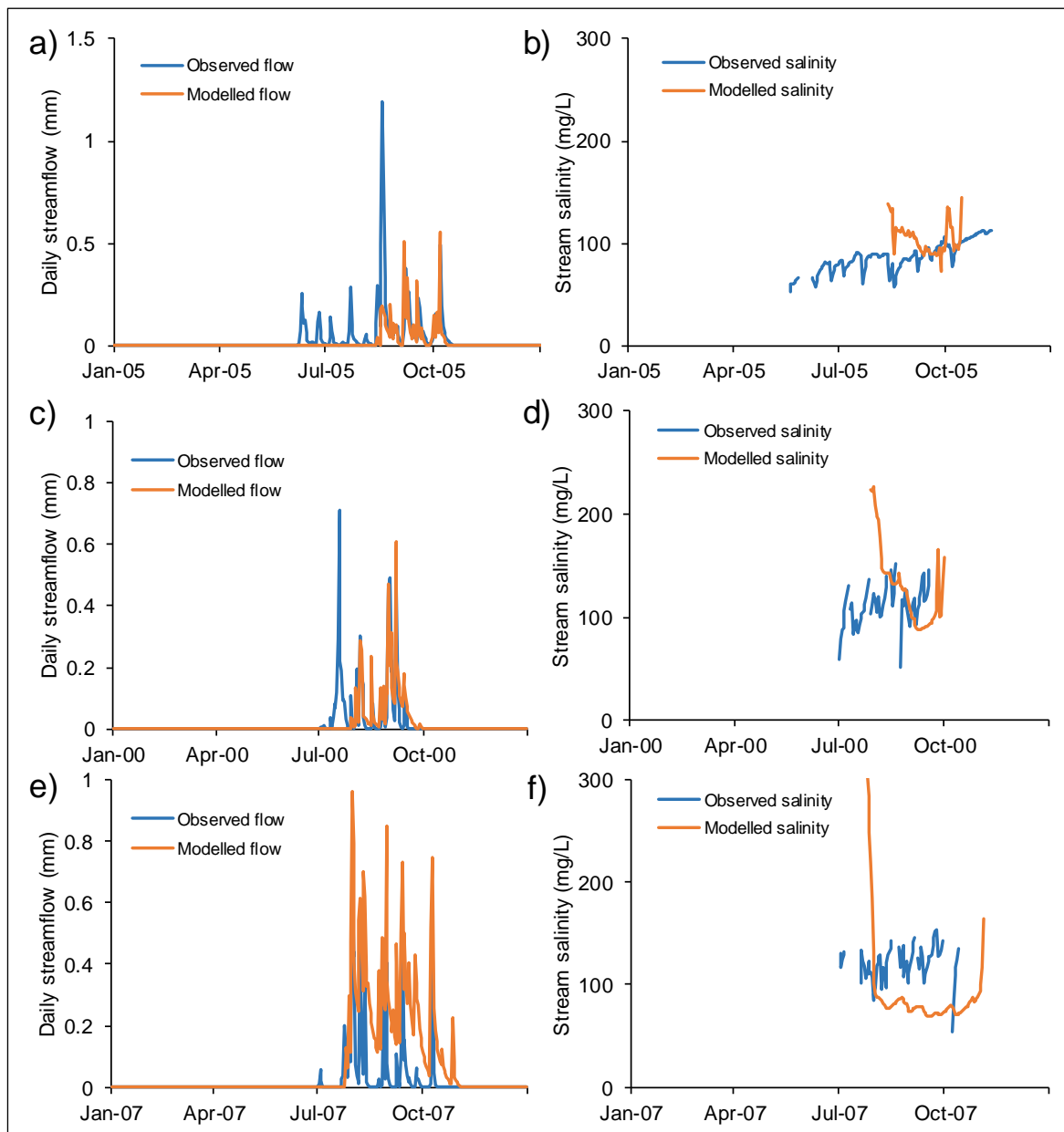


Figure 10 Daily flow and stream salinity hydrographs for (a, b) Jayrup in 2005, (c, d) Cameron Central in 2000 and (e, f) Cameron Central in 2007

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).

