Appendix 54 Hydrology and Bauxite Mining on the Darling Plateau

Hydrology and Bauxite Mining on the Darling Plateau

James T. Croton[1,2] and Amanda J. Reed[3]

Abstract

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

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

Introduction

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

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

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

The Darling Plateau

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

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

[1] Water & Environmental Consultants, 28 Orpheus Street, Robertson 4109, Australia
[2] Address correspondence to J. T. Croton, email jcroton@bigpond.net.au
[3] Alcoa World Alumina Australia, PO Box 172, Pinjarra 6208, Australia
Conflict of Interest Statement: J.T. Croton is a consultant to Alcoa. A. J. Reed is a paid employee of Alcoa.

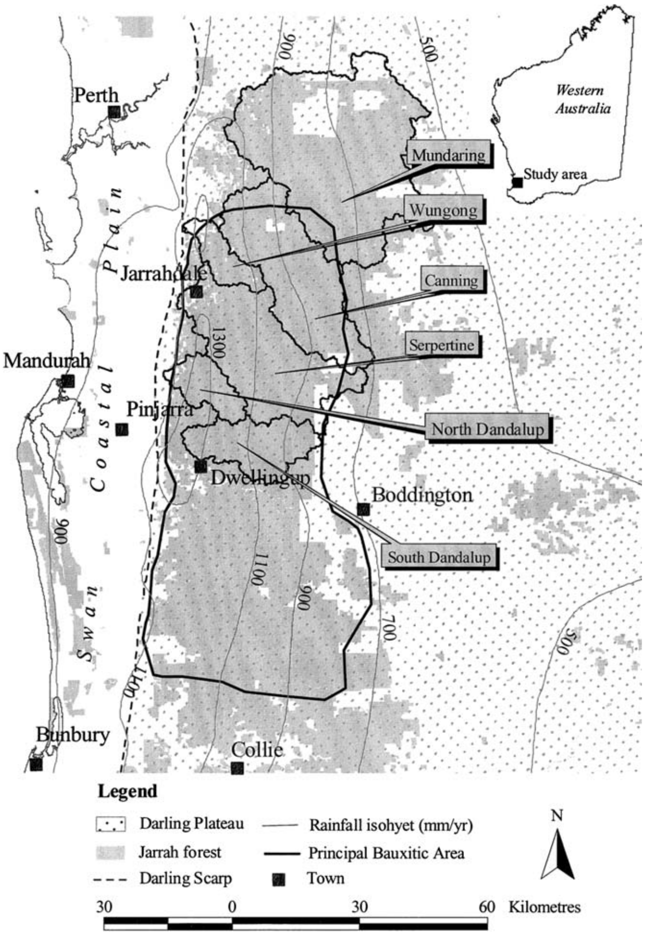

Figure 1. Locality plan for the Darling Plateau with rainfall isohyets, water supply catchment boundaries, and the principal bauxitic area. After Bartle and Slessar (1989).

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

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

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

From Water Corporation (2005).

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

Streamflow and Salinity

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

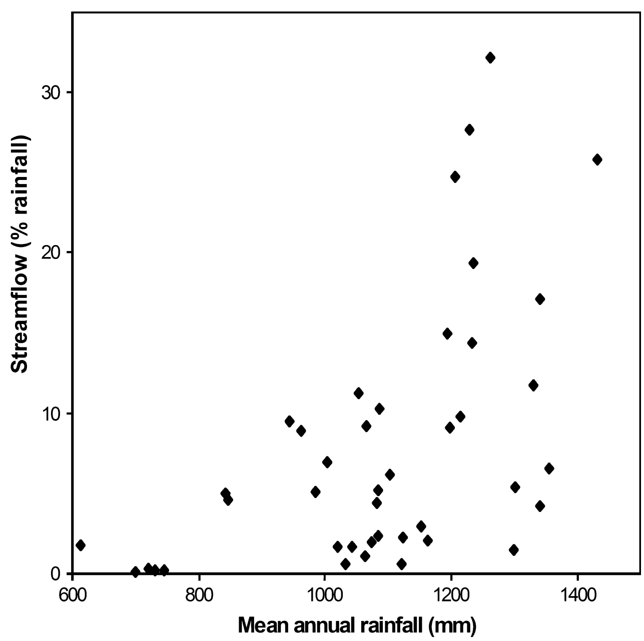

Figure 2. Comparison of rainfall versus streamflow for Jarrah forested catchments. From Schofield et al. (1989).

