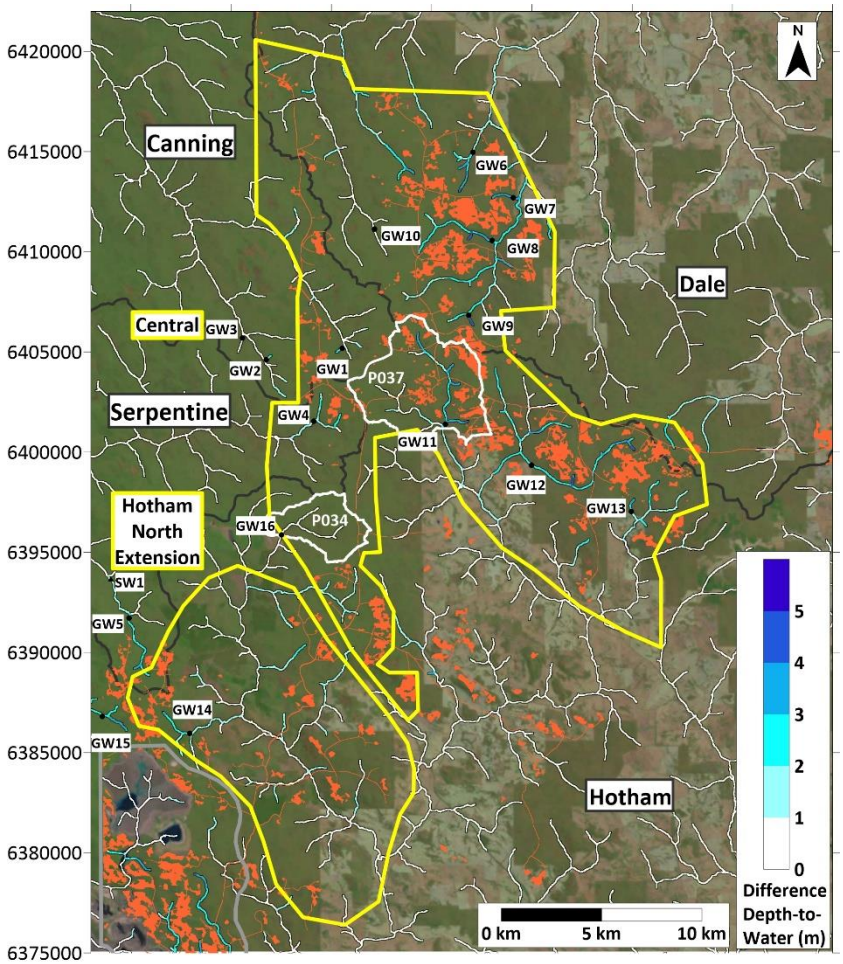
**REPORT**
**TO**
**SOUTH 32 WORSLEY ALUMINA PTY LTD**

# SALINITY RISK ASSESSMENT FOR THE CENTRAL & HOTHAM NORTH EXTENSION MINING AREAS 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 Central Mining Area (CMA) and Hotham North Extension Mining Area (HNEMA) to develop an understanding of the current state of the groundwater and surface-water systems: it evaluates available information on the climate, hydrogeology, soil-salt storage, groundwater level and quality, and surface-water level/flow and quality. Flux Density Analysis (FDA) is then used to assess the potential salinity-risk and identify potential salinity-hotspots.

Rainfall has been declining since 1975, with rainfall over the recent period on average fifteen-percent lower than pre-1975 rainfall. This has led to associated declines in the groundwater-table under the forested areas of Boddington Bauxite Mine (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 CMA and HNEMA is similar 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 in forested areas disconnected from the surface water; it is often connected to the stream in agricultural areas.

The CMA is spread across four catchments, Hotham and Dale catchments where the majority of the bauxite is, and Canning and Serpentine drinking-water catchments which both have small areas of identified bauxite. The land is mostly State Forest or Timber Reserve, with agricultural land downslope in both the Dale and Hotham catchments. The HNEMA is predominantly in Hotham catchment with a small area in Serpentine catchment. Plantation forestry is the main land use in HNEMA.

Groundwater data for CMA and HNEMA is very limited. In 2007-09 WEC undertook extensive surface-water monitoring of sub-catchments in the area, and there is some publicly available surface-water data going back to the 1970s. Samples from agricultural areas were saline, while those in forested areas were generally fresh, except for two unusual sub-catchments.

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 these areas, given the size of CMA and HNEMA, and variance in forest-density and rainfall, 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 minor tributaries of the Dale and Hotham catchments, both of which have cleared agricultural land downslope. There may be some increase in salinity and surface-water expression on agricultural properties directly downslope of bauxitic areas, but this is expected to be limited to minor tributaries. Because the bauxitic areas are small and the groundwater table has fallen since the 1970's, water quality in the Canning and Serpentine drinking water catchments is not expected to be affected by mining activities. However, as the catchments supply public drinking-water, any mining within them will have a significant profile.

Sixteen groundwater-monitoring sites have been recommended to develop an understanding of the current groundwater state and to monitor any changes. Renewed monitoring of surface-water sites in the 2007-09 studies, and the inclusion of an additional surface water site is also recommended. Automated surface-water monitoring with the Canning and Serpentine catchments is 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 Central Mining Area (CMA) and Hotham North Extension Mining Area (HNEMA). 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 CMA and HNEMA, 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.

