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:
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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 This material has been collated from published scientific literature, departmental and industry reports, and unpublished data and internal reports in commercial, academic and government departments.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.

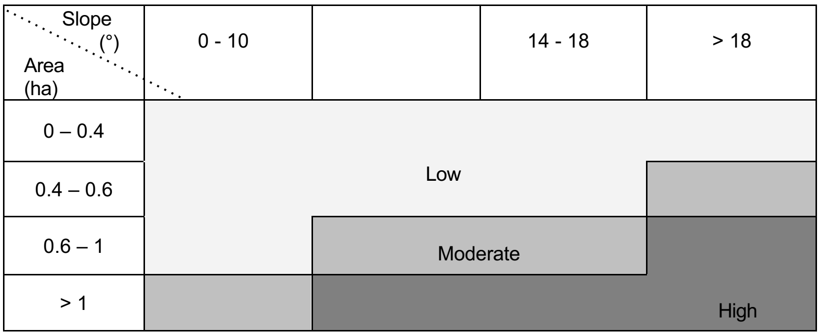
Mauger *et al.* (1998) reviewed research on hydrological effects of bauxite mining undertaken to 1997. However, this review does not mention the words “turbidity” or “erosion”, except in citing a reference to a technical report on minimising erosion on mine pits and gives no specific data relevant to 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.



Slope (°) / Area (ha)	0 - 10		14 - 18	> 18
0 – 0.4	Low	Low	Low	Low
0.4 – 0.6	Low	Low	Low	Moderate
0.6 – 1	Low	Moderate	Moderate	High
> 1	Moderate	High	High	High

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.

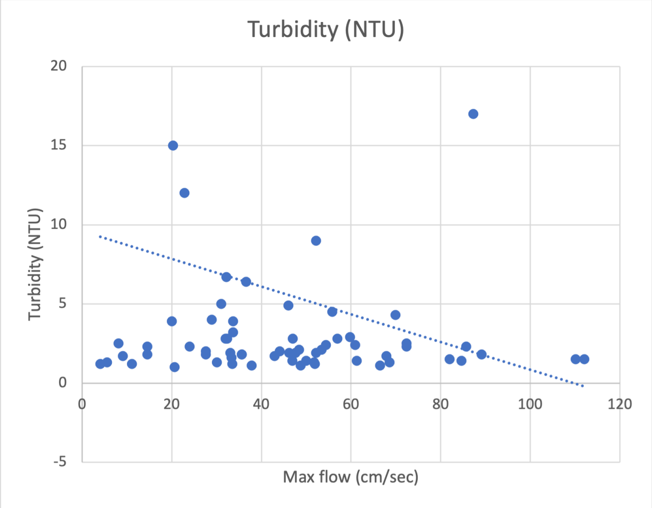


Figure 2. Turbidity against maximum stream velocity in rivers assessed by Pennifold and Pinder (2011). This figure is for illustration, and does not show a robust causal relationship but is indicative the complexities that may exist in the interconnections between different stream condition indicators.

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.

