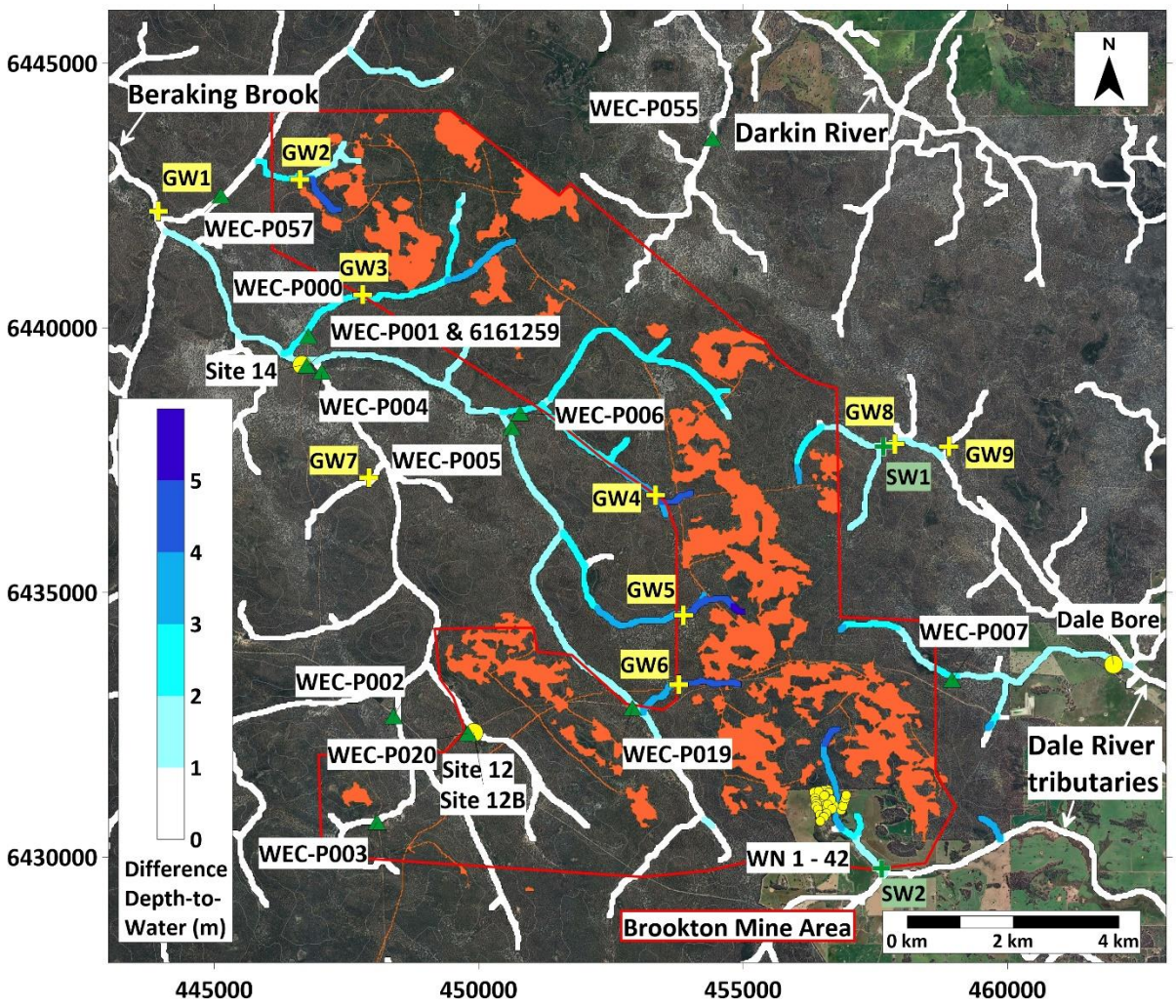
REPORT
TO
SOUTH 32 WORSLEY ALUMINA PTY LTD

SALINITY RISK ASSESSMENT FOR THE BROOKTON MINING AREA USING FLUX DENSITY ANALYSIS



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SUMMARY

South32 Worsley Alumina Pty Ltd (Worsley) proposes to extend their bauxite mining activities to five mining envelopes: Brookton, Central, Hotham North Extension, East Quindanning and Morgans. Due to known issues associated with salinity and agricultural clearing in the south-west of W.A., Worsley has commissioned Water & Environmental Consultants (WEC) to conduct salinity-risk assessments for the extended mining areas. This report focuses on the Brookton Mining Area (BMA) and evaluates available information on the climate, hydrogeology, soil-salt storage, groundwater and surface-water level/flow and quality to develop an understanding of the current state of the groundwater and surface-water systems. Flux Density Analysis (FDA) is then used to assess the potential salinity-risk and identify potential salinity-hotspots.

The average rainfall in the BMA is approximately twenty-percent lower than the Boddington Bauxite Mine (BBM) area. Rainfall has been declining since 1975, with percentage rainfall declines at BMA similar to those seen across the region; which has led to associated declines in the groundwater-table under the forested areas of BBM. Rainfall is a significant unknown in estimating the salinity risk, given the high inter-annual variability, and its direct role in water-table rises and declines.

The hydrogeology at BMA is equivalent to that of BBM; with up to three aquifers, a small, shallow, superficial aquifer that is usually not connected to the deeper aquifers in the saprolite and fractured rock (which are connected). The soils are highly permeable with little runoff, so streamflow is generated through interflow in the upper layers and by a seasonal perched aquifer. The main groundwater aquifer tends to be saline and disconnected from the surface water in forested areas, but is often connected to the stream in agricultural areas.

The BMA straddles two catchments, the Darkin River catchment and the Dale River catchment. These two catchments are significantly different in their land-use and current hydrology. The Darkin River catchment is mostly forested with areas of old-growth forest and national park as well as being in the Mundaring Weir drinking-water catchment. While these factors illustrate that the ecosystem is highly valued and negative effects on the ecosystem will be scrutinised, they also suggest that the ecosystem is resilient, especially given the declines in streamflow and salinity noted since the 1970's and the deep groundwater table in the Beraking Brook catchment where most of the bauxite is located. The Dale River catchment by contrast is largely cleared for agriculture with high stream salinities and high groundwater-levels.

A Flux Density Analysis (FDA) was conducted, to assess the potential water-table rise from bauxite-mining activities and to identify hotspots where we expect a greater groundwater-flux due to the local topography and mine-plan. There is insufficient local data to review the FDA equation for this area, given the differences in rainfall and forest-density caution should be taken in interpreting the estimated magnitude of groundwater flux, however locations of greatest flux should be reasonable. The largest fluxes are expected in tributaries to Beraking Brook, which appears to have deep groundwater, so there is not expected to be a high risk of saline discharge, however, additional monitoring in the catchment is recommended to better understand the hydrology and monitor any effects of mining. Moderate fluxes are expected in a tributary to Dale River; there may be some increase in salinity and surface-water expression on the agricultural-property downslope of the bauxitic areas, given the existing shallow groundwater-depth and high salinity in the lower slopes. These effects are likely to be limited to this minor tributary. Mining should have only a minor effect on the vegetation cover of the Dale River catchment, however, monitoring of this tributary is still recommended.

1. INTRODUCTION

South32 Worsley Alumina Pty Ltd (Worsley) proposes to extend their bauxite mining activities to five mining envelopes: Brookton, Central, Hotham North Extension, East Quindanning and Morgans. These mining envelopes are in Worsley's mining lease 258SA in the northern jarrah forest on the Darling Plateau, both north and south of existing mining activities (see Figure 1). The focus of this review is the northern-most mining envelope, Brookton Mining Area (BMA). Due to known issues associated with salinity and agricultural clearing in the south-west of W.A., Worsley has commissioned Water & Environmental Consultants (WEC) to conduct a salinity-risk assessment for the extended mining areas. This report evaluates available information on the climate, hydrogeology, soil-salt storage, groundwater and surface-water level/flow and quality for the BMA, to develop an understanding of the current state of the groundwater and surface-water systems. Flux Density Analysis (FDA) is then used to assess the potential salinity-risk and identify potential salinity-hotspots.

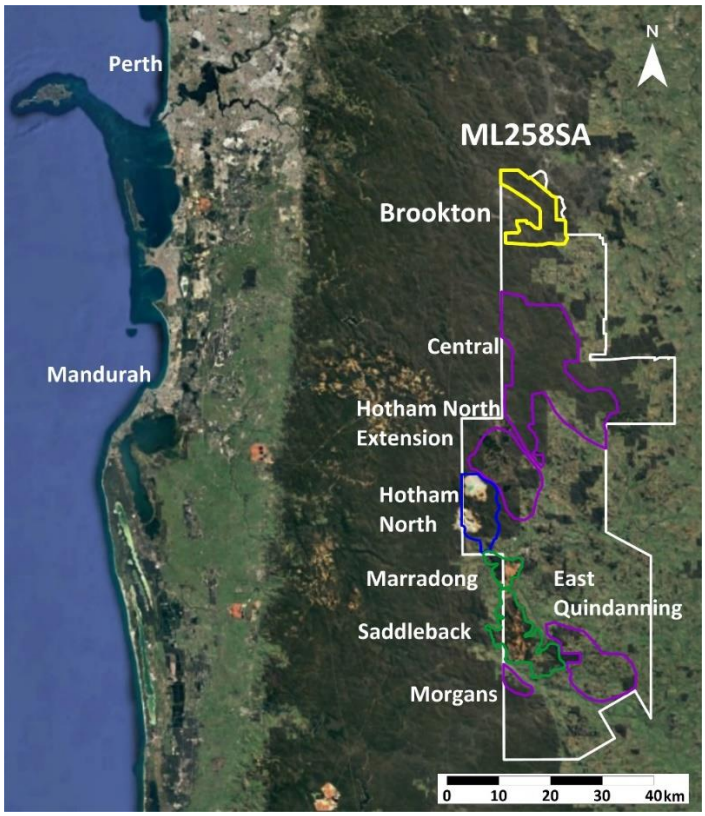


Figure 1: Location of current and extended mining areas within Worsley's ML258SA.

1.1 Bauxite Mining and Salinity Risk

Bauxite mining has the potential to affect the groundwater-table due to changes in recharge caused by vegetation clearing. In the Low Rainfall Zone (LRZ) of the northern jarrah forest evapotranspiration normally accounts for the vast majority of rainfall; when this forest is cleared the bare-soil evaporation rate is significantly lower resulting in higher infiltration, some of which can increase the groundwater-table level, particularly in the lower-slope and valley-floor areas. Clearing for bauxite is transient in nature, with land being promptly revegetated after mining except for areas of haul roads and infrastructure. If this revegetation is hydrologically equivalent to what is cleared, then the rise in the groundwater will be temporary. The potential salinity-risk of bauxite-mining depends on the initial groundwater-depth, the potential for the groundwater to rise, the salinity of the groundwater, the soil salt-storage profile of the valley floor, and the initial stream-salinity. To give an initial assessment of the salinity-risk potential of Brookton bauxite-mining this report assesses these factors, using available data.