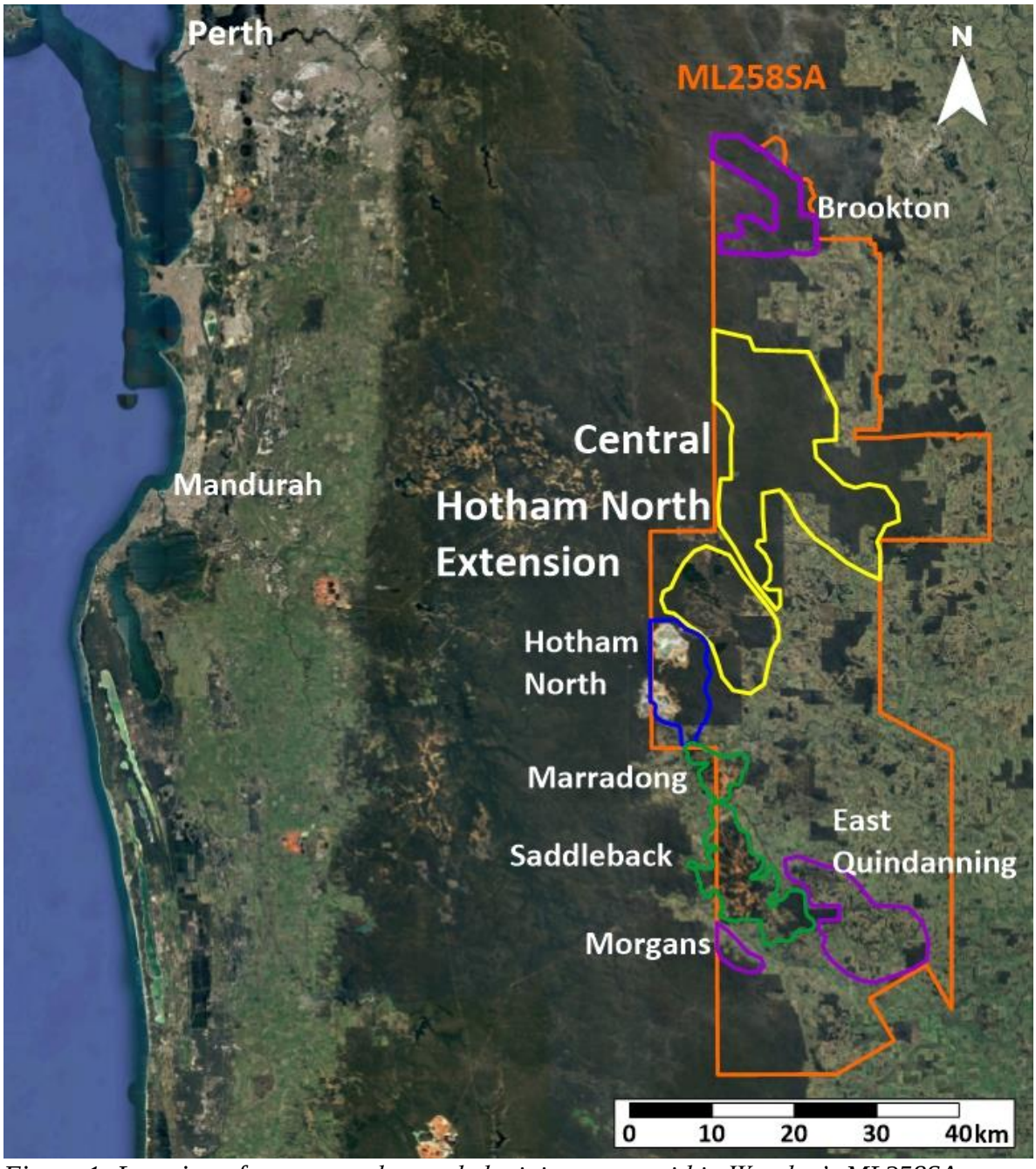


*Figure 1: Location of current and extended mining areas within Worsley's ML258SA.*

## 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 bauxite-mining in CMA and HNEMA this report assesses these factors, using available data.

## 1.2 Climate

The Central Mining Area (CMA) and Hotham North Extension Mining Area (HNEMA) are 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 the Marradong pluviometer shown in Figure 2. This pluviometer is located between the Marradong and Saddleback mining areas. The average rainfall since 1975 (642 mm/yr) is fifteen percent (117 mm) lower than the pre-1974 average (759 mm/yr). The rainfall decline 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.

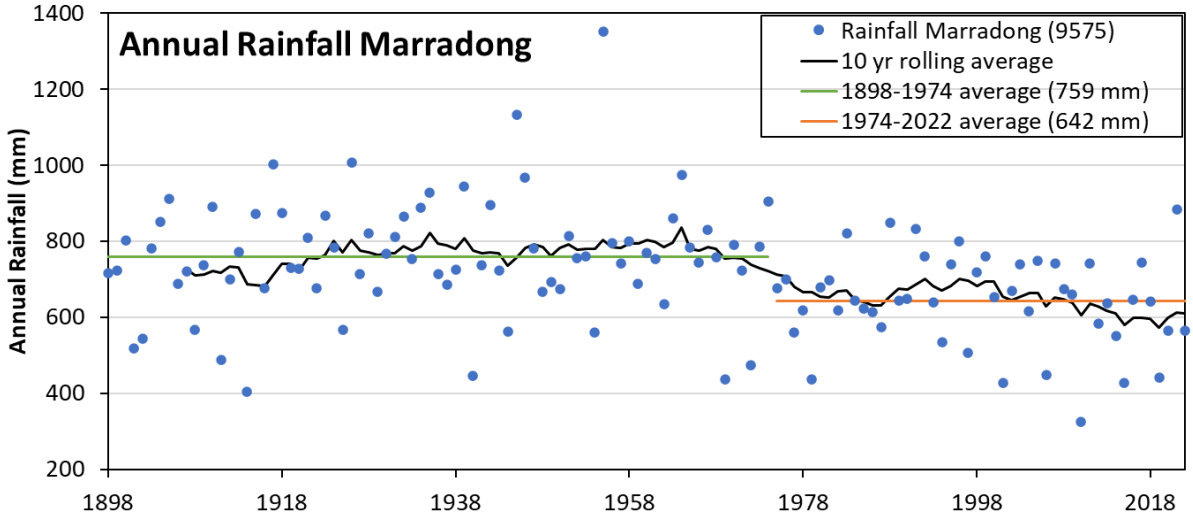


*Figure 2: Annual rainfall for Marradong rain gauge 9575.*

## 1.3 Hydrogeology

The hydrogeology of CMA and HNEMA is similar to that at Worsley BBM operations which lie to the south of these areas, 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 mid and upper-slope 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. In the lower slopes and valley-floor the duricrust can be absent; the top-layer of gravel and the bauxite layer can form a single entity which in total is usually thinner than the mid and upper-slope layers. The near-surface soils are highly permeable, so streamflow is usually generated from lateral flows in the upper layer and in 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. In forested areas these aquifers are usually disconnected from surface water 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 CMA and HNEMA to these areas it is expected that the findings from these studies will provide insight to the CMA and HNEMA. The underlying bedrock in CMA and HNEMA is Yilgarn Craton granites. 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$^3$) in BBM. 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

Land use in CMA and HNEMA is a mixture of cleared agricultural land and forested areas, Figure 3 shows the major land use and Serpentine and Canning Public Drinking Water Source Areas (PDWSAs). The majority of CMA is State Forest and Timber Reserves, there are some proposed Conservation Parks and a proposed National Park bordering the mining area. The western side edge of the CMA is part of the Canning and Serpentine PDWSAs. The north of CMA drains to the Dale River catchment, which flows north-east through mostly agricultural land before joining the Avon River. The southern area drains to the Hotham River, which flows south around the BBM area before merging with Williams River to form the Murray River. The HNEMA has large areas of plantation forest of varying ages and includes a small area inside the Serpentine PDWSA, with the remainder inside Hotham River catchment.