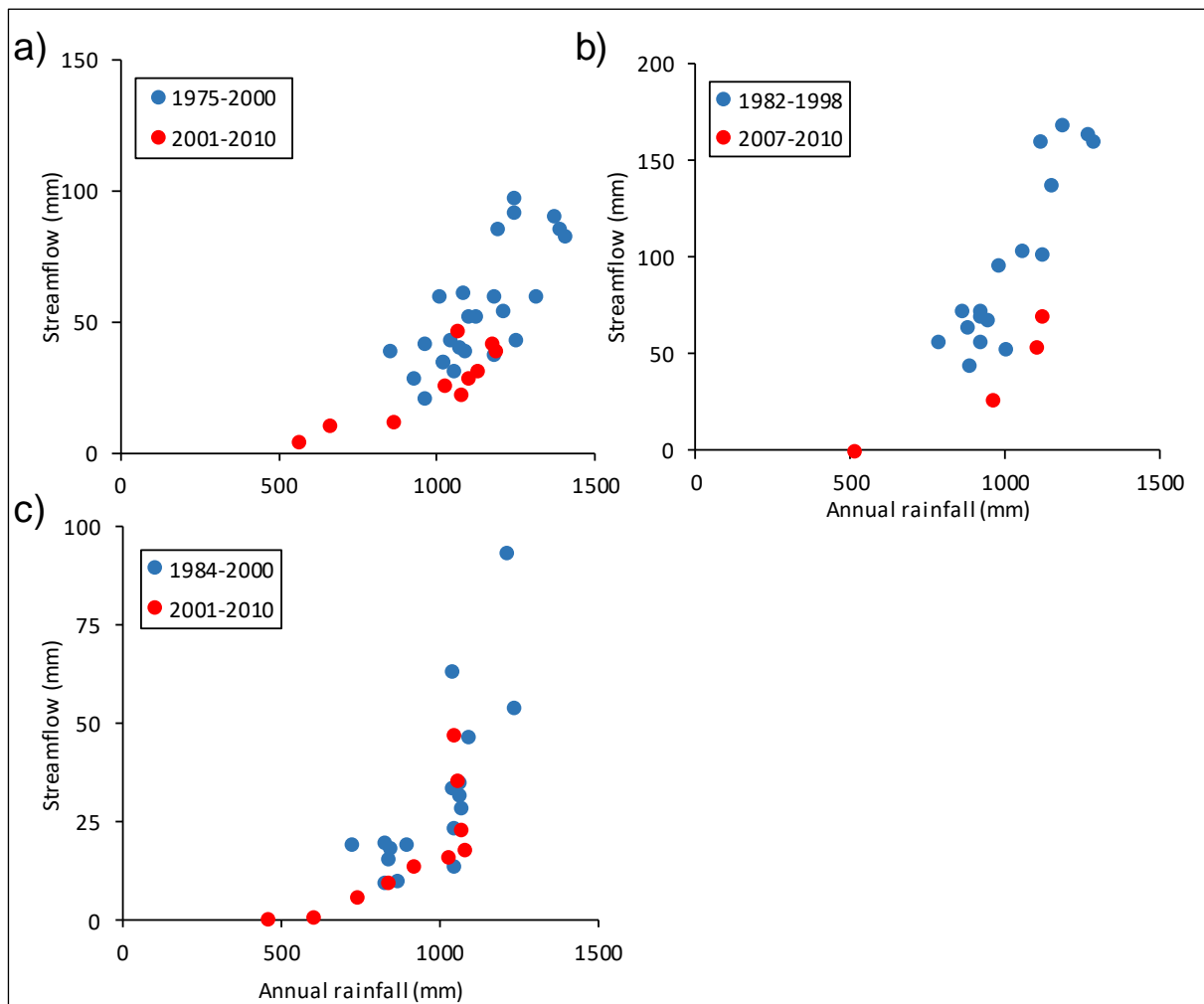


Figure 11 Relationship between annual rainfall and streamflow for a) Serpentine Reservoir, b) Jack Rocks and c) Big Brook catchment. Note that in b) complete annual flow was not recorded for the years 1999-2006

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 km² (Table 4) or 12 per cent of the total catchment. A smaller footprint of 62 km² (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 overstorey 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