1.2 Climate

The Brookton Mining Area (BMA) is located in the Low Rainfall Zone (LRZ, <900 mm/annum rainfall) of the northern jarrah forest, with a Mediterranean climate of hot dry summers and wet winters. The rainfall in the area has been declining, with the annual rainfall at nearby Oakland and Mt. Westdale gauging stations shown in Figure 2 (see Figure 3 in the following section for gauge locations). The average rainfall since 1975 (461 mm/yr) is 105 mm lower than the pre-1974 average (566 mm/yr). The rainfall in the BMA is approximately twenty-percent lower than in the area of current Worsley operations at Boddington; the average rainfall since 1975 at Boddington Shire gauge is 576 mm. The percentage rainfall declines are similar to those seen across the region, which has led to associated declines in the groundwater-table under forested areas of the Boddington Bauxite Mine area (BBM) (Green *et al* 2021). These declines in the groundwater-table reduce the salinity risk of mining activities as the gap between the groundwater-table and valley-floor soil-surface increases. Rainfall is a significant unknown in estimating the salinity risk, given the high inter-annual variability, and its direct role in water-table rises and declines.

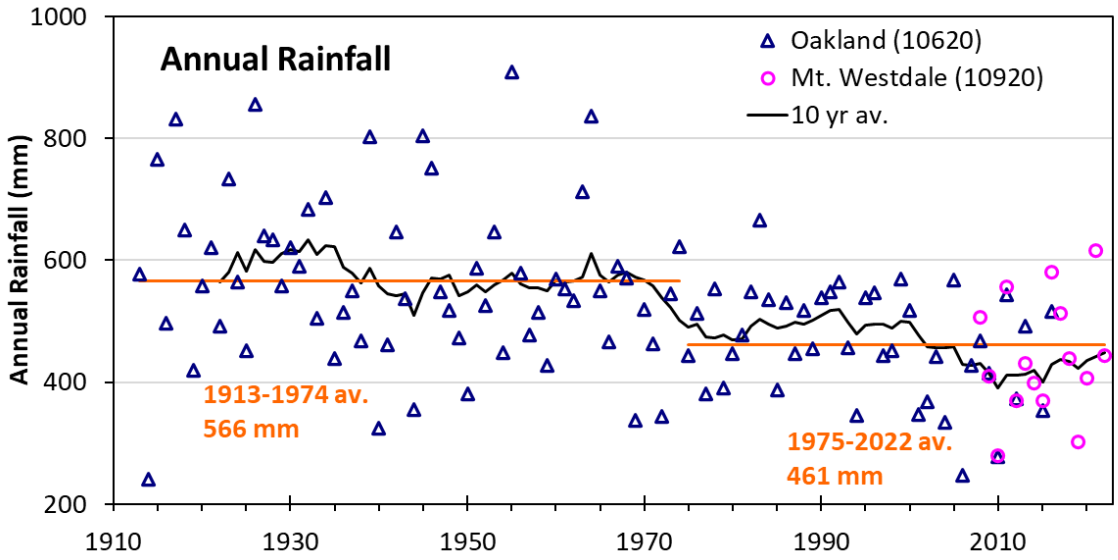


Figure 2: Annual rainfall for Oakland and Mt. Westdale raingauges.

1.3 Hydrogeology

The hydrogeology of BMA is similar to that at Worsley BBM operations to the south, with no significant differences in the overall structure. There are up to three aquifer-layers: a shallow seasonal-aquifer, a deep weathered-zone aquifer, and a fractured-bedrock aquifer. The existence and extent of these three aquifers varies across the region. The soil profile typically varies from 10 m to over 50 m but averages around 25 m. The typical soil-profile involves: a shallow top-layer of gravelly sand (0-2 m), in which can form a superficial aquifer; a low-permeability duricrust underlies this layer (0-3 m thick) and forms the upper section of a bauxite layer (0-10 m thick); next come the mottled and pallid zones; followed by a saprolite layer, which forms the second aquifer; below this is the fractured-rock aquifer within the bedrock. The saprolite and fractured-rock aquifers are in hydraulic-continuity and are distinguished from each other by their material properties. The near-surface soils are highly permeable, so streamflow is usually generated from lateral flows in the upper layer and the superficial aquifer. The salinity is usually low in these upper layers and the low volume and high permeability of the superficial aquifer generally results in ephemeral streams, with flow periods dependent on the catchment area and superficial-aquifer thickness. As well as generating streamflow some water penetrates to the connected saprolite and fractured-rock aquifers. These aquifers are usually disconnected from surface water in forested areas with

their water-table remaining at depth, even in the stream zone. Rises of this water-table can result in discharge of saline groundwater to streams, significantly affecting the stream and riparian ecosystems, as has been observed following historical clearing for agriculture in the region.

1.4 Soil-Salt Storage

Croton and Dalton have conducted a number of studies into the soil-salt storage in the Boddington Bauxite Mine (BBM) areas (2000, 2001, 2004 & 2007a). Given the similarities in the hydrogeology of BMA to these areas it is expected that the findings from these studies will provide insight to the BMA. The underlying bedrock in BBM has regions of both greenstone and granite bedrock, with only the Yilgarn Craton granite bedrock present in BMA. The 2007 study found that mean volumetric total soluble salts (VTSS) was statistically higher over granite bedrock (1.29 kg/m^3) compared to greenstone bedrock (0.97 kg/m^3). These studies also found the VTSS to be significantly lower than other literature values of 1.78 kg/m^3 (Stokes *et al* 1980) and 1.94 kg/m^3 (Tsykin & Croton 1988); the underlying cause of this difference is not clear, however it was suggested that it may be due to the high porosity of soils associated with bauxite (Croton & Dalton 2007a).

2. LAND & WATER USE

The bauxite identified in the BMA is in forested areas, with the majority in Mundaring State Forest and a small area in the south-east outside the state forest boundary, see Figure 3. On the eastern and north-eastern boundary of the BMA is Wandoo National Park, in the north-west after the State Forest is Helena National Park, with areas of bauxite within the catchment of both these national parks. In the current and draft future Forest Management Plan (FMP) (Conservation Commission, 2013 & 2022), the area of State Forest surrounded on three sides by the BMA has been proposed as a Conservation Park. There is an area of old-growth forest identified in the western part of this proposed area, which extends into the BMA (Conservation Commission, 2013 & 2022). While the presence of these national parks and conservation areas downslope and downstream of the bauxite area may result in greater attention to the salinity risk, the forested nature of these areas is also likely to lower this risk as there has been no agricultural clearing in the catchment to the raise the water-table. A moderate salt-tolerance has been reported for *Eucalyptus wandoo* (Pepper & Craig 1986), so there may be some resilience in the forest structure to changes in salinity. The BMA is on the border between wandoo dominated vegetation to the north and jarrah dominated vegetation to the south, with a vegetation density notably lower than in the areas surrounding current BBM operations.

The identified bauxite straddles two water catchments, Darkin River in the west and Dale River in the east. Within the Darkin River catchment, most of the bauxite is in Beraking Brook catchment, a major tributary to Darkin River, and a small area flowing directly to Darkin River in the north. Beraking Brook catchment is forested with a small area of pine plantation, and the remainder native vegetation. Darkin River catchment contains some cleared agricultural land at the eastern head of the catchment, and a rectangular agricultural area surrounded by Wandoo National Park. There are also some small pine plantations along Darkin River in the state forest, with the remainder native vegetation. Darkin River catchment forms part of the Mundaring Weir public drinking water source area (DWER, 2022). Salinity standards for palatable drinking water is a consideration for the salinity risk with good water quality considered below 600 mg/L total dissolved solids (TDS) and a maximum acceptable level of 1,200 mg/L in the Australian Drinking Water Guidelines (NRMMC, 2011).

The Dale River catchment is predominantly cleared agricultural land with small areas of native forest, mostly in the upper reaches. The historical clearing has raised the water-table compared to the forested areas, resulting in the saline-main-aquifer piezometric-level above the soil-

surface in the valley floor. The waterways have high salinity, and the additional clearing area for mining is small in comparison to existing clearing so is unlikely to affect the river and riparian ecosystems or the utility of the water. The temporary clearing for mining may slightly reduce the salinity locally due to the increased volume flowing through the low-salinity upper-layers and superficial aquifer.

There are several small areas of unusual or dense vegetation noted along valley floors that have been identified as potential groundwater-maintained vegetation (purple areas in Figure 3). Streamflow and water-quality studies of the area conducted by Water & Environmental Consultants (WEC) between 2007 and 2009 (Croton *et al* 2007b, Olsen *et al* 2009, and Olsen *et al* 2010) found no significant evidence of groundwater dependence and are further discussed in the following section.

The vegetation density of BMA and surrounding forests is significantly lower than forest surrounding the current BBM area, with large areas of open wandoo-woodlands. Perhaps therefore the relationship between land-clearing and groundwater-level rise is somewhat different in this northern area, most likely the effects of mining will be less for the BMA.