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

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

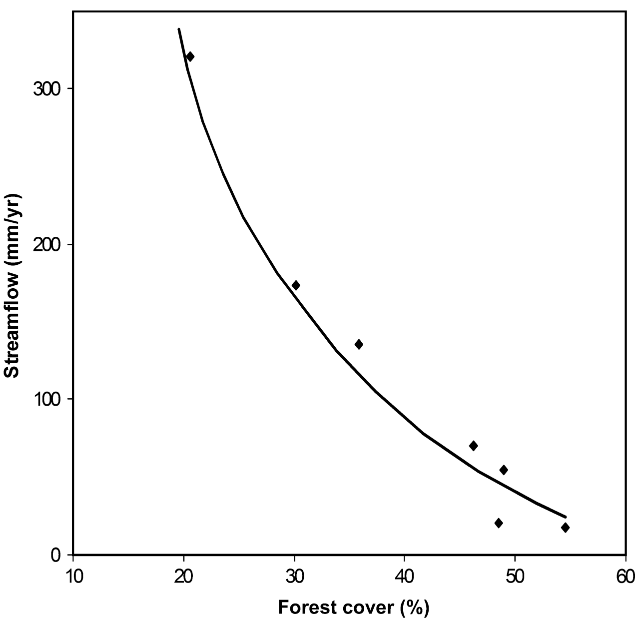

Figure 3. Comparison of forest cover versus streamflow for seven higher rainfall zone catchments. From Schofield et al. (1989).

Bauxite Mining in the Higher Rainfall Zone

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

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

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

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

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

Bauxite Mining in the Lower Rainfall Zone

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

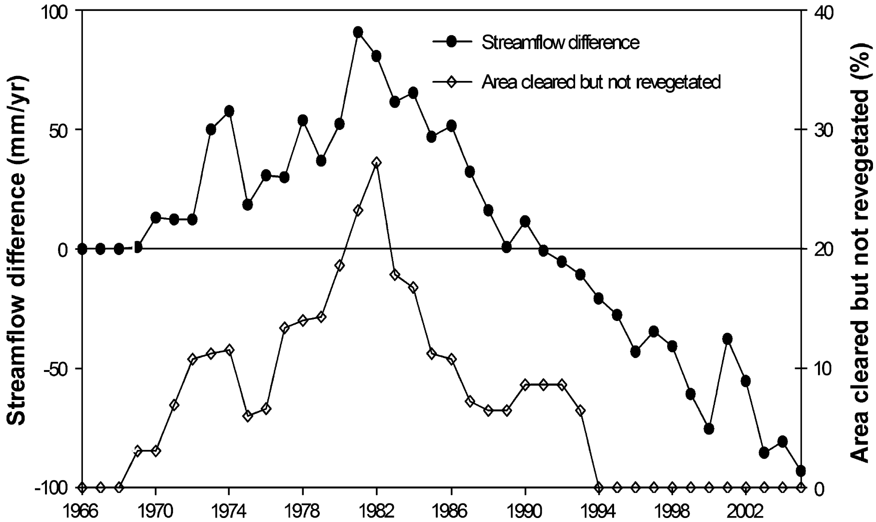

Figure 4. Difference between mined and unmined streamflows for More Seldom Seen catchment. Area cleared but not revegetated is plotted for comparison. After Croton et al. (2005).

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

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

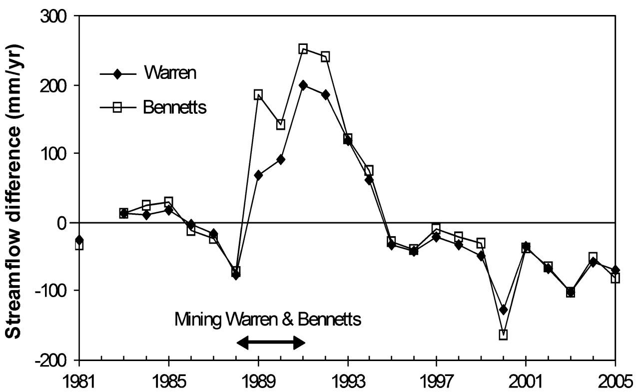

Figure 5. Flow differences between Warren and Bennetts catchments and Vardi Road control catchment.