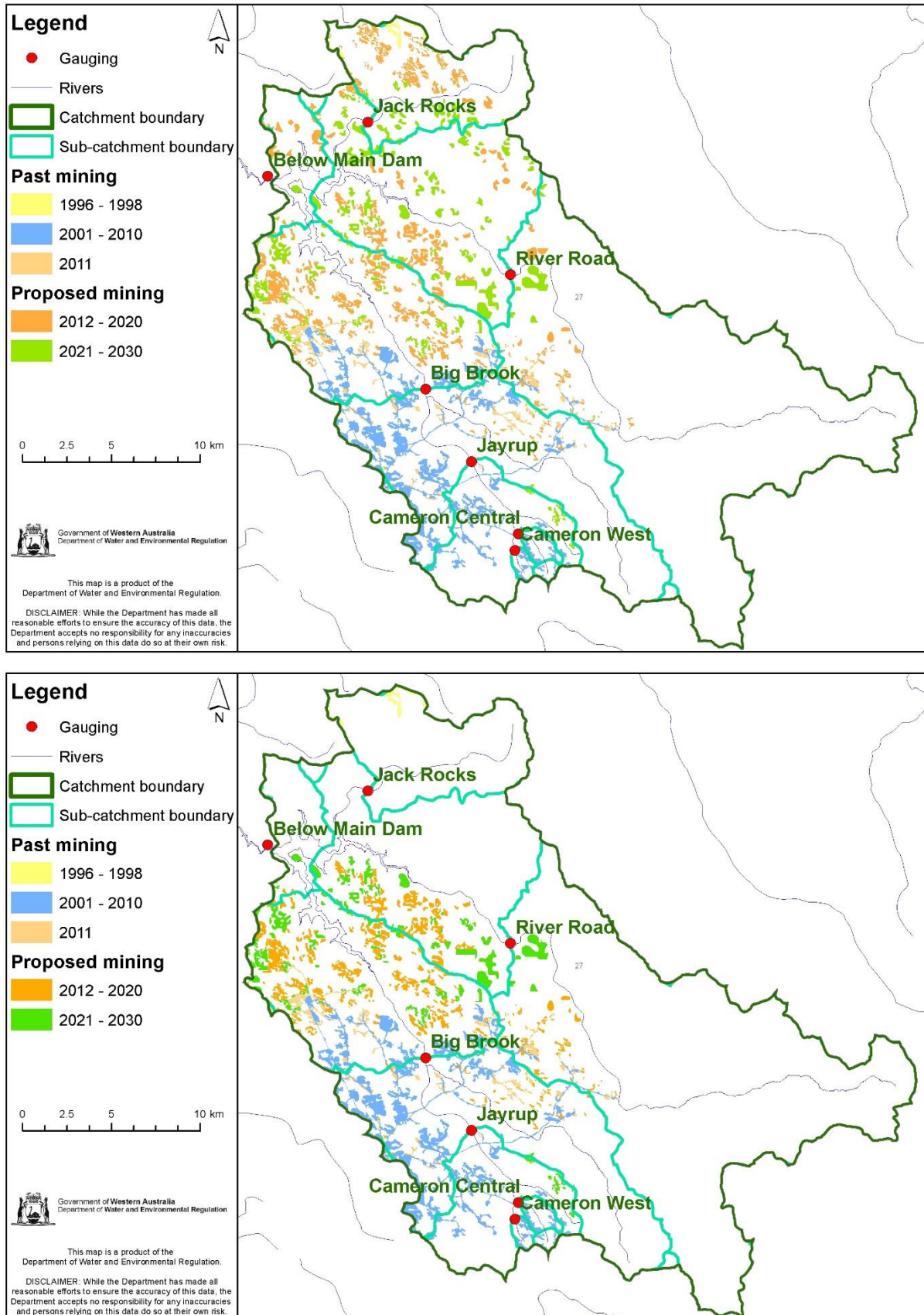


Figure 12 Existing (pre-2011) and proposed future mining areas in the Upper Serpentine catchment for a) Case A and b) Case B

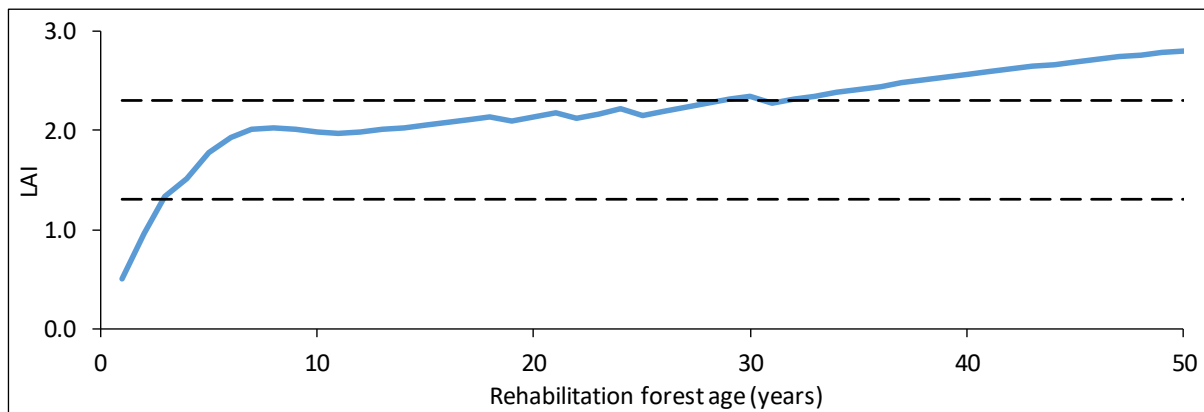


Figure 13 Assumed growth curve for rehabilitated jarrah forest. The dotted lines indicate the range in LAI of typical unmined jarrah forest at the plot scale

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).