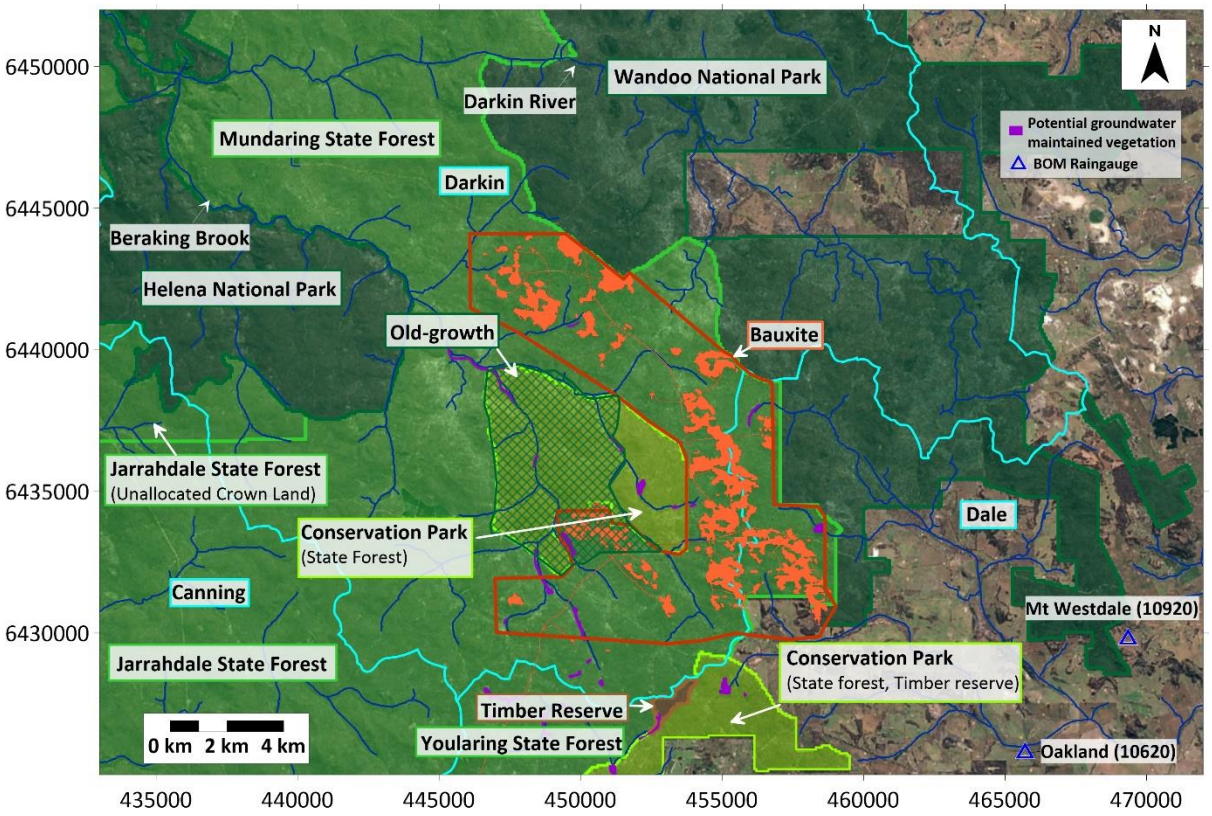


Figure 3: Land use surrounding the BMA - proposed land use from the FMP, with current use shown below in brackets when it differs.

3. GROUNDWATER REVIEW

Within the BMA region there are fourteen bores distributed around the area shown in Figure 4, and another forty-two bores in one agricultural property shown in Figure 5. The data for these bores is summarised in Table 1 and Table 2 respectively. Each bore has only one set of monitoring data, therefore there is no information on temporal changes to groundwater levels and salinity in the area. The data can be separated into three groups based on the catchments, with eight bores in the Darkin River catchment, four bores in the Beraking River catchment, and a total of forty-six in Dale River catchment.

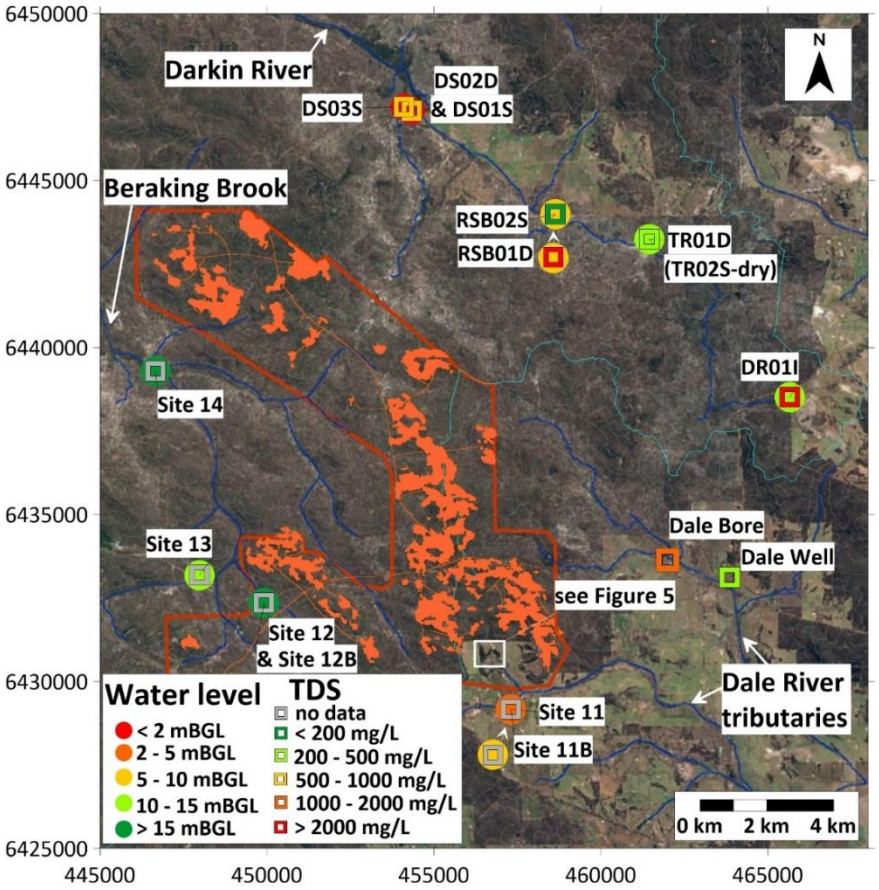


Figure 4: Groundwater-monitoring locations in the BMA and surrounds.

The eight bores along Darkin River were sampled on 4th November 2009, and include three pairs of shallow and deep bores. The data quality listed for these measurements is "Fair", all samples were collected using a bailer and there is a significant difference between the field and laboratory conductivity. The field readings have higher conductivity than laboratory for all bores except for RSB01D which has a laboratory conductivity of 9,150 µS/cm, and a field reading of only 397 µS/cm. RSB01D is screened at two depths, which are likely to be the main deep weathered-zone aquifer (24 – 28 m Below Ground Level, mBGL) and the fractured rock aquifer (48 – 49.5 mBGL); the large difference in conductivity may be due to differences in the salinity of these two aquifers and layering in the bore water column, or simply a measurement/recording error. While caution should apply to interpreting the results, the shallow screened bores have lower conductivity (both field and laboratory) than the deep screened bores, along with a 17 cm difference in level of the DS01S/DS02D pair, suggesting that there is a shallow superficial-aquifer with low salinity. Therefore, the hydrogeology seems similar to what is seen in the BBM area with a fractured rock aquifer, deep weathered-zone aquifer and shallow superficial aquifer. Going down the valley floor the water-table rises; starting with a level of 13.95 mBGL at DR01I near the head of the catchment, going to 1.82 mBGL at DS02D. The salinity of the deep aquifer appears to decrease going down the valley, whereas the salinity of the superficial aquifer seems to increase. When the water-table is within 2 mBGL, the salinity of each screening-depth is below 1,000 mg/L.

In the Beraking River catchment there are four bores drilled for Department of Main Roads in 1992, including two bores within the BMA. Three of these bores were dry when drilled at depths of 21 to 30 m (Site 12, 12B and 14). At Site 13, water was first encountered at 20.5 mBGL in fractured granite, but the level was noted at 11.7 mBGL, suggesting either that the fractured rock aquifer may be locally confined or that the regolith is very low yielding and that the bore only filled with water after casing establishment was completed. Overall, in the Beraking River catchment it appears that the water-table is disconnected from the surface water, there is no information on groundwater salinity.

Table 1: Groundwater monitoring data from the BMA and surrounds.

Bore	Site Ref.	Easting	Northing	Bore Depth (mBGL)	Screening (mBGL)	Date	Water Level (mBGL)	Sample depth (mBGL)	Conductivity (µS/cm)	pH	Field Temp. (°C)	TDS (mg/L)
DS01S	61500241	454329	6447087	7.5	5.5 - 7.5	4-Nov-09	1.65	6	1110			640
						4-Nov-09		6	1683	5.9	25.5	
DS02D	61500242	454331	6447089	32.5	28.5 - 32.5	4-Nov-09	1.82	31	1520			880
						4-Nov-09		31	2603	6.0	21.1	
DS03S	61500243	454102	6447206	5.8	3.8 - 5.8	4-Nov-09	1.66	5	1760			990
						4-Nov-09		5	2423	6.0	20.4	
RSB01D	61500246	458635	6443987	49.5	24-28, 48-49.5	4-Nov-09	9.25	26	9150			5870
						4-Nov-09		26	397	6.4	20.3	
RSB02S	61500247	458637	6443987	10.5	8.5 - 10.5	4-Nov-09	9.26	11	240			130
						4-Nov-09		11	295	5.4	20.8	
TR01D	61500244	461447	6443241	24	20 - 24	4-Nov-09	12.57	21	900			490
						4-Nov-09		21	1432	5.6	20.4	
TR02S	61500245	461449	6443241	12	10 - 12	4-Nov-09	>12 (dry)					
DR01I	61500248	465649	6438511	20.5	18.5 - 20.5	4-Nov-09	13.95	21	9270			6060
						4-Nov-09		21	15730	6.3	19.5	
Site 11	61510544	457305	6429162	37.5	11.5 - 37.5	29-Jun-92	4.9 (initial water 11.5)					
Site 11B	61510545	457305	6429162	30	unknown	1-Jul-92	5.7					
Site 12	61607221	449909	6432349	30	unknown	11-Jul-92	>30 (dry)					
Site 12B	61607222	449909	6432349	21	unknown	11-Jul-92	>21 (dry)					
Site 13	61607220	447982	6433177	26	3.5 - 26	14-Jul-92	11.7 (initial water 20.5)					
Site 14	61607219	446654	6439295	30	unknown	9-Jul-92	>30 (dry)					
Dale Well	61513373	463856	6433119	4.6	unknown	unknown						250
Dale Bore	61513374	462002	6433640	16.8	unknown	15-Feb-76						1500

In the Dale River catchment, there are a further two bores drilled by Department of Main Roads, Site 11 and 11B, which have groundwater depths of 4.9 and 5.7 mBGL respectively, although water was not encountered until 11.5 mBGL when drilling Site 11. The shallower water-table in this catchment is likely due to agricultural clearing, resulting in higher infiltration. Again, there is no salinity readings for these bores, however notes for Site 11 state that it is "salty" without any quantification. The Dale Bore and Dale Well do not have water levels however a salinity of 1,500 mg/L was recorded at the bore in 1976, and a salinity of 250 mg/L at the shallow well on an unknown date.