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

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

Discussion

Higher Rainfall Zone

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

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

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

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

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

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

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

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

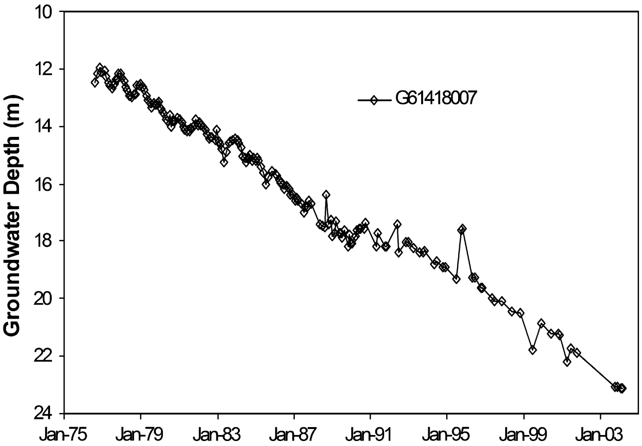

Figure 6. Depth to groundwater for a long-term, mid-slope piezometer in the Tunnel Road control catchment to the east of the CEME.

Lower Rainfall Zone

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

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

Conclusions

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

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

Implications for Practice

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

Acknowledgments

The authors express their gratitude to Alcoa World Alumina Australia for their support in preparation of this manuscript and to J. Koch and J. Dalton for their technical editing.

LITERATURE CITED

Abbott, I. 1984. Comparisons of spatial pattern, structure, and tree composition between virgin and cut-over jarrah forest in Western Australia. Forest Ecology and Management **9:**101–126.

Abbott, I., P. van Heurck, T. Burbidge, and M. Williams. 1993. Damage caused by insects and fungi to eucalypt foliage: spatial and temporal patterns in Mediterranean forest of Western Australia. Forest Ecology and Management **58:**85–110.

Alcoa of Australia Ltd. 1978. Wagerup alumina project environmental review and management programme [draft and supplement]. Alcoa of Australia Ltd. and Dames & Moore, Perth, Australia.

Bari, M. A., and J. T. Croton. 2000. Predicting the impacts of land use changes on streamflow and salinity by a fully distributed catchment model. Pages 311–316 in Hydro'2000, Third International Hydrology and Water Resources Symposium, November 20–23, Institution of Engineers Australia, Perth, Australia.

Bari, M. A., and J. T. Croton. 2002. Assessing the effects of valley reforestation on streamflow and salinity using the WEC-C model. in Hydrology 2002, 27th Hydrology and Water Resources Symposium, May 20–23, 2002. Institution of Engineers Australia, Melbourne, Australia.

Bari, M. A., and J. K. Ruprecht. 2003. Water yield response to land use change in south-west Western Australia. Department of Environment, Salinity and Land Use Impacts Series Report No. SLUI 31, Perth, Australia.

Bartle, J., and G. C. Slessar. 1989. Mining and rehabilitation. Pages 357–377 in B. Dell, J. J. Havel, and N. Malajczuk, editors. The jarrah forest: a complex Mediterranean ecosystem. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Beverly, C. R., and J. T. Croton. 2002. Formulation and application of the unsaturated/saturated catchment models SUSCAT and WEC-C. Hydrological Processes **16:**2369–2394.

Churchward, H. M., and G. M. Dimmock. 1989. The soils and landforms of the northern jarrah forest. Pages 13–21 in B. Dell, J. J. Havel, and N. Malajczuk, editors. The jarrah forest: a complex Mediterranean ecosystem. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Colquhoun, I. J., and N. L. Kerp. 2007. Minimizing the spread of a soil-borne plant pathogen during a large-scale mining operation. Restoration Ecology Supplement **15:**S85–S93.

Cornish, P. M. 1993. The effects of logging and forest regeneration on water yields in a moist eucalypt forest in New South Wales. Journal of Hydrology **150:**301–322.

Croton, J. T. 1991*a*. Groundwater salinities of the intermediate rainfall zone of the northern jarrah forest, Western Australia. Environmental Research Bulletin No. 25. Alcoa of Australia Ltd., Perth, Australia.

Croton, J. T. 1991*b*. Relationships of groundwater levels and salt storages to the geomorphology of the intermediate rainfall zone of the northern jarrah forest. Environmental Research Bulletin No. 24. Alcoa of Australia Ltd., Perth, Australia.