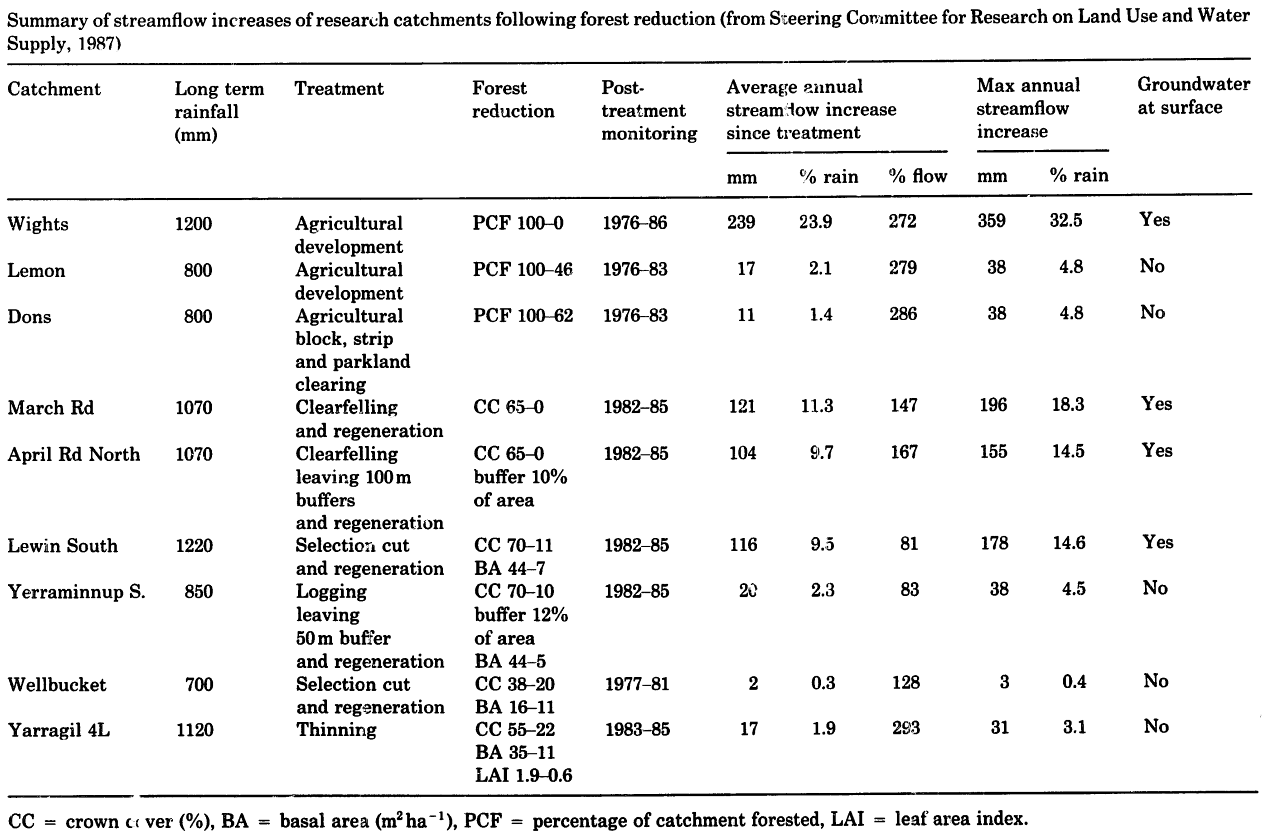
The dataset provided by Pennifold and Pinder (2011) provide a large amount of data on invertebrate biodiversity, physical and chemical properties of streams in jarrah and karri forest. It may be useful to examine these data in combination with a more detailed flow regime analysis, and to include more 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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[1] I have sent a query to Steve Charles at CSIRO asking this question.

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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:

$$\Omega = pgQS \tag{1}$$

in which p is fluid density (1000 kg m^{-3}), g is gravitational acceleration (9.81 m s^{-2}), Q is bankfull discharge (m^{3}s^{-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:

$$Q = kL^m \tag{2}$$

and slope is made a negative exponential function of L (Rana et al., 1973):

$$S=S_oe^{-rL} \tag{3}$$

in which S is channel slope and r is the coefficient of slope reduction. Multiplying gives:

$$QS = (kL^m)\ (S_oe^{-rL}) \tag{4}$$

which, when differentiated, yields the downstream rate of change of the stream power index:

$$\delta(QS)/\ \delta L = (mkL^{m-1})(S_oe^{-rL}) + (kL^m)(-rS_oe^{-rL}) \tag{5}$$

or:

$$\delta(QS)/\ \delta L = kL^mS_oe^{-rL}\ [(m/L) - r] \tag{6}$$

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:

$$L_c = m/r \tag{7}$$

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