An extensive network of 42 bores has been formed in a 650 by 700 m area of mostly cleared agricultural land downslope of bauxite ore in the BMA. The location of this area is shown in Figure 4 and bore locations are shown in Figure 5, with details summarised in Table 2. Data for these bores was collated from the interactive groundwater and salinity map for the south-west agricultural region (DPIRD, 2023). No information is available on the screening depth or overall depth of these bores and only single readings are available of the level and conductivity. Note that the location for WN42 is given as two kilometres east of where it is shown, however this places it upslope in a forested area; based on its data and the location of other bores it is likely this easting is erroneous. There are several pairs of adjacent bores within the area with significantly different water-depths and/or salinity; while the monitoring dates are not the same, the differences are larger than expected for temporal changes given there has been no significant change in land-use, for example WN11 and WN18 have a 9.41 m difference in depth over a four-year period. The data suggests that there is a shallow perched aquifer with relatively low salinity and a main aquifer with significantly higher salinity. In upslope areas there is a significant difference in the level of these two aquifers; however, lower down near the drainage channel, bore WN4 has a water-level of 0.15 mBGL and a salinity of 12,350 mg/L suggesting that there is saline groundwater discharging in the valley.

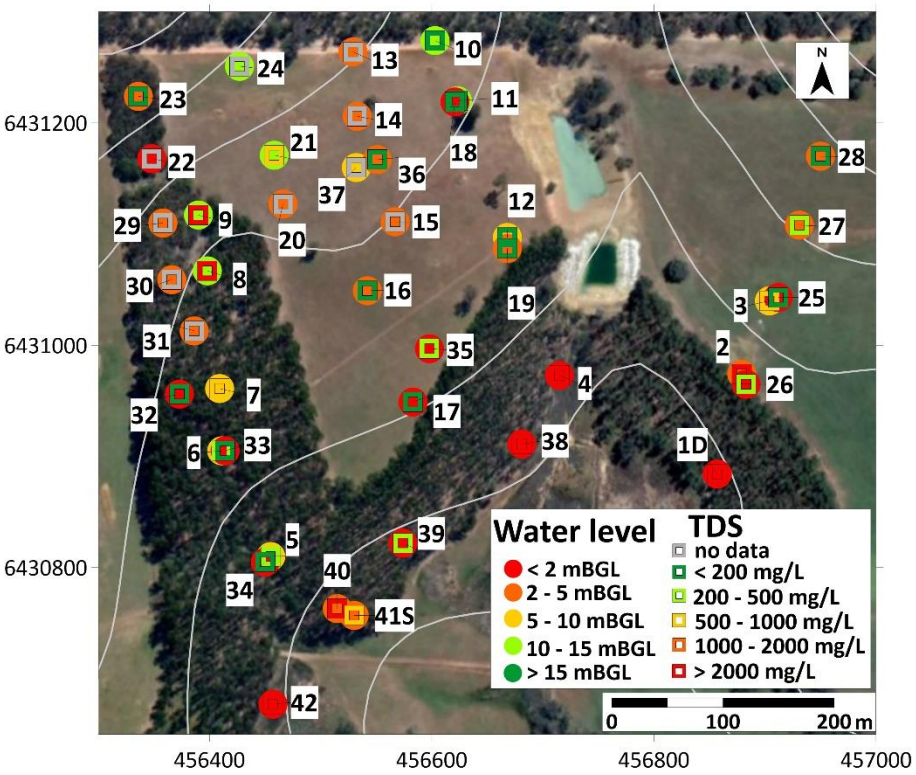


Figure 5: Location of groundwater-monitoring bore series WN1D to WN42.

Table 2: Groundwater monitoring data for bore series WN1D to WN42.

ID	Easting	Northing	Date	Level (mBGL)	Date	Cond. (µS/cm)	TDS (mg/L)
WN 1D	456857	6430884	10-Jun-13	1.58	10-Jun-13	16000	10400
WN 2	456879	6430974	10-Jun-13	3.68	10-Jun-13	4100	2665
WN 3	456904	6431040	10-Jun-13	6.76	10-Jun-13	800	520
WN 4	456715	6430973	10-Jun-13	0.15	10-Jun-13	19000	12350
WN 5	456455	6430810	10-Jun-13	5.13	10-Jun-13	700	455
WN 6	456411	6430905	10-Jun-13	7.42	10-Jun-13	700	455
WN 7	456409	6430961	10-Jun-13	8.55	10-Jun-13	1100	715
WN 8	456398	6431067	10-Jun-13	11.2	10-Jun-13	14000	9100
WN 9	456390	6431117	10-Jun-13	13.37	10-Jun-13	12000	7800
WN 10	456603	6431274	10-Jun-13	14.12	10-Jun-13	300	195
WN 11	456623	6431220	10-Jun-13	10.28	10-Jun-13	300	195
WN 12	456668	6431097	10-Jun-13	7.67	10-Jun-13	200	130
WN 13	456529	6431264	8-Feb-08	4.35			
WN 14	456533	6431206	8-Feb-08	2.6			
WN 15	456567	6431111	25-Aug-05	2.8			
WN 16	456542	6431049	8-Feb-08	2.6	19-May-05	300	195
WN 17	456583	6430949	8-Feb-08	1.27	8-Feb-08	300	195
WN 18	456621	6431219	1-Jul-09	0.87	1-Jul-09	200	130
WN 19	456668	6431087	8-Feb-07	2.3	19-May-05	200	130
WN 20	456466	6431127	25-Aug-05	3.45			
WN 21	456458	6431171	10-Jun-13	14.76	10-Jun-13	900	585
WN 22	456348	6431168	25-Aug-05	1.75			
WN 23	456336	6431224	25-Aug-05	3.92	19-May-05	200	130
WN 24	456427	6431251	25-Aug-05	14.9			
WN 25	456912	6431043	1-Jul-09	1.53	1-Jul-09	200	130
WN 26	456883	6430965	1-Jul-09	0.8	1-Jul-09	500	325
WN 27	456931	6431108	25-Aug-05	2.65	19-May-05	400	260
WN 28	456950	6431170	10-Jun-13	2.5	25-Aug-05	300	195
WN 29	456358	6431110	25-Aug-05	3.44			
WN 30	456366	6431059	25-Aug-05	3.68			
WN 31	456386	6431013	25-Aug-05	2.41			
WN 32	456373	6430956	1-Jul-09	1.5	1-Jul-09	200	130
WN 33	456414	6430905	25-Feb-09	1.22	25-Feb-09	200	130
WN 34	456450	6430805	1-Jul-09	0.83	1-Jul-09	300	195
WN 35	456598	6430997	1-Jul-09	0.98	1-Jul-09	400	260
WN 36	456551	6431167	25-Aug-05	2.33	7-Jul-99	200	130
WN 37	456532	6431160	25-Aug-05	5.35			
WN 38	456681	6430911	25-Oct-12	1.68	25-Oct-12	12000	7800
WN 39	456574	6430822	10-Jun-13	1.8	10-Jun-13	400	260
WN 40	456515	6430763	10-Jun-13	3.09	10-Jun-13	6000	3900
WN 41S	456530	6430757	23-Mar-04	2.45	4-Oct-01	1300	845
WN 42	458457	6430677	10-Jun-13	0.28	10-Jun-13	7000	4550

4. SURFACE WATER REVIEW

Surface water studies of mining expansion areas in ML258SA including BMA and surrounding areas were conducted between 2007 and 2009 by WEC (Croton *et al* 2007b, Olsen *et al* 2009 & 2010). These studies measured the streamflow rate and water quality to develop an understanding of the local hydrology including groundwater interactions. The locations of the relevant WEC monitoring points are shown in Figure 6 with the relevant data summarised in Table 3. Other monitoring locations with water quality data are also shown in Figure 6 with plots included in the Appendix.

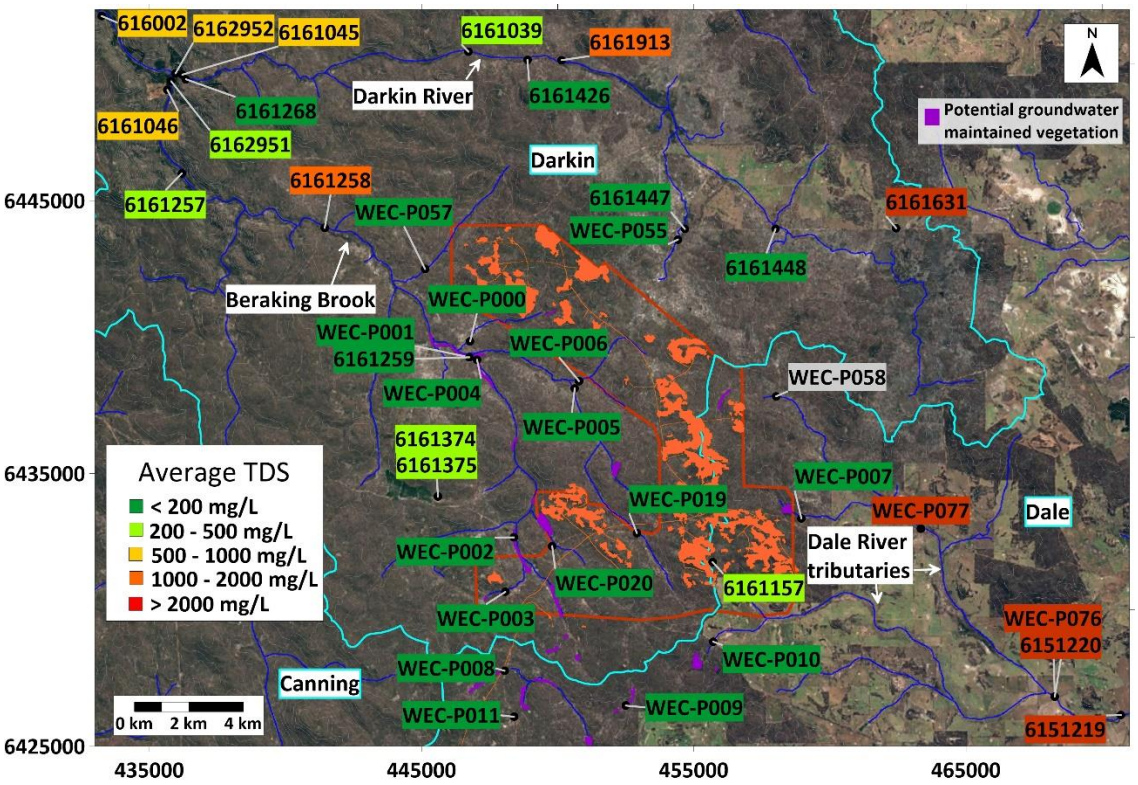


Figure 6: Surface-water monitoring locations in BMA and surrounds.

Table 3: Summary of relevant surface water monitoring data from WEC studies 2007-2009.