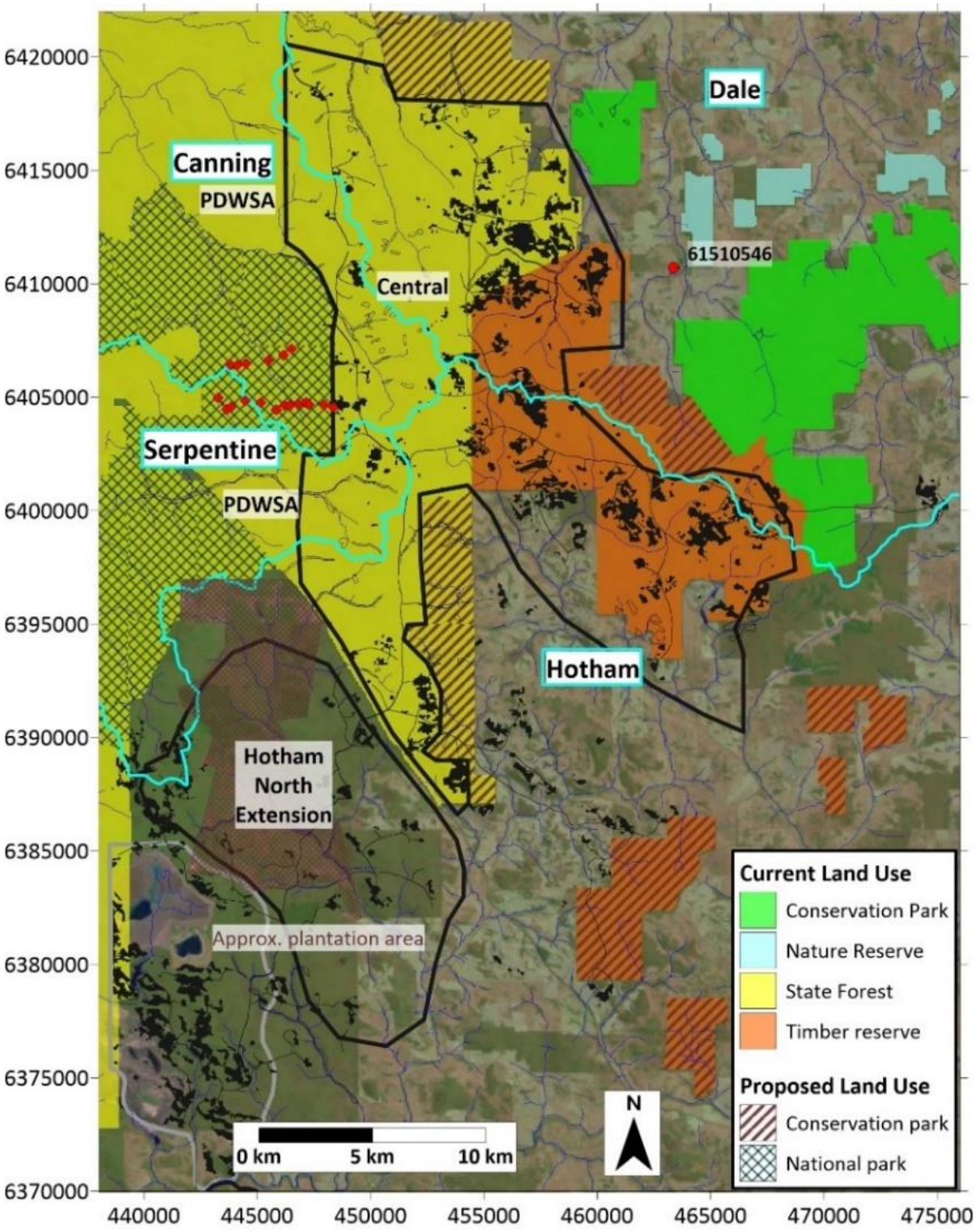


*Figure 3: Land use and water catchments of CMA, HNEMA, and surrounds.*

# 3. GROUNDWATER REVIEW

There is very limited groundwater information for the CMA and HNEMA, there is one salinity measurement available in the publicly available Water Information Resources (WIR) database, for bore 61510546 located in agricultural land to the east of CMA (see Figure 3). This bore has a salinity reading of 7,150 mg/L, the date of measurement and depth of the water-table are unknown, the bore has a total depth of 8.5 m. In the late 1970's several bores were drilled for Alcoa, to the west of CMA in Canning and Serpentine catchments. The observed water-table level at the time of drilling was recorded for these; this is not an accurate water-table

measurement as it is affected by the soil hydraulic-conductivity, however it provides some indication of the level. The observed level in meters below-ground-level is shown in Figure 4 ('>' indicates the level was below the drilled depth). The water-table along the valley floor was observed within ten meters of the surface, while further upslope it was significantly deeper.

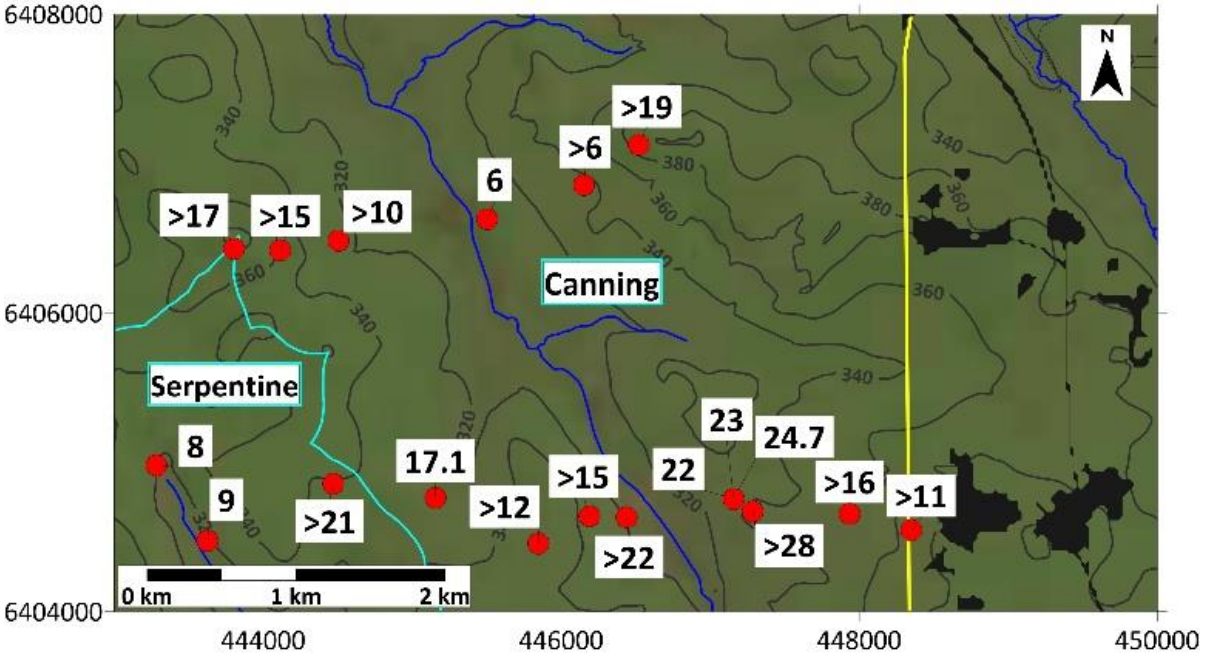


*Figure 4: Observed groundwater table at time of drilling.*

# 4. SURFACE WATER REVIEW

Surface water monitoring of many sites in the CMA and HNEMA catchments was conducted between 2007 and 2009 by Croton and Olsen (Croton *et al.* 2007b, Olsen *et al.* 2009 & 2010). Below, the results from these studies and relevant publicly available surface-water data are discussed by catchment.