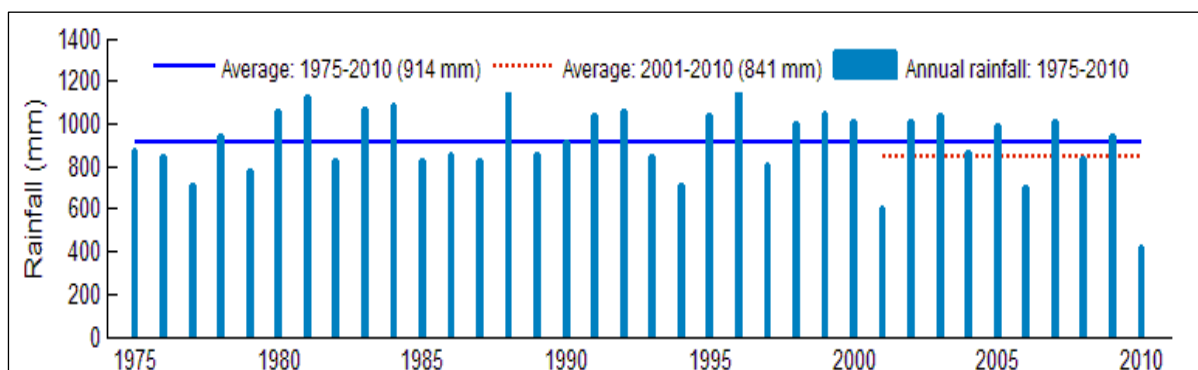


Figure 14 Time series of estimated annual rainfall at the centroid of the Upper Serpentine catchment

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.