Site	Flow (L/sec)						TDS (mg/L)				
	Aug-07	Nov-08	Jul-09	Aug-09	Sep-09	Oct-09	Aug-07	Jul-09	Aug-09	Sep-09	Oct-09
WEC-P000	-	Nil	Ceased	1.9	6.0	Dry	-	97	76	87	-
WEC-P001	-	Nil	0.08	30	30	Ceased	-	81	71	81	115
WEC-P002	Ceased	Nil	Ceased	0.2	0.01	Dry	66	110	73	89	-
WEC-P003	0.3	Nil	Ceased	0.75	0.01	Dry	91	77	70	90	-
WEC-P004	-	Nil	Ceased	34	6.7	Ceased	-	82	75	85	102
WEC-P005	-	Nil	Ceased	11	5.0	Dry	-	90	80	86	-
WEC-P006	-	Nil	Ceased	0.6	0.75	Dry	-	70	73	79	-
WEC-P007	9	Nil	Ceased	2.4	0.25	Ceased	91	61	75	101	141
WEC-P008	Nil	Nil	Dry	Ceased	1.2	Dry	-	-	66	89	-
WEC-P009	Nil	Nil	Dry	0.56	0.08	Dry	-	-	147	154	-
WEC-P010	11	Nil	0.31	18	18	Dry	137	250	113	189	-
WEC-P011	5.0	Nil	Ceased	8.0	3.0	Ceased	86	76	87	95	116
WEC-P019	30.0	Nil	Ceased	4.1	0.10	Dry	81	81	77	83	-
WEC-P020	4.0	Nil	Ceased	2.0	0.20	Dry	76	73	70	82	-
WEC-P055	-	Nil	Ceased	0.10	1.5	Dry	-	99	99	110	-
WEC-P057	-	Nil	Ceased	0.01	0.07	Dry	-	92	113	122	-
WEC-P058	-	Nil	Dry	Dry	Dry	-	-	-	-	-	-
WEC-P076	-	-	350	1125	100	2	-	4190	2912	3849	6569
WEC-P077	-	-	-	28	3.2	Ceased	-	-	1116	1782	7747

The average salinities of all WEC monitoring locations in forested areas were below 200 mg/L, with many below 100 mg/L for all measurements. By contrast at the monitoring locations in cleared agricultural catchments the salinity was over 1,000 mg/L for all measurements. The streamflow in the forested catchments was ephemeral; combined with the low salinity this suggests the flow is due to surface runoff and shallow interflow with no connection to the deep groundwater aquifers. Monitoring location WEC-P002 has low streamflow for the catchment size and along the valley floor has the largest extent of potential groundwater dependent vegetation. This suggests that the runoff to infiltration ratio is low in this relatively flat catchment, and denser vegetation may be due to increased seasonal water-levels in the upper layers.

Monitoring location 616002 on the Darkin River, downstream of the confluence with Beraking River, has the most extensive monitoring record with water quality and flow measurements from 1968 and in-situ logger data from 2000. The TDS and daily streamflow data for the entire monitoring period is presented in Figure 7. It can be seen that both streamflow and salinity have declined since the 1970's; the highest salinity over the last decade is 325 mg/L and this was after flow had ceased. The decline in both flow and salinity suggests that there has been a disconnection, or at least a significant reduction in connection, between the surface and groundwater over recent decades, correlating with the declining rainfall.

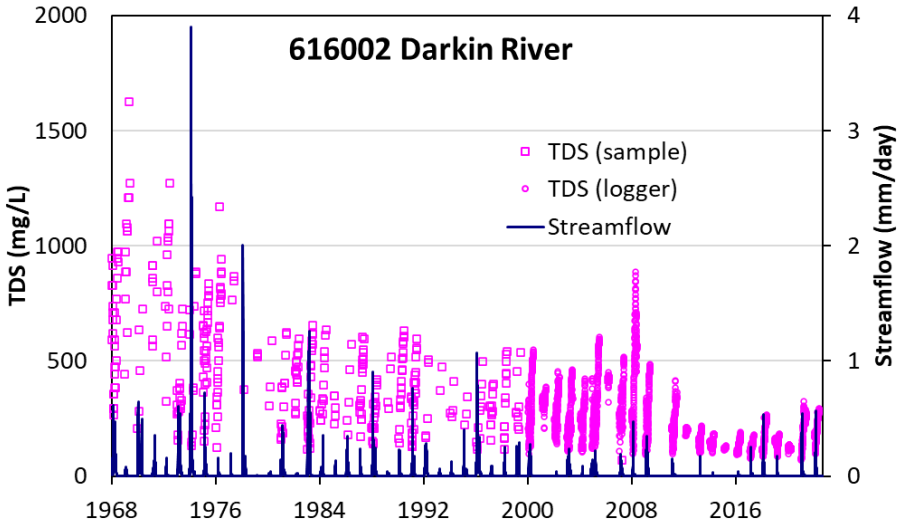


Figure 7: Streamflow and salinity for Darkin River 616002 stream-gauge.

A comparison of 1970 and 2022 streamflow, salinity and rainfall is shown in Figure 8. While the peak streamflow is somewhat similar between the two years, close to 400 ML/day, the period with significant streamflow was approximately four months in 1970 and only two in 2022. The streamflow in 2022 is highly responsive to rainfall events, rising and falling rapidly, whereas streamflow response in 1970 is slower to rise and fall. This suggests that streamflow in 2022 is primarily driven by runoff and shallow interflow in the highly permeable and conductive upper layers; this is supported by the low salinities which remain below 150 mg/L during peak flows. In 1970, there appears to be a connection to the groundwater system with more sustained hydrograph-recession flows and a higher salinity.

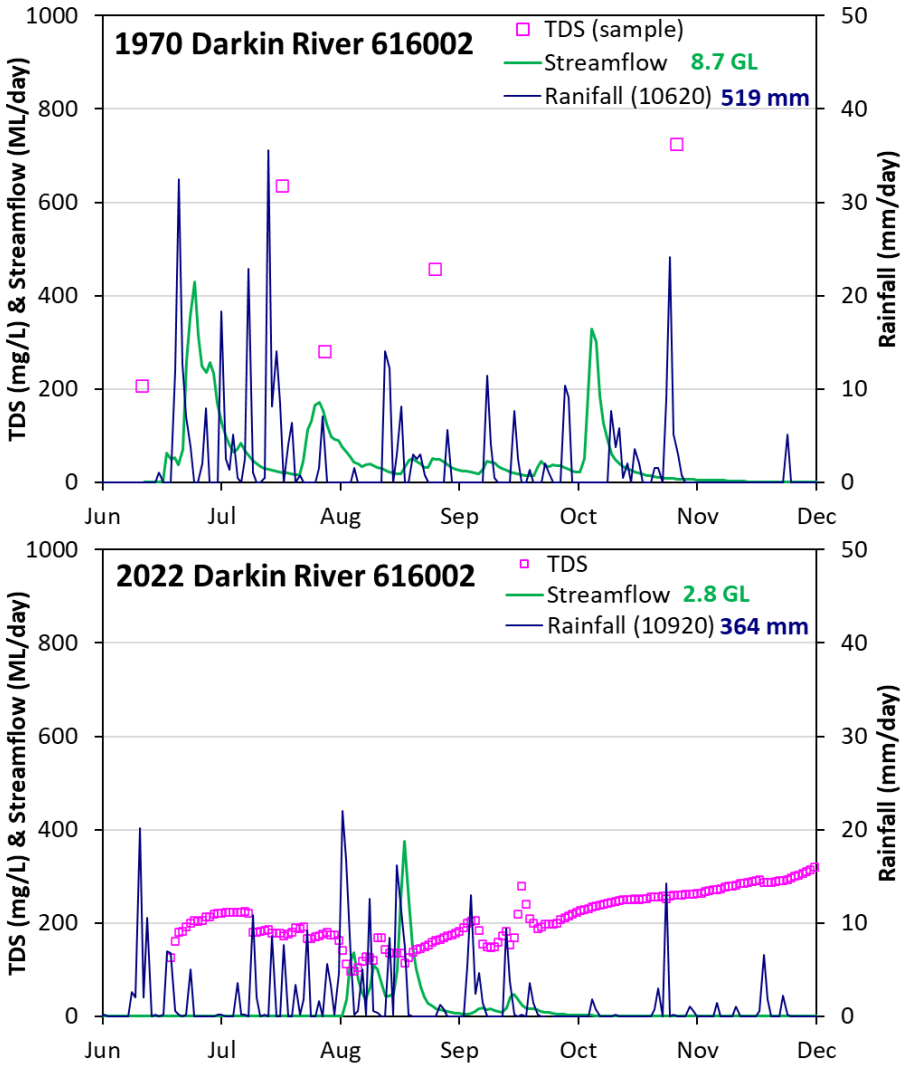


Figure 8: Comparison of 1970 and 2022 streamflow, TDS, and rainfall.

The historically higher flow-rates and salinity in the Darkin catchment suggests that the ecosystem may be tolerant to increases in these factors. The changes in streamflow also suggest that over decades the groundwater and surface-water interactions have changed significantly with the low-rainfall years of 2010 and 2012 marking the start of what appears to be a disconnection between these two. Given this change it would take significant and sustained increases in infiltration to reverse the disconnection process. The Dale River tributaries by contrast have high salinity with all readings above 4,000 mg/L at the monitoring locations below the confluence of the two tributaries (6151219 & 6151200), suggesting that the ground and surface water systems are connected in this agricultural catchment.

5. FLUX DENSITY ANALYSIS & RECOMMENDATIONS

Flux Density Analysis (FDA) is based on the concept of tracing possible groundwater flow-pathways across the landscape to calculate their catchment area, and on the concept of weighting areas of different land-use to account for differences in potential groundwater-recharge due to differences in vegetation-cover. The method factors in the effects of topography and vegetation cover on groundwater flux-densities. The significance of flux density is illustrated by Figure 9, which shows two theoretical minepits, the one on the west has convergent drainage to the valley head, whereas the northern one has divergent drainage dispersed along the stream flank. While both minepits are the same size, the one with convergent drainage has a narrowing flow path and therefore a much higher flux-density where

the flowpath meets the stream, all the flux is focused on the valley head. The northern minepit with its divergent drainage has a distributed flux as it meets the stream along its length and thereby has a much lower flux-density. The net result is that the western pit has a greater potential to cause groundwater rise at the stream contact-point compared to the northern minepit. A limitation of FDA is that it is driven just by surface-topography and vegetation-cover as these are the only two parameters readily available; the complexities of local hydrogeology are lacking. However, given that it is a first-pass tool designed to identify areas that may require further investigation and the possible installation of monitoring (piezometers), this limitation is acceptable.