### *Dale catchment*

There are thirty relevant WEC surface-water monitoring locations in the Dale catchment; the locations are shown in Figure 5 with the catchments shaded based on the highest recorded salinity; the flow and salinity data is summarised in

Table 1. There is a significant difference in stream salinity; in forested-areas compared to agricultural-areas, with all forested-area stream-salinity below 200 mg/L, and all agricultural-land stream-salinity above 2,500 mg/L. Streamflow is ephemeral, with flow ceasing by October at all monitoring locations except for the three large agricultural catchments.

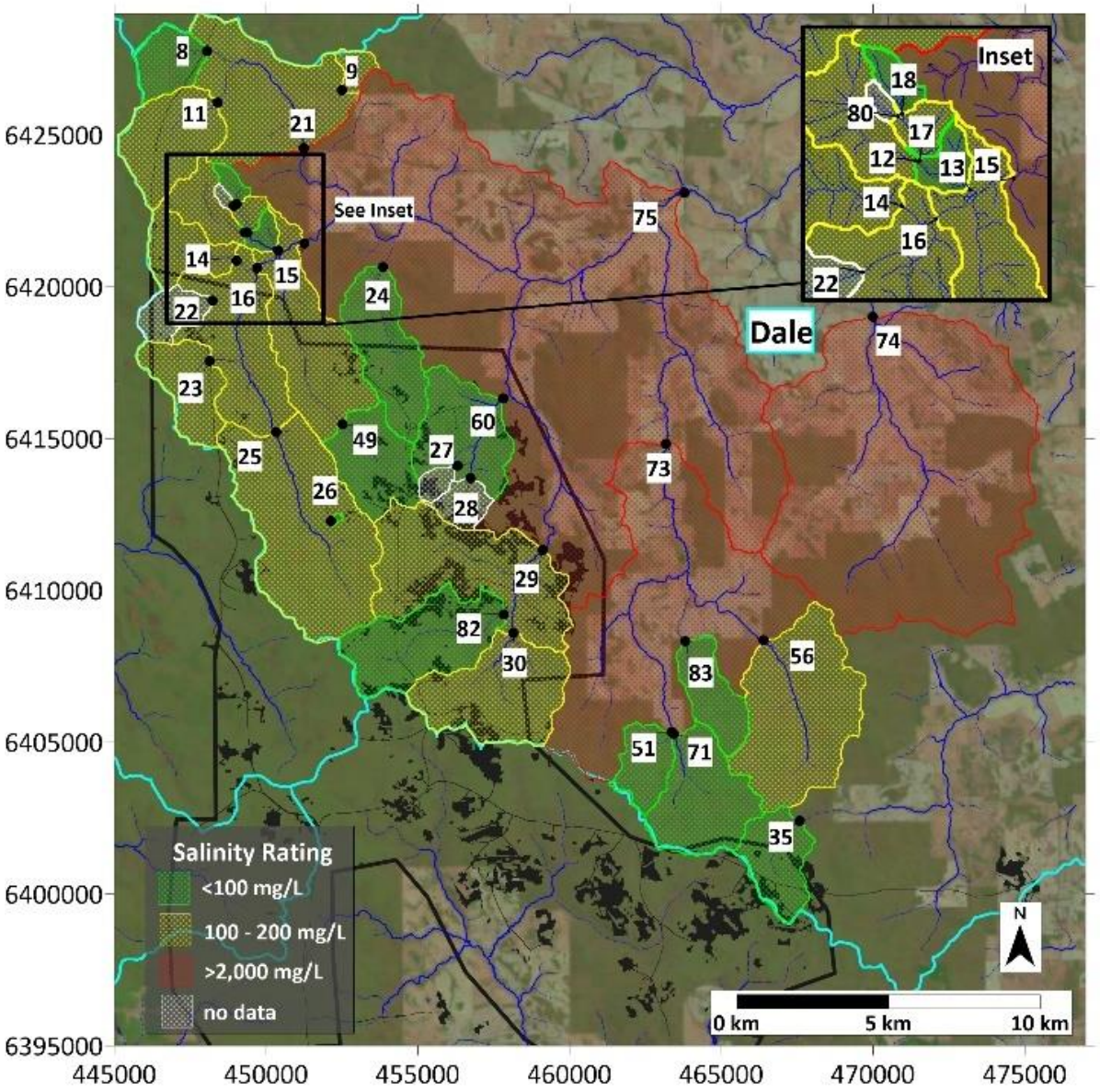


*Figure 5: Relevant surface-water monitoring locations in Dale catchment.*

*Table 1: Summary of relevant surface water monitoring data for Dale catchment from WEC studies 2007-2009.*