Croton, J. T. 2004*a*. Salinity management modelling of the Lemon catchment using WEC-C. Pages 349–354 in Engineering Salinity Solutions—1st National Salinity Engineering Conference, 9–12 November 2004, Perth, Australia.

Croton, J. T. 2004*b*. Simulation of the hydrologic response of the Del Park catchment to bauxite mining. Environmental Research Bulletin No. 32. Alcoa of Australia Ltd., Perth, Australia.

Croton, J. T., and M. A. Bari. 2001. Using WEC-C, a distributed, deterministic catchment model, to simulate hydrologic responses to agricultural clearing. Environmental Modelling and Software **16:**601–614.

Croton, J. T., and D. A. Barry. 2001. WEC-C: a distributed, deterministic catchment model—theory, formulation and testing. Environmental Modelling and Software **16:**583–599.

Croton, J. T., L. H. Boniecka, J. K. Ruprecht, and M. A. Bari. 2005. Estimated streamflow changes due to bauxite mining and forest management in the Seldom Seen catchments, Western Australia. Department of Environment, Salinity and Land Use Impacts Series Report No. SLUI 37, Perth, Australia.

Croton, J. T., and D. T. A. Tierney. 1985. Red—a hydrological design model used in the rehabilitation of bauxite minepits in the Darling Range, Western Australia. Environmental Research Bulletin No. 15. Alcoa of Australia Ltd., Perth, Australia.

Farley, K. A., E. G. Jobbágy, and R. B. Jackson. 2005. Effects of afforestation on water yield: a global synthesis with implications for policy. Global Change Biology **11:**1565–1576.

Gardner, J. H., and D. T. Bell. 2007. Bauxite mining restoration by Alcoa World Alumina Australia in Western Australia: social, political, historical, and environmental contexts. Restoration Ecology Supplement **15:**S3–S10.

Gentilli, J. 1989. Climate of the jarrah forest. Pages 23–40 in B.Dell, J. J. Havel, and N. Malajczuk, editors. The jarrah forest: a complex Mediterranean ecosystem. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Gilmour, D. A. 1977. Effect of rainforest logging and clearing on water yield and quality in a high rainfall zone of north-east Queensland. Pages 156–160 in The hydrology of Northern Australia. Proceedings of the Institute of Engineers. Institution of Engineers Australia, Brisbane, Australia.

Grant, C. D. 2006. State-and-transition successional model for bauxite mining rehabilitation in the jarrah forest of Western Australia. Restoration Ecology **14:**28–37.

Havel, J. J. 1975. Site-vegetation mapping in the northern jarrah forest (Darling Range). 2. Location and mapping of site-vegetation types. Forest Department, W.A. Bulletin No. 87, Perth, Australia.

Hibbert, A. R. 1967. Forest treatment effects on water yield. Pages 527–543 in Proceedings International Symposium on Forest Hydrology. Pennsylvania State University.

Hornbeck, J. W., M. B. Adams, E. S. Corbett, E. S. Verry, and J. A. Lynch. 1993. Long-term impacts of forest treatments on water yield: a summary for northeastern USA. Journal of Hydrology **150:** 323–344.

Institution of Engineers, Australia. 1987. Australian rainfall and runoff: a guide to flood estimation. D. H. Pilgrim, editor. Institution of Engineers, Canberra, Australia.

Johnston, C. D. 1981. Salt content of soil profiles in bauxite mining areas of the Darling Range, Western Australia. CSIRO Australia, Division of Land Resources Management Technical Paper No. 10:1–19, Perth, Australia.

Kew, G. A., F. C. Mengler, and R. J. Gilkes. 2007. Regolith strength, water retention and implications for ripping and plant root growth in bauxite mine restoration. Restoration Ecology Supplement **15:** S54–S64.

Kinal, J. 1986. Perching and throughflow in a laterite profile in relation to the impact of Phytophthora cinnamomi in the northern jarrah forest. Honours thesis, Murdoch University, Perth, Australia.

Koch, J. M., and G. P. Samsa. 2007. Restoring jarrah forest trees after bauxite mining in Western Australia. Restoration Ecology Supplement **15:**S17–S25.

Kuczera, G. A. 1985. Prediction of water yield reductions following a bushfire in ash-mixed species eucalypt forest. Melbourne and Metropolitan Board of Works, Catchment Hydrology Research Report, MMBW-W-0014, Melbourne, Australia.