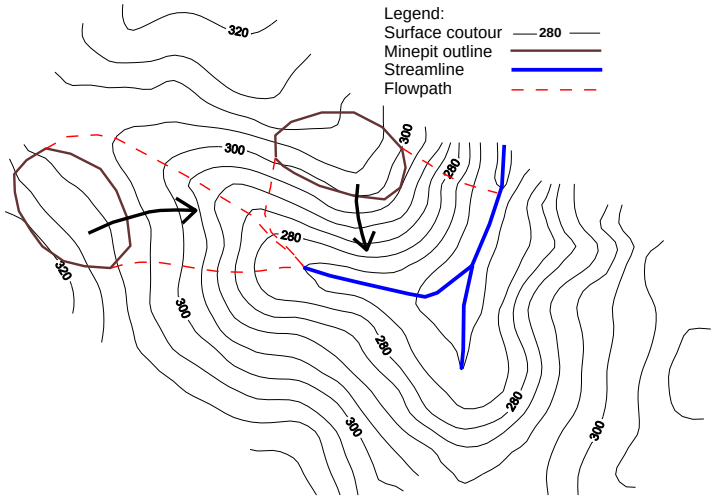


Figure 9: A theoretical landscape with two minepits illustrating the application of FDA.

The FDA concept discussed above is applied to the Brookton Mining Area (BMA) through computational analysis of a digital elevation model (DEM). The DEM is created with a 25 m square grid-cell, consisting of 1,836,544 cells for the Brookton study area. Weighting layers are then created for different land-use scenarios with cleared areas given a weighting of five, and forested areas a weighting of one: that is the assumption that groundwater recharge beneath cleared areas is five times that under forested areas. This weighting is the same as has been used in previous studies (Croton & Dalton 2003, Green *et al* 2023) which was developed based on observed-data to model-fit. The weighting layers were combined with the DEM to create weighted catchment layers. Previous studies have developed estimates of the relationship between catchment area and groundwater depth. A relationship was developed for the intermediate rainfall zone (IRZ) by Croton (1991) analysing 24 valley floor piezometers, with the depth-to-water (DTW) = 30.15 - 4.76*ln(Area) where DTW is in metres and Area is in hectares. This relationship was adapted for the BBM LRZ to 30.0 - 3.95*ln(Area) (Croton & Dalton 2003), and later for the Hotham North area to 25.2 - 3.32*ln(Area) (Green *et al* 2023). This relationship from the Hotham North area will be used to estimate the flux density in the BMA as there is insufficient data to develop a local relationship and Hotham North is the closest area. The BMA has similar hydrogeology to Hotham North, but the rainfall and forest density are significantly lower, so it is not expected that this function will be a good estimate of the groundwater levels. However, as FDA is a tool for identifying hotspots where larger groundwater fluxes may occur to guide further monitoring and investigations, the analysis should be sufficient to locate these areas even if the magnitude of change is uncertain.

The effects of prior clearing in the study area were first reviewed, to understand the current level of disturbance. Land currently cleared for agriculture activities was identified by analysing satellite imagery with cleared land given a 5:1 weighting to the forested areas. There are some small pine-plantation areas, most adjacent to the Darkin River; these were left with the standard forest weighting of 1. Plantation areas are likely to have an oscillating water-

table, with rises occurring after harvest followed by falls as the dense revegetation becomes established. The net effect is likely to be a water-level decline; accurate modelling of these plantations would require annual land-use mapping. Given that the plantation areas are not close to the bauxite ore-bodies it was decided that treatment of these areas as equivalent to other forested areas, as a conservative approximation, would be sufficient. The estimated valley-floor groundwater-level rise due to current land-use is shown in Figure 10. There are significant rises in the Dale River tributaries, with some rises also in the Darkin River, with these falling below one metre after the confluence with Beraking Brook.

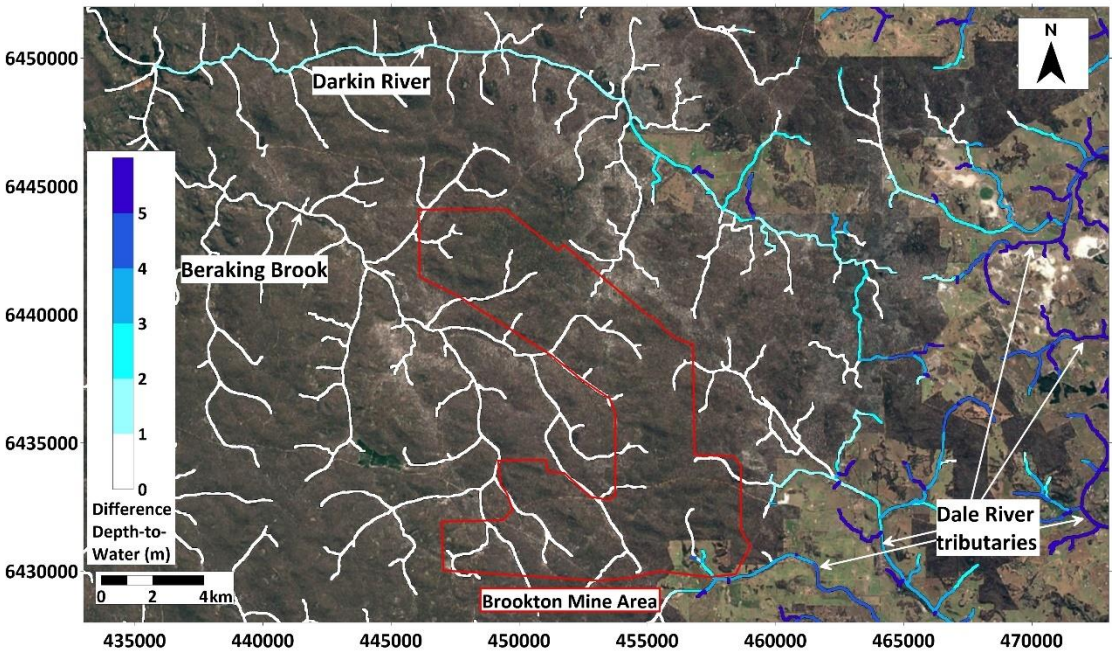


Figure 10: Map of the FDA-estimated changes in valley-floor groundwater levels due to existing agricultural clearing.

The potential effect of bauxite-mining activities on the groundwater table was analysed using FDA with a weighting of six given to the areas of bauxite and planned roads to allow for twenty percent additional perimeter clearing. The resulting groundwater change along the valley floor compared to the current land-use is shown in Figure 11 with relevant ground and surface monitoring locations. Within the Beraking Brook catchment there are rises in groundwater levels in the upper valley of several tributaries, with less than two metre rises along the main channel, which falls to below one metre before the confluence with Darkin River. Groundwater bores along the Beraking River have all been dry when monitored, with depths of thirty metres at Site 12 and 14. It is expected that groundwater levels in the main aquifer of the Beraking Brook catchment are sufficiently low that rises in the water-table due to land clearing associated with mining activities will not result in discharge of saline deep-groundwater into the waterways. The bores Site 12, 12B and 14 are likely to still be dry given the decline in rainfall since their construction in 1992, however it would be useful to verify this. Seven additional bores, GW1 to GW7, are recommended to monitor the water-table in the Beraking Brook catchment. GW1 is in the valley floor downslope of all mining activity to capture any broad changes to the water-table. GW2 to GW6 are in the valley floor of tributaries with the largest anticipated flux. GW7 is in the valley floor of a forested tributary remote from the mining area to provide a control monitor for any climatic induced changes to the water-table. As well as changes in the main aquifer there may be an increase in surface-runoff and shallow-groundwater interflow which may result in an increase in the flow volume of Beraking River, and potentially an increase in end of season salinity due to shallow interflow. These increases in flow and salinity are expected to be small in comparison to the inter-annual variability and the historical flow and salinity changes noted at 616002 Darkin River monitoring point. It is

recommended that monitoring is resumed at the WEC surface monitoring sites shown in Figure 11.

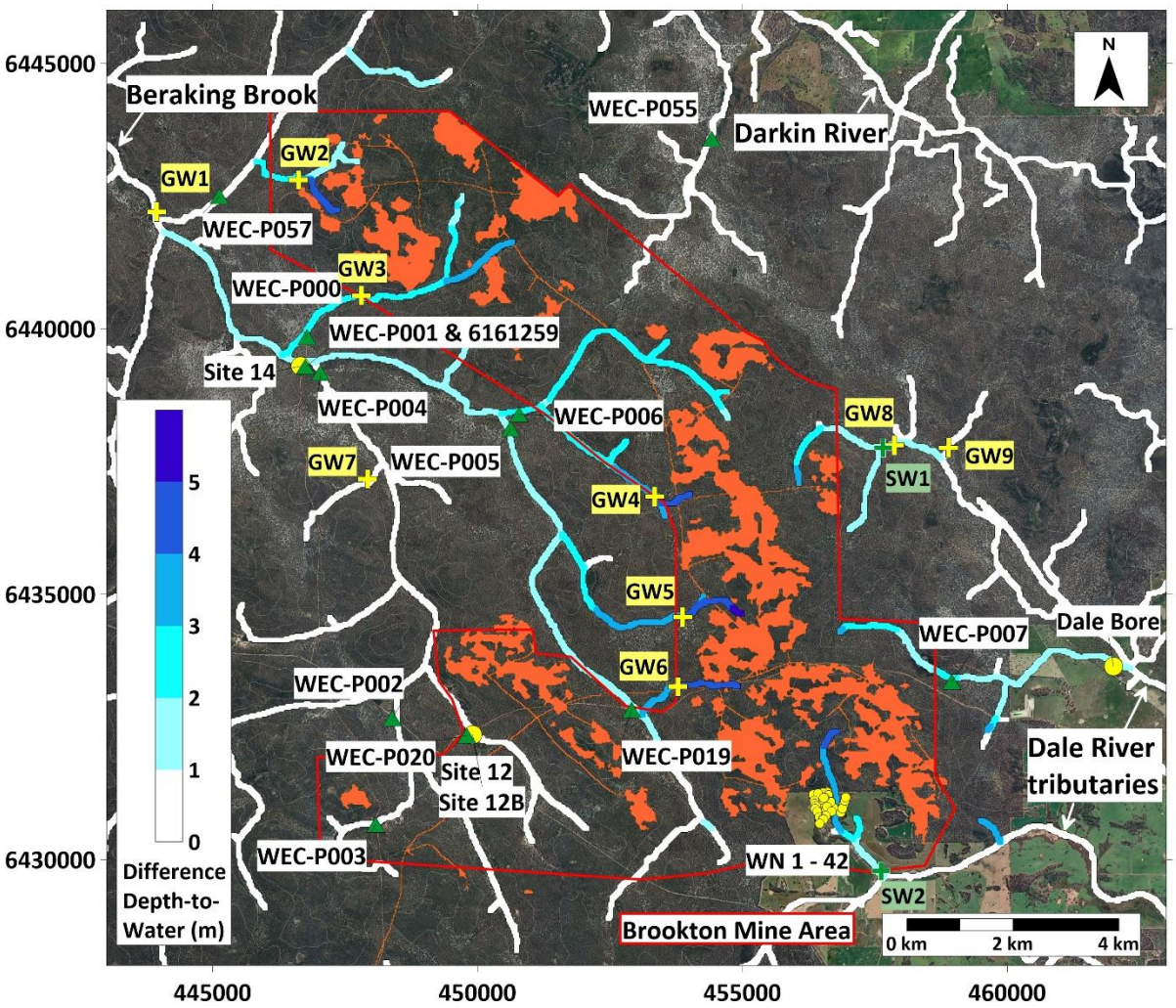


Figure 11: Map of FDA-estimated change in groundwater-level along the valley floor due to land cleared for mining activities; with relevant existing groundwater (yellow circle) and surface-water (green triangle) monitoring locations and proposed sites (+).