| Site | Area ($km^2$) | 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-P012** | 3.7 | 35 | dry | 2.1 | 32 | 19 | ceased | 81 | 83 | 72 | 79 | 109 |
| **WEC-P013** | 6.9 | 17 | dry | 1.9 | 53 | 18 | dry | 86 | 87 | 76 | 84 | - |
| **WEC-P014** | 4.8 | 1.3 | dry | ceased | 27 | 6.0 | dry | 106 | 109 | 84 | 93 | - |
| **WEC-P015** | 78.6 | - | dry | 1.5 | 30 | 50 | ceased | - | 84 | 90 | 89 | 106 |
| **WEC-P016** | 51.0 | 0.9 | dry | ceased | 32 | 13 | ceased | 106 | 92 | 85 | 97 | 136 |
| **WEC-P017** | 2.1 | - | - | ceased | ceased | dry | dry | - | - | 104 | - | - |
| **WEC-P018** | 0.8 | - | dry | ceased | 2.1 | 0.60 | dry | - | 72 | 60 | 67 | - |
| **WEC-P021** | 30.2 | 46 | dry | 0.20 | 69 | 21 | ceased | 86 | 106 | 85 | 95 | 192 |
| **WEC-P022** | 2.9 | dry | dry | dry | dry | dry | dry | - | - | - | - | - |
| **WEC-P023** | 6.1 | 0.3 | dry | ceased | 0.10 | 0.25 | dry | 122 | 108 | 111 | 95 | - |
| **WEC-P024** | 9.2 | - | dry | - | 3.0 | 10 | dry | - | - | 84 | 84 | - |
| **WEC-P025** | 24.3 | 2.3 | dry | ceased | 0.05 | ceased | dry | 137 | 128 | 127 | 129 | - |
| **WEC-P026** | 0.1 | 0.2 | dry | ceased | 0.09 | 0.25 | dry | 49 | 44 | 46 | 44 | - |
| **WEC-P027** | 1.0 | - | dry | dry | dry | dry | dry | - | - | - | - | - |
| **WEC-P028** | 2.2 | dry | dry | dry | dry | dry | dry | - | - | - | - | - |
| **WEC-P029** | 42.5 | 2.2 | dry | ceased | 0.80 | 0.40 | dry | 127 | 57 | 100 | 115 | - |
| **WEC-P030** | 12.8 | 0.1 | dry | ceased | 0.31 | ceased | dry | 91 | 117 | 91 | 100 | - |
| **WEC-P035** | 6.1 | dry | dry | ceased | ceased | dry | dry | - | 64 | 68 | - | - |
| **WEC-P049** | 7.5 | - | dry | ceased | ceased | ceased | dry | - | 66 | 87 | 79 | - |
| **WEC-P051** | 4.1 | - | dry | ceased | 0.67 | ceased | dry | - | 83 | 83 | 94 | - |
| **WEC-P056** | 19.4 | - | dry | dry | ceased | ceased | dry | - | - | 54 | 150 | - |
| **WEC-P060** | 12.4 | - | - | - | ceased | ceased | ceased | - | - | 95 | 82 | 76 |
| **WEC-P071** | 10.4 | - | - | dry | ceased | dry | dry | - | - | 92 | - | - |
| **WEC-P073** | 84.5 | - | - | 100 | 300 | 100 | 4 | - | 6393 | 3743 | 5168 | 8100 |
| **WEC-P074** | 75.5 | - | - | 210 | 360 | 60 | 3 | - | 5615 | 3813 | 5745 | 10809 |
| **WEC-P075** | 396.2 | - | - | 530 | 3000 | 330 | 10 | - | 5474 | 2683 | 3872 | 7217 |
| **WEC-P080** | 0.3 | - | - | dry | dry | dry | dry | - | - | - | - | - |
| **WEC-P081** | 9.3 | - | - | 0.04 | ceased | 0.10 | dry | - | 91 | 85 | 86 | - |
| **WEC-P082** | 11.6 | - | - | - | ceased | ceased | dry | - | - | 76 | 66 | - |
| **WEC-P083** | 5.1 | - | - | - | - | ceased | dry | - | - | - | 71 | - |

### *Canning catchment*

The Canning catchment contains four WEC monitoring sites, all of which have publicly available data for the same location or nearby in the WIR database; these are shown in Figure 6 with two additional WIR monitoring locations. The data from WEC and WIR monitoring sites are summarised in Table 2 and Table 3 respectively.

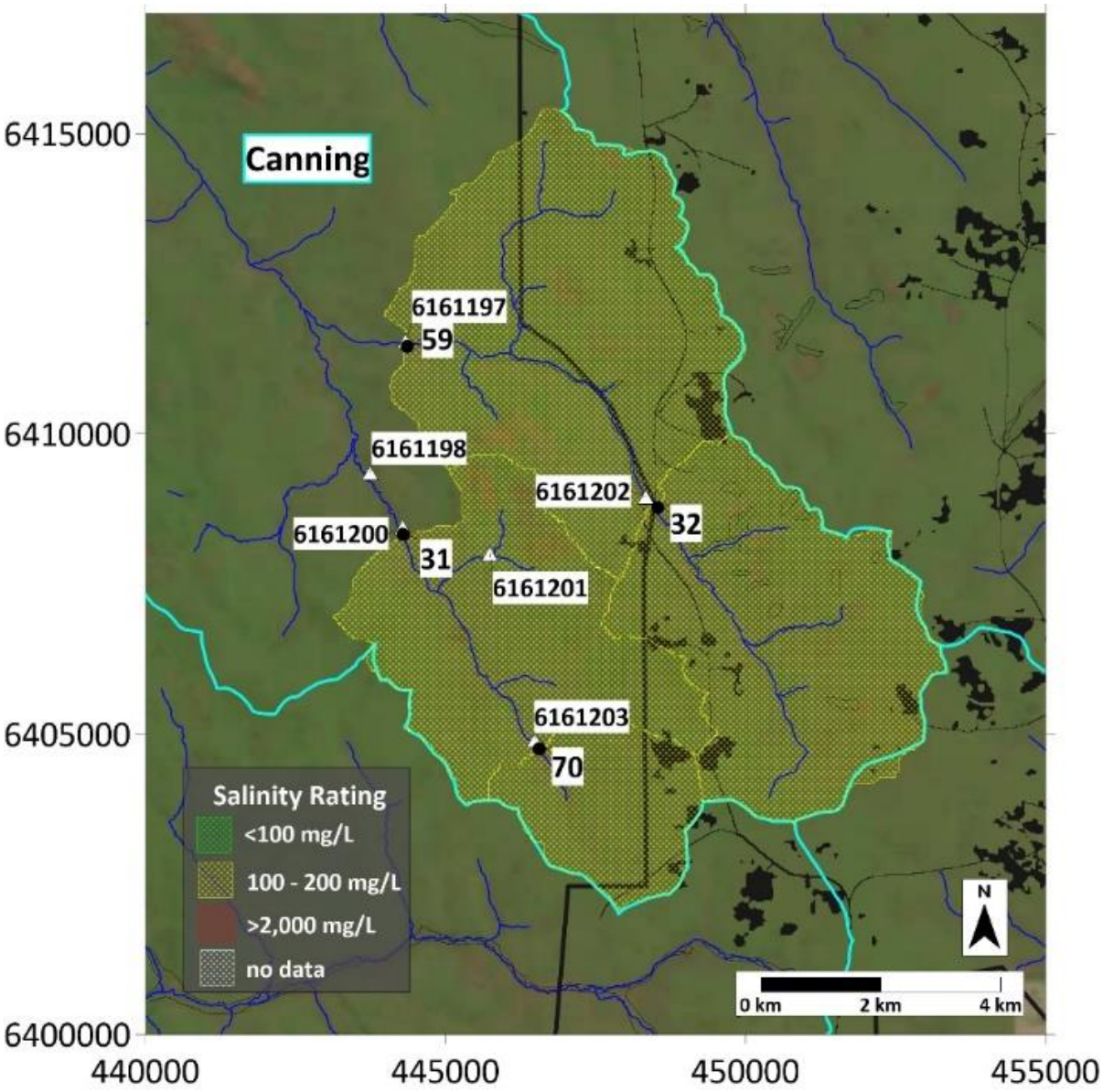


*Figure 6: Relevant surface-water monitoring locations in Canning catchment.*

*Table 2: Summary of relevant surface-water monitoring data for Canning catchment from WEC studies 2007-2009.*

| Site | Area | Flow (L/sec) | | | | | TDS (mg/L) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Nov-08 | Jul-09 | Aug-09 | Sep-09 | Oct-09 | Jul-09 | Aug-09 | Sep-09 | Oct-09 |
| **WEC-P059** | 49.9 | dry | ceased | 2.0 | 6.0 | ceased | 80 | 91 | 97 | 197 |
| **WEC-P032** | 21.9 | dry | 0.02 | 2.5 | 6.0 | ceased | 108 | 107 | 111 | 134 |
| **WEC-P031** | 25.4 | dry | 2.8 | 8.0 | 25 | ceased | 85 | 94 | 101 | 119 |
| **WEC-P070** | 7.3 | - | 0.13 | 0.20 | 0.40 | ceased | 64 | 72 | 82 | 109 |