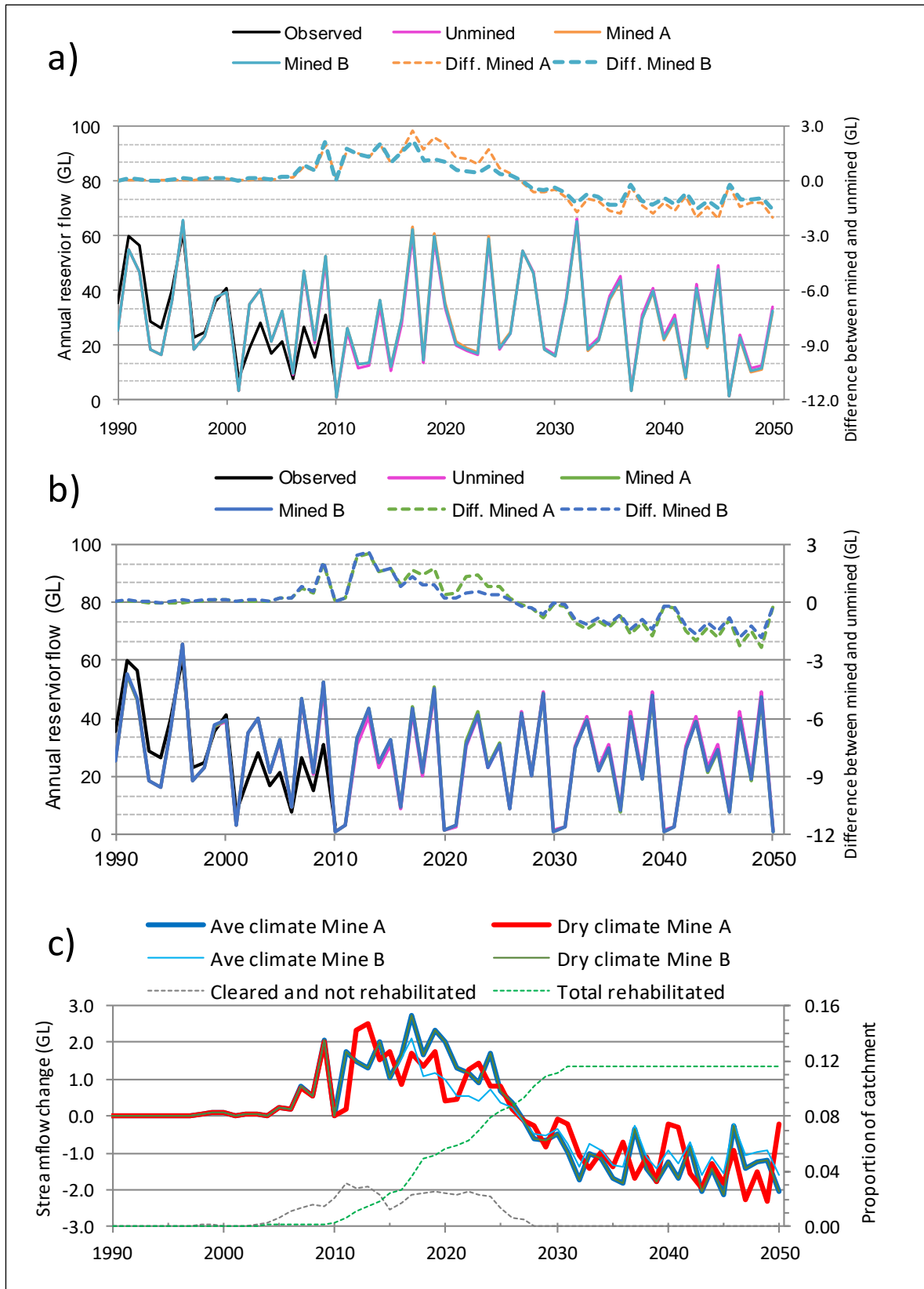


Figure 15 Projected annual inflows to the Serpentine Reservoir and inflow differences for two mining scenarios relative to an unmined case for a) a future 'average' climate, b) a future 'dry' climate and c) inflow differences between scenarios showing mining and rehabilitation in the catchment

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.

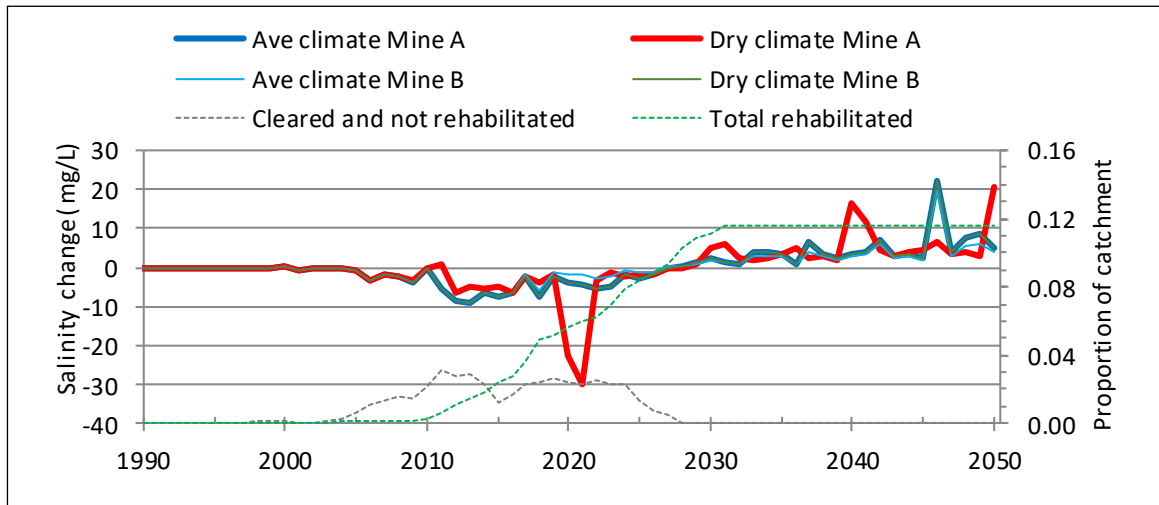


Figure 16 Changes in salinity inflow to the Serpentine Reservoir between unmined and mined scenarios

6 Conclusion and recommendations

The LUCICAT model was successfully applied to the Upper Serpentine catchment, a large (664 km²) 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_{II})
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)
UZWMI	0.080000	mm/mm	Dry Store water content threshold
UZWMI_IN	0.300000	mm/mm	Dry store maximum initial water content
UZWMI	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_F ACTOR	0.00000		Multiplier of farm dam capacity for annual demand (-)
PAN_MORT_FACT OR**	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
km²	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 (<i>Eucalyptus marginata</i>)
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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