Kuczera, G. A. 1987. Prediction of water yield reductions following a bushfire in ash-mixed species eucalypt forest. Journal of Hydrology **94:**215–236.

Langford, K. J. 1976. Change in yield of water following a bushfire in a forest of *Eucalyptus regnans*. Journal of Hydrology **29:**87–114.

Mauger, G. W., J. E. Day, and J. T. Croton. 1998. Hydrological and associated research related to bauxite mining in the Darling Range of Western Australia—1997 review. Water and Rivers Commission, Water Resource Technical Series No. WRT 26, Perth, Australia.

Mayer, X. M., J. K. Ruprecht, and M. A. Bari. 2005. Stream salinity status and trends in south-west Western Australia. Department of Environment, Salinity and Land Use Impacts Series. Report No. SLUI 38, Perth, Australia.

Peck, A. J. 1976. Modelling the effect of a change in land use on stream salinity. in Joint DCE/CSIRO/PWD Workshop on Land Use and Stream Salinity, Perth, Australia.

Ruprecht, J. K., and G. L. Stoneman. 1993. Water yield issues in the jarrah forest of south-western Australia. Journal of Hydrology **150:**369–391.

Sahin, V., and M. J. Hall. 1996. The effects of afforestation and deforestation on water yields. Journal of Hydrology **178:**293–309.

Schofield, N. J. 1988. Predicting the effects of land disturbances on stream salinity in south west Western Australia. Australian Journal of Soil Research **26:**425–438.

Schofield, N. J., and J. R. Bartle. 1984. Bauxite mining in the jarrah forest: impact and rehabilitation. Department of Conservation and Environment W.A., Bulletin No. 169. Perth, Australia.

Schofield, N. J., G. L. Stoneman, and I. C. Loh. 1989. Hydrology of the jarrah forest. Pages 179–201 in B. Dell, J. J. Havel, and N. Malajczuk, editors. The jarrah forest: a complex Mediterranean ecosystem. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Scott, D. F., and R. E. Smith. 1997. Preliminary empirical models to predict reductions in total and low flows resulting from afforestation. Water South Africa **23:**135–140.

Sharma, M. L., R. J. W. Barron, and M. S. Fernie. 1987. Areal distribution of infiltration parameters and some soil physical properties in laterite catchments. Journal of Hydrology **94:**109–127.

Slessar, G. C., N. J. Murray, and T. Passchier. 1983. Salt storage in the bauxite laterite region of the Darling Range, Western Australia. Environmental Research Bulletin No. 16. Alcoa of Australia Ltd., Perth, Australia.

Stokes, R. A., K. A. Stone, and I. C. Loh. 1980. Summary of soil salt storage characteristics in the northern Darling Range. Water Resources Branch, Public Works Department W.A., Technical Report No. WRB 94, Perth, Australia.

Stoneman, G. L., F. J. Bradshaw, and P. Christensen. 1989. Silviculture. Pages 335–355 in B. Dell, J. J. Havel, and N. Malajczuk, editors. The jarrah forest: a complex Mediterranean ecosystem. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Trimble, S. W., and F. H. Weirich. 1987. Reforestation reduces streamflow in the southeastern United States. Journal of Soil and Water Conservation **42:**274–276.

Tsykin, E. N., and G. C. Slessar. 1985. Estimation of salt storage in the deep lateritic soils of the Darling Plateau, Western Australia. Australian Journal of Soil Research **23:**533–541.

Turner, J. V., D. K. Macpherson, and R. A. Stokes. 1987. The mechanisms of catchment flow processes using natural variations in deuterium and oxygen-18. Journal of Hydrology **94:**143–162.

Water Corporation. 2005. Wungong catchment environment and water management project. Water Corporation, Perth, Australia (available from http://www.watercorporation.com.au/wungong/) accessed 21 December 2004.

Waterloo, M. J. 1994. Water and nutrient dynamics of *Pinus caribaea* plantation forests on former grassland soils in southwestern Vitu Levu, Fiji. Cip-Data Koninklijke Bibliotheek, The Hague, The Netherlands.

Williamson, D. R., R. A. Stokes, and J. K. Ruprecht. 1987. Response of input and output of water and chloride to clearing for agriculture. Journal of Hydrology **94:**1–28.