*Table 3: Summary of relevant surface-water monitoring data for Canning catchment from WIR database.*

| Site | WEC Site | Easting | Northing | Date range | TDS range (mg/L) |
|---|---|---|---|---|---|
| **6161197** | **WEC-P059** | 444340 | 6411551 | Jul-Sept 1978 | 60 |
| **6161202** | **WEC-P032** | 448340 | 6408951 | 1975-1984 | 10 - 310 |
| **6161200** | **WEC-P031** | 444290 | 6408451 | 1975-1984 | 10 - 410 |
| **6161201** | **-** | 445740 | 6408001 | 1975-1984 | 10 - 470 |
| **6161203** | **WEC-P070** | 446490 | 6404901 | 1975-1980 | 40 - 80 |
| **6161198** | **-** | 443740 | 6409351 | 1976-1984 | 10 - 240 |

The pairs of upstream and downstream monitoring of two waterways suggest a difference in the hydrology of the adjacent catchments; plots of paired monitoring-locations are shown in Figure 7. In the north-east catchment the upstream monitoring point, WEC-032, has flow equal to or greater than the downstream monitoring point WEC-059 with more than double the catchment area, suggesting that some of the upstream flow is infiltrating the soil. In the earlier monitoring period, the upstream site (6161202) has significantly higher salinity in October 1978, whereas salinity is more stable downstream (6161197). In the 2009 monitoring data, by contrast, the upstream salinity (WEC-P032) is more stable, whereas the downstream salinity (WEC-059) more than doubles in October. It is difficult to draw strong conclusions from the limited data as factors such as the timing and volume of rainfall before measurements could affect the results, and no flow-monitoring occurred in the earlier period. The sharp rises in late-season salinity suggest that there is some interflow contribution at the upstream site in the 1978, and at the downstream site in 2009. The movement of this effect downstream may be due to the declining rainfall resulting in a greater disconnect of the surface and ground-water systems at the upstream site, while interflow may contribute a greater share of total flow at the downstream site.

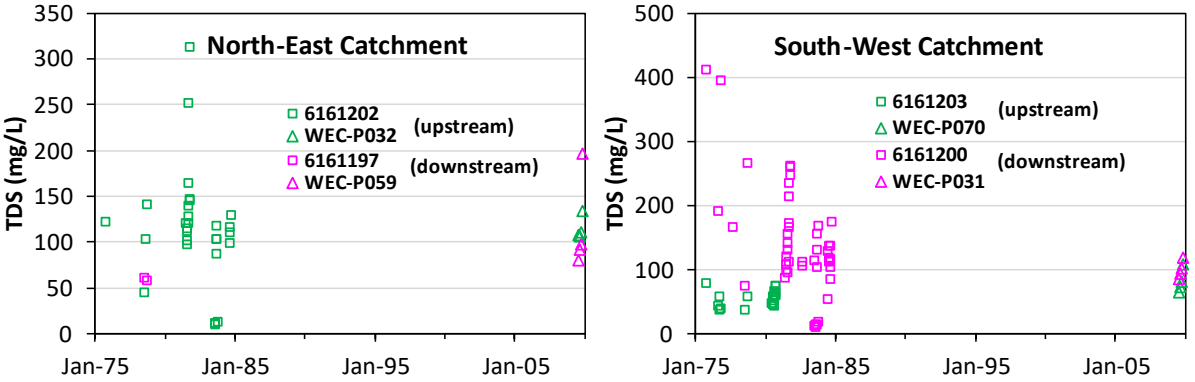


*Figure 7: Plots of surface-water salinities in Canning catchment.*

In the south-west catchment the flow at the downstream location (WEC-P031) is significantly higher than at the upstream location (WEC-P070), and the flows in the north-east catchment, even when adjusting for catchment size. Salinities are also slightly higher at the downstream location suggesting that there is some contribution from interflow. The measured salinity at the downstream location is higher in the earlier monitoring period than in 2009, indicating that there may have been a larger contribution from interflow in the earlier period. Monitoring point 6161201 on a small tributary has the highest recorded salinity in this catchment suggesting that there may be some interflow contribution from this tributary.

### *Serpentine catchment*

There are five WEC monitoring sites and five relevant WIR database monitoring sites in the Serpentine catchment. All monitoring locations are in the eastern headwaters of the catchment, as shown in Figure 8, with data for the WEC monitoring sites summarised in Table 4 and WIR data summarised in Table 5.