The main Darkin River catchment in the north-east has limited mining within the catchment with no rises in the valley-floor groundwater-level above one metre expected, therefore no significant change to the ground and surface water-level and quality is expected. Resumption of surface water monitoring at WEC-P055 is recommended, as well as reviewing salinity and flow data from the government operated 616002 below the confluence with Beraking Brook.

In the Dale River tributaries, there are some rises in groundwater level in the upper valleys; however, rises are below one metre in the main channels. The highest groundwater rises are upslope of the heavily monitored property with bores WN1 to WN42. This rise is expected to be less than four metres in the monitored area, dropping to less than one metre at the confluence with another minor tributary. Given that just under a third of these bores have water levels less than two metres below ground, the rises in groundwater due to clearing for mining activities may result in an increase in surface-water expression on the property, depending on rainfall. In the upper reaches of the property this surface water is likely to be from the shallow perched aquifer with low salinity. Lower in the property there is saline water near the surface, bore WN4 is 0.15 m below-ground-level and has a salinity of 12,350 mg/L. Therefore, additional saline-water discharge is anticipated in the lower valley-floor of this property. Based on the bore data and satellite imagery surface salinity already appears to be affecting this property. The additional clearing of land for mining is likely to increase this; however, this is expected

to be limited to this valley with no significant rise after it joins the other minor tributary. Given the existing salinity issues this is unlikely to significantly affect the valley-floor ecosystem but may affect the utility of some of the land. It is recommended that full construction and monitoring details for the WN1 to WN42 bores are obtained, if possible, and monitoring (water-level and electric-conductivity) of a selection of these bores is continued. Two additional groundwater bores are recommended, GW8 in the valley floor downslope of mining in the northern tributary, and GW9 in an undisturbed forested tributary to provide a control. Locating and monitoring of the Dale Bore is also recommended if accessible. For surface water it is recommended that WEC-P007 is monitored as well as two additional monitoring locations, SW01 on the northern tributary in the national park downstream of bauxite areas and SW2 downslope of the WN1-42 bores, to monitor changes at this agricultural property.

All new bores, GW1 to GW9, should be screened in the saprolite aquifer, with an additional shallow nested bore included at GW1. Quarterly monitoring of the water-level and salinity of new and existing bores is recommended. Surface-water monitoring at the two new locations, SW1 and SW2, and existing WEC locations shown in Figure 11, should occur annually in late winter, if accessible. To monitor any changes in surface-water flow and quality; initial quarterly monitoring would be desirable to establish current seasonal trends.

6. CONCLUSIONS

The Brookton Mining Area straddles two catchments, the Darkin River catchment and the Dale River catchment. These two catchments are significantly different in their land-use and current hydrology. The Darkin River catchment is mostly forested with areas of old-growth forest and national park as well as being in the Mundaring Weir drinking-water catchment. While these factors illustrate that the ecosystem is highly valued and negative effects on the ecosystem will be scrutinised, they also suggest that the ecosystem is resilient, especially given the declines in streamflow and salinity noted since the 1970's and the deep groundwater-table in Beraking Brook catchment where most of the bauxite is located. The Dale River catchment by contrast is largely cleared for agriculture with high stream-salinities and shallow groundwater-depths, in this catchment there may be some increase in salinity and surface-water expression on the property downslope of most of the bauxite, but the effects are likely to be limited to this minor tributary as mining will have only a minor effect on the vegetation cover of the overall catchment.

The FDA method has been developed for areas with higher rainfall and higher forest density, therefore the applicability of this method to this area is unknown but is expected to be conservative. The method is expected to be useful in identifying areas of greatest flux, however, the estimated magnitude of this flux is not expected to have a high degree of accuracy, so caution should be applied to interpreting the results. While the overall salinity risk of bauxite mining in the Brookton Mining Area is expected to be low, the groundwater monitoring data in the area is limited and there is only one observation at each bore. Further monitoring is recommended before mining activities, to develop a better understanding of the current hydrology. An additional nine groundwater, and two surface-water monitoring sites are recommended, as well as resumption of monitoring at existing sites.

References

Conservation Commission, 2013. *Forest Management Plan 2014-2023*, Conservation Commission of Western Australia, Perth.

Conservation Commission, 2022. *Draft Forest Management Plan 2024-2033*, Conservation Commission of Western Australia, Perth.

Croton, J.T., 1991. *Relationships of Groundwater Levels and Salt Storages to the Geomorphology of the Intermediate Rainfall Zone of the Northern Jarrah Forest.* Alcoa Environmental Research Bulletin No. 24.

Croton, J.T. & Dalton, J.A. 2000. *Review of the Salinity Research and Development Programme for the Boddington Bauxite Mine*. Water & Environmental Consultants Report to Worsley Alumina Pty. Ltd.

Croton, J.T. & Dalton, J.A. 2001. *Review of the Soil Salinity Database for the Boddington Bauxite Mine*. Water & Environmental Consultants Report to Worsley Alumina Pty. Ltd.

Croton, J.T. and Dalton, J.A., 2003. *Salinity Risk Assessment for the Boddington Bauxite Mine using FDA*. Water & Environmental Consultants Report to Worsley Alumina Pty. Ltd.

Croton, J.T. & Dalton, J.A. 2004. *Soil Salt Storages and Salinity Risk Assessment for the Boddington Bauxite Mine*. Water & Environmental Consultants Report to Worsley Alumina Pty. Ltd.

Croton, J.T. & Dalton, J.A., 2007a. *Summary of Soil Salt Storages for the Boddington Bauxite Mine*. Water & Environmental Consultants Report to Worsley Alumina Pty. Ltd.

Croton, J.T., Mauger, G.W., and Dalton, J.A., 2007b. *Stream Sampling Programme for Expansion in ML258SA*. Water & Environmental Consultants Report to Worsley Alumina Pty. Ltd.

Department of Primary Industries and Regional Development (DPIRD), 2023. *Interactive Groundwater and Salinity Map for South-West Agricultural Region*, accessed 24th April 2023 https://www.agric.wa.gov.au/resource-assessment/interactive-groundwater-and-salinity-map-south-west-agricultural-region

Department of Water and Environmental Regulation (DWER), 2022. *Public Drinking Water Source Areas (DWER-033)*, accessed 10th March 2023 https://catalogue.data.wa.gov.au/dataset/public-drinking-water-source-areas

Green, K.A., Croton, J.T., & Dalton, J.A., 2021. *Boddington Bauxite Mine Triennial Aquifer Review July 2017 – June 2020*. Water & Environmental Consultants Report to South32 Worsley Alumina Pty. Ltd.

Green, K.A., Croton, J.T., G.T. Dalton, & Dalton, J.A., 2023. *Salinity Risk Assessment for the Hotham North Mining Area Using Flux Density Analysis*. Water & Environmental Consultants Report to South32 Worsley Alumina Pty. Ltd.

National Resource Management Ministerial Council (NRMMC), 2011. *Australian Drinking Water Guidelines Paper 6 National Water Quality Management Strategy*. National Health and Medical Research Council, National Resource Management Ministerial Council, Commonwealth of Australia, Canberra.

Olsen, G., Croton, J.T., & Vickery, E.A., 2009. *Report on the 2008 Stream Sampling Programme for Expansion in ML258SA*. Water & Environmental Consultants Report to Worsley Alumina Pty. Ltd.

Olsen, G., Croton, J.T., & Vickery, E.A., Mauger, G.W., 2010. *Report on the 2009 Stream Sampling Programme for Expansion in ML258SA*. Water & Environmental Consultants Report to Worsley Alumina Pty. Ltd.

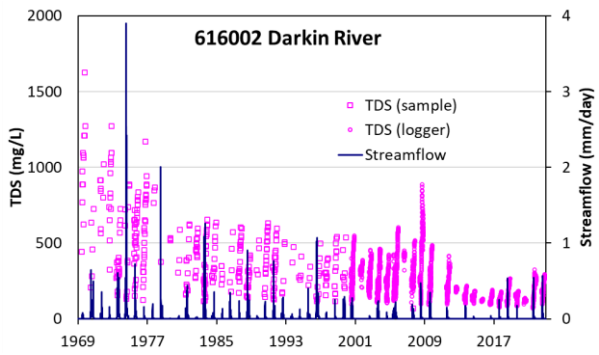
Pepper, R. & G., & Craig, G. F. (1986). *Resistance of Selected Eucalyptus Species to Soil Salinity in Western Australia*. Journal of Applied Ecology, 977-987.

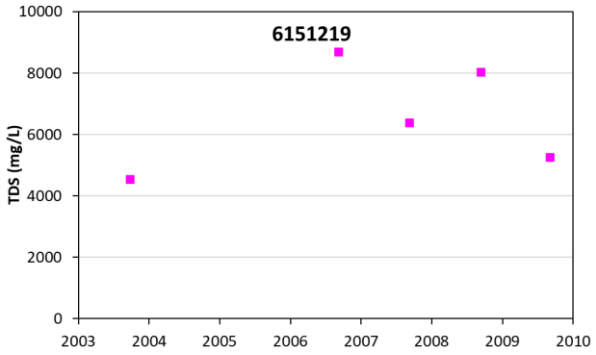
Stokes, R.A., Stone, K.A. & Loh, I.C. 1980. *Summary of soil salt storage characteristics in the northern Darling Range*. Water Resources Branch, Public Works Depart. W.A., Tech. Rep. No. WRB 94.