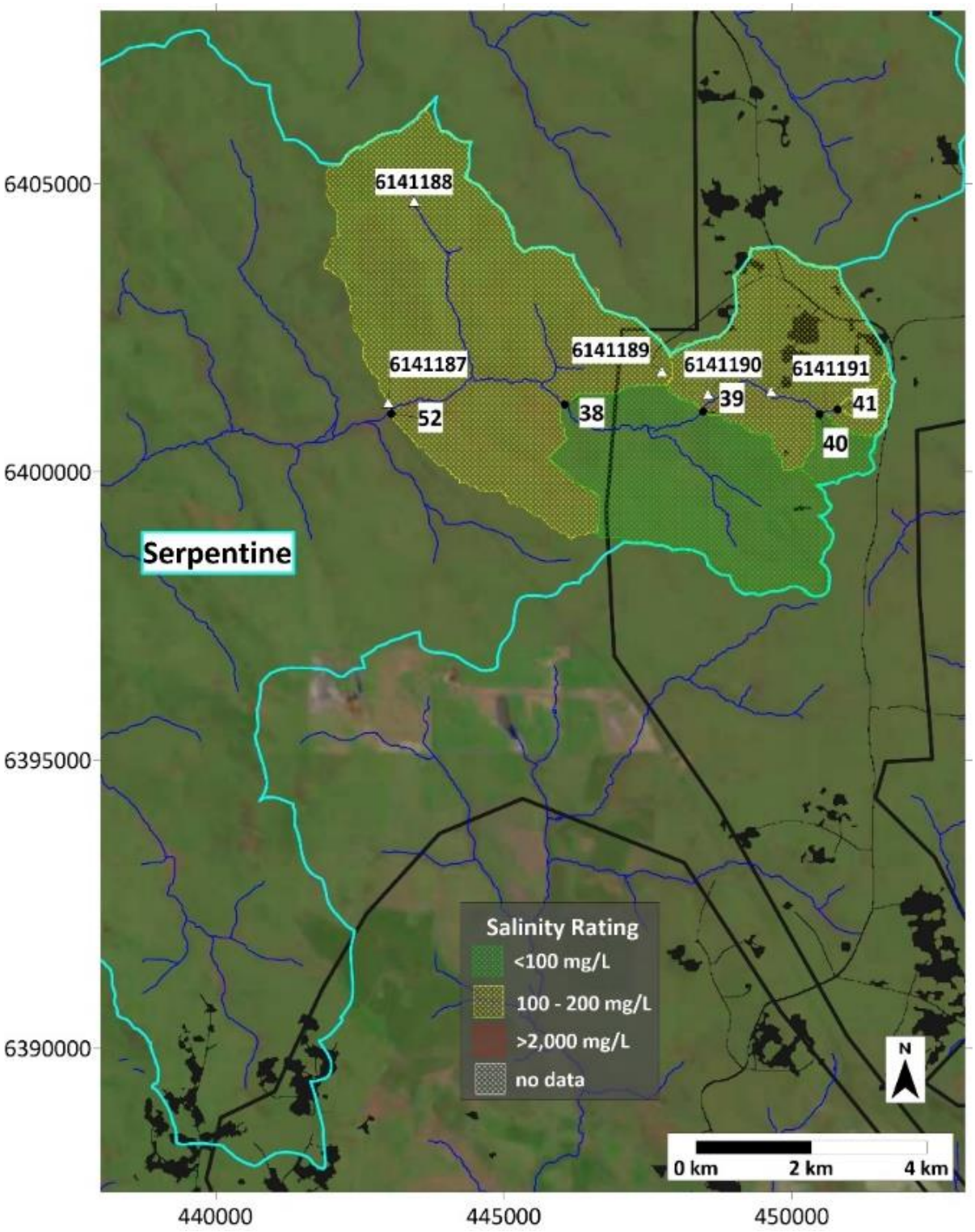


*Figure 8: Relevant surface-water monitoring locations in Serpentine catchment.*

*Table 4: Summary of relevant surface-water monitoring data for Serpentine catchment from WEC studies 2007-2009.*

| Site | Area | Flow (L/sec) | | | | | TDS (mg/L) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Nov-08 | Jul-09 | Aug-09 | Sep-09 | Oct-09 | Jul-09 | Aug-09 | Sep-09 | Oct-09 |
| **WEC-P038** | 20.9 | dry | ceased | 1.2 | 4.5 | dry | 68 | 78 | 80 | - |
| **WEC-P039** | 9.8 | dry | ceased | 0.25 | 1.0 | dry | 121 | 88 | 92 | - |
| **WEC-P040** | 1.0 | dry | 0.01 | 0.10 | 0.25 | dry | 86 | 88 | 90 | - |
| **WEC-P041** | 0.4 | dry | dry | 0.05 | 0.03 | dry | - | 104 | 105 | - |
| **WEC-P052** | 43.2 | dry | 15 | 97 | 80 | ceased | 101 | 95 | 117 | 188 |

*Table 5: Summary of relevant surface-water monitoring data for Serpentine catchment from WIR database.*

| Site | WEC Site | Easting | Northing | Date range | TDS range (mg/L) |
|---|---|---|---|---|---|
| **6141187** | **WEC-P052** | 442990 | 6401201 | 1975-1984 | 60 - 4720 |
| **6141188** | **-** | 443440 | 6404701 | 1976-1980 | 240 - 1900 |
| **6141189** | **-** | 447740 | 6401751 | 1976-1978 | 60 - 80 |
| **6141190** | **WEC-P039** | 448540 | 6401351 | 1976-1978 | 40 - 50 |
| **6141191** | **-** | 449640 | 6401401 | 1976-1978 | 30 |

The salinities at all monitoring points within Serpentine catchment in 2009 were below 200 mg/L. The salinity at the downstream location, WEC-P052, increased significantly in October suggesting there may be some interflow. Figure 9 shows the salinity at 6141187 in the earlier monitoring period and at nearby WEC-P052 in 2009. It appears that there have been two significant drops in the salinity with measurements over 1000 mg/L in the 1970's suggesting a significant groundwater connection, this falls to under 700 mg/L in the 1980's with a reduced groundwater contribution. In 2009 salinities are under 200 mg/L, suggesting there is likely only a small contribution of interflow and no deep groundwater connection at this time.

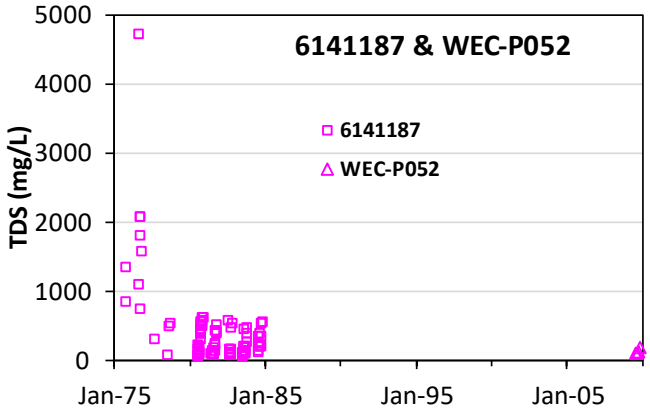


*Figure 9: Plot of salinity at 6141187 and nearby WEC-P052 surface-water monitoring location in Serpentine catchment.*

### Hotham catchment

There are twenty-six WEC and fourteen WIR database surface-water monitoring sites in the Hotham catchment, with the majority along the Bannister River and its tributaries; the locations are shown in Figure 10, and data summarised in

Table 6 and Table 7, respectively. Within the Bannister River catchment all monitoring sites on agricultural land have high salinities with readings up to 13,860 mg/L at 6140871. The salinities in forested areas are generally significantly lower (73 – 174 mg/L) except for two monitoring locations, WEC-P034 & P037 in forested catchments which both have maximum salinities over 2,000 mg/L. These high salinities coincided with lower pH values suggesting that there may be a contribution of acidic deep groundwater (Olsen *et al.*, 2009). There is planned mining within the catchment of WEC-P034, the additional infiltration due to the land clearing in this catchment may result in greater discharge of saline groundwater. Further investigation to identify the source of this salinity would be helpful to understand and minimise the salinity risk in this tributary.