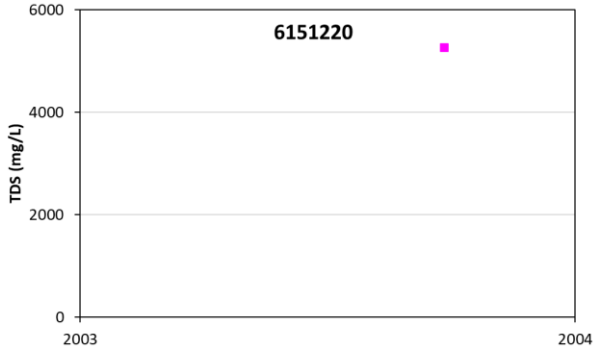
Tsykin, E.N. & Croton, J.T. 1988. *General salt storage-terrain relationships for the Darling Range, W.A.* Alcoa Environmental Research Note No. 14.

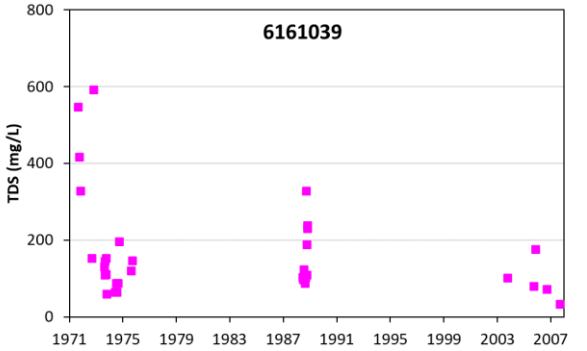
Appendix

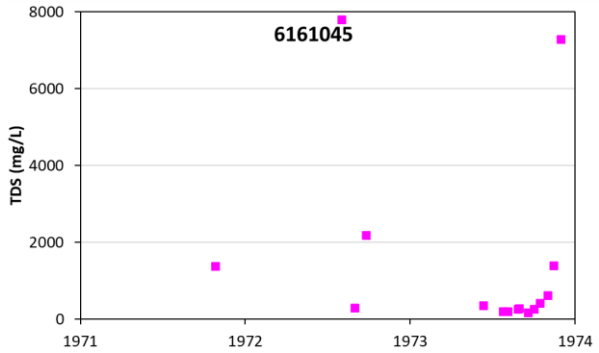
Surface-water monitoring plots (see Figure 6 for locations).

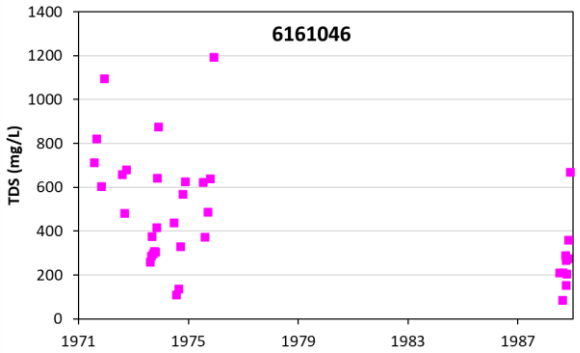


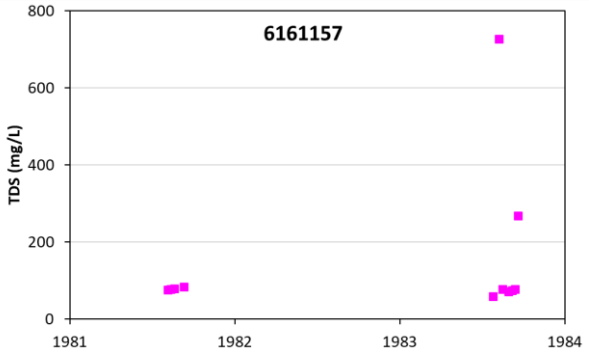


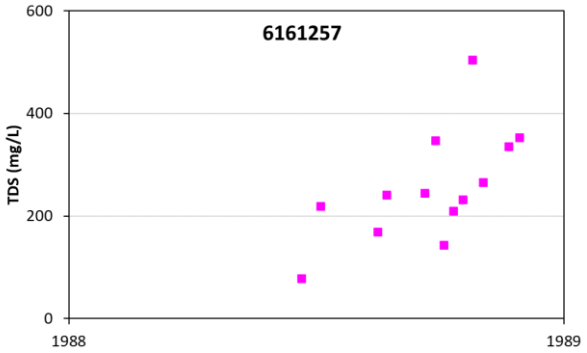


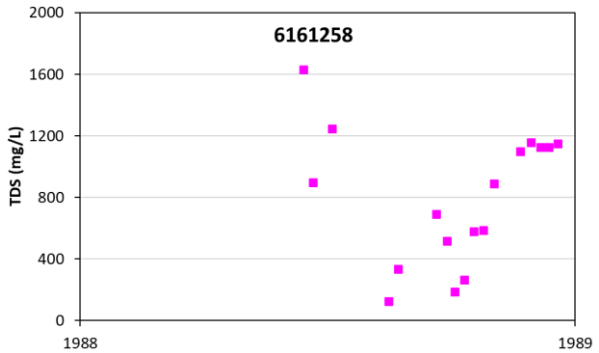


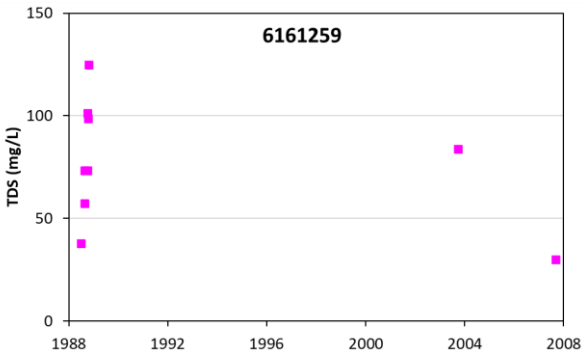


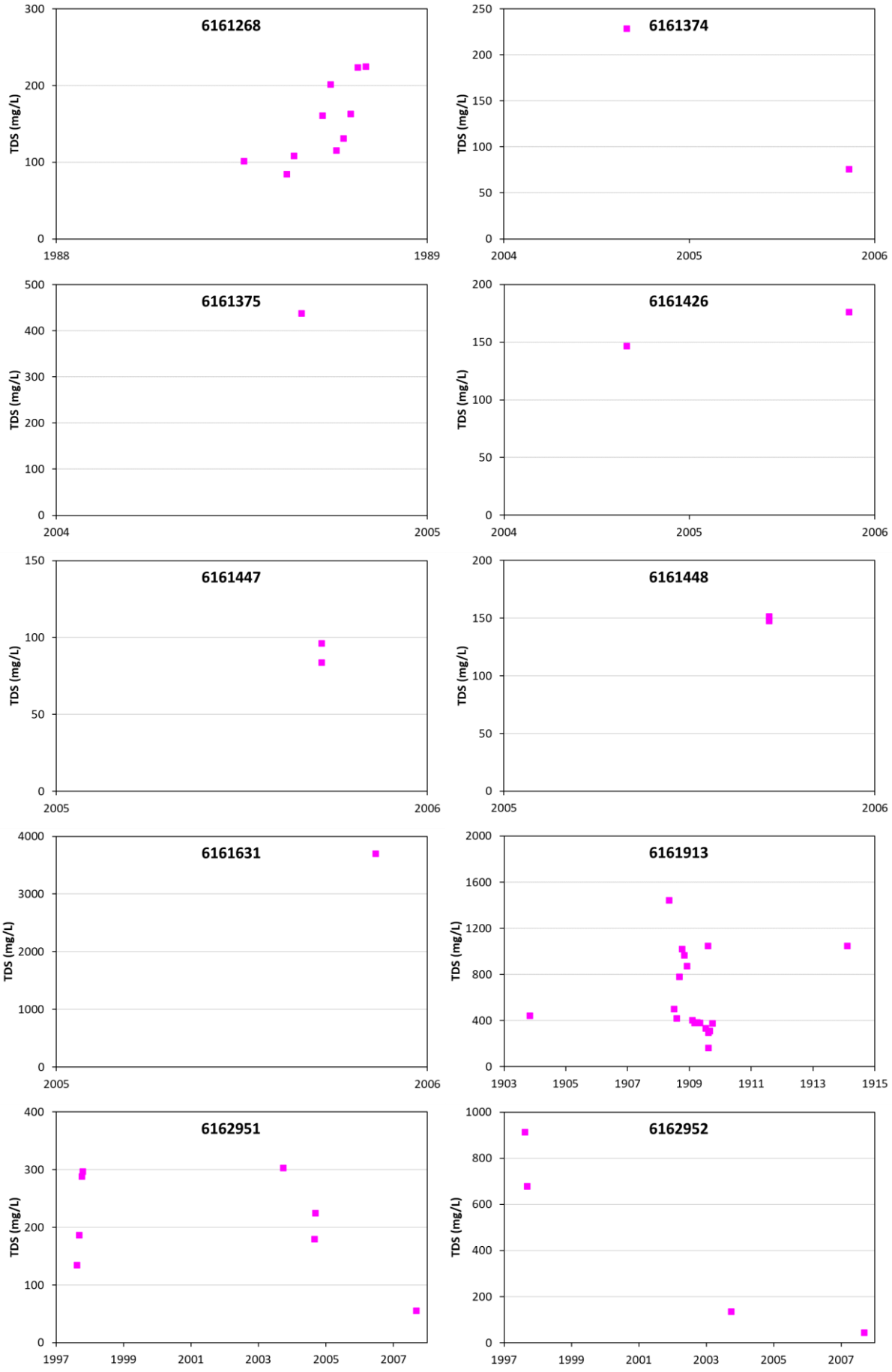











6161268
TDS (mg/L)
300
200
100
0
1988
1989
6161374
TDS (mg/L)
250
200
150
100
50
0
2004
2005
2006
6161375
TDS (mg/L)
500
400
300
200
100
0
2004
2005
6161426
TDS (mg/L)
200
150
100
50
0
2004
2005
2006
6161447
TDS (mg/L)
150
100
50
0
2005
2006
6161448
TDS (mg/L)
200
150
100
50
0
2005
2006
6161631
TDS (mg/L)
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3000
2000
1000
0
2005
2006
6161913
TDS (mg/L)
2000
1600
1200
800
400
0
1903
1905
1907
1909
1911
1913
1915
6162951
TDS (mg/L)
400
300
200
100
0
1997
1999
2001
2003
2005
2007
6162952
TDS (mg/L)
1000
800
600
400
200
0
1997
1999
2001
2003
2005
2007