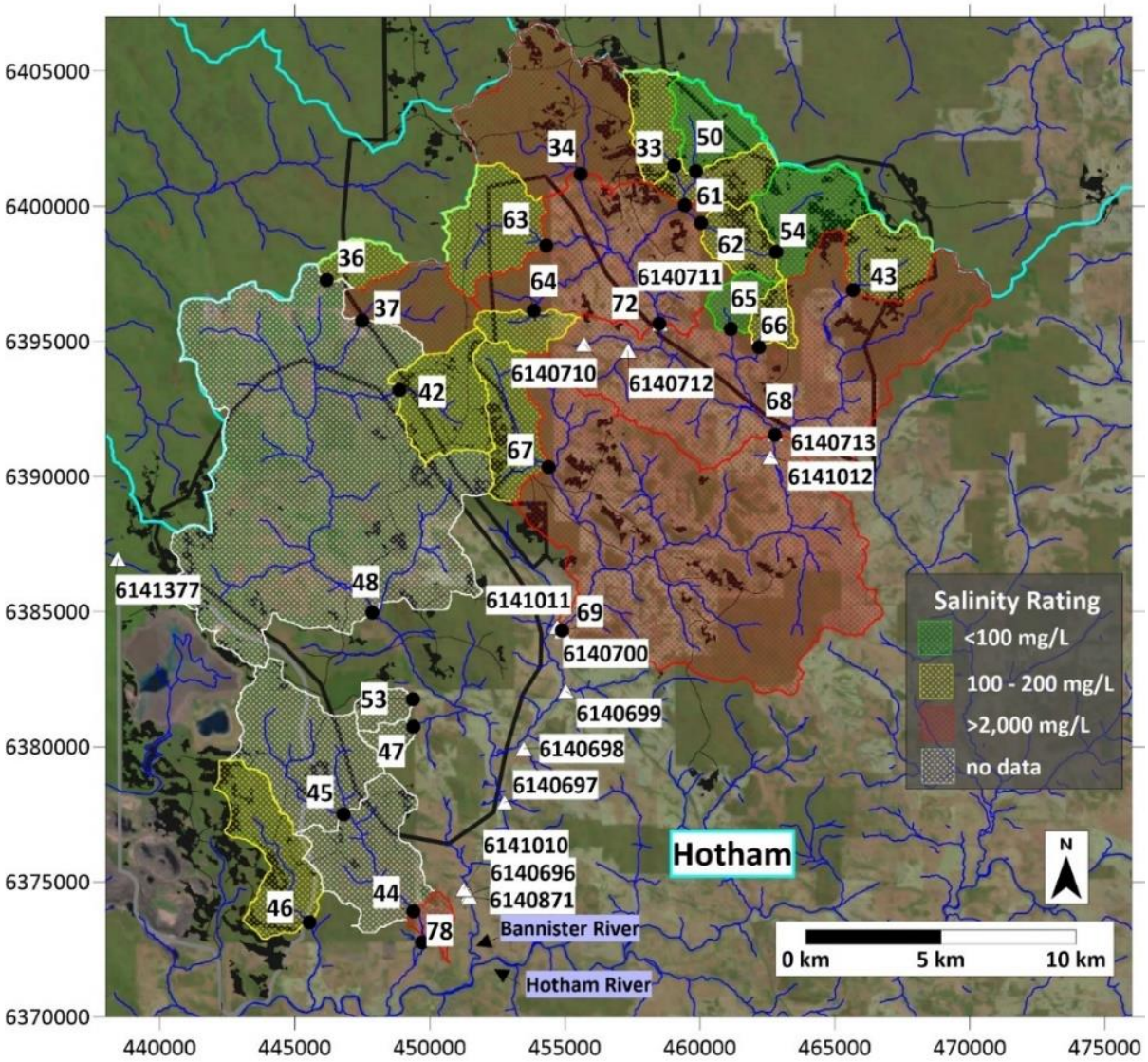


*Figure 10: Relevant surface-water monitoring locations in Hotham catchment.*

*Table 6: Summary of relevant surface-water monitoring data for Hotham catchment from WEC studies 2007-2009.*

| Site | Area ($km^2$) | Flow (L/sec) | | | | | | TDS (mg/L) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Aug-07 | Nov-08 | Jul-09 | Aug-09 | Sep-09 | Oct-09 | Aug-07 | Nov-08 | Jul-09 | Aug-09 | Sep-09 | Oct-09 |
| **WEC-P033** | 6.4 | dry | dry | dry | 0.10 | ceased | dry | - | - | - | 88 | 106 | - |
| **WEC-P034** | 27.7 | 3.0 | dry | 0.32 | 7.5 | 1.6 | ceased | 568 | - | 462 | 303 | 404 | 4420 |
| **WEC-P036** | 3.9 | 1.5 | dry | 0.01 | 15 | 4.0 | ceased | 147 | - | 101 | 93 | 93 | 95 |
| **WEC-P037** | 10.2 | 2.3 | dry | ceased | 15 | 5.0 | 0.15 | 619 | - | 2435 | 157 | 316 | 1233 |
| **WEC-P042** | 11.8 | 6.0 | dry | 0.40 | 10 | 6.0 | ceased | 86 | - | 84 | 79 | 86 | 126 |
| **WEC-P043** | 8.2 | 0.04 | dry | ceased | 0.15 | 0.02 | dry | 137 | - | 106 | 98 | 112 | - |
| **WEC-P044** | 36.1 | - | - | - | - | - | - | | - | - | - | - | - |
| **WEC-P045** | 20.3 | - | - | - | - | - | - | | - | - | - | - | - |
| **WEC-P046** | 12.8 | - | dry | 6.0 | 53 | 8.4 | dry | | - | 93 | 91 | 103 | - |
| **WEC-P047** | 1.9 | - | - | - | - | - | - | | - | - | - | - | - |
| **WEC-P048** | 134.6 | - | - | - | - | - | - | | - | - | - | - | - |
| **WEC-P050** | 7.2 | - | dry | dry | 0.10 | ceased | dry | | - | - | 77 | 87 | - |
| **WEC-P053** | 2.6 | - | - | - | - | - | - | | - | - | - | - | - |
| **WEC-P054** | 10.8 | - | dry | ceased | 1.5 | 0.01 | dry | | - | 86 | 85 | 94 | - |
| **WEC-P061** | 19.8 | - | dry | ceased | ceased | 0.20 | dry | | - | 92 | 84 | 112 | - |
| **WEC-P062** | 16.5 | - | dry | ceased | 6.0 | ceased | dry | | - | 126 | 92 | 86 | - |
| **WEC-P063** | 12.0 | - | dry | 0.56 | 10 | 3.0 | ceased | | - | 88 | 80 | 90 | 174 |
| **WEC-P064** | 4.2 | - | - | 0.001 | 9.0 | 0.50 | ceased | | - | 85 | 74 | 95 | 130 |
| **WEC-P065** | 3.3 | - | dry | dry | ceased | dry | dry | | - | - | 98 | - | - |
| **WEC-P066** | 2.9 | - | dry | ceased | 3.0 | 0.02 | dry | | - | 73 | 102 | 117 | - |
| **WEC-P067** | 9.9 | - | dry | 0.02 | 4.0 | 1.5 | dry | | - | 120 | 91 | 103 | - |
| **WEC-P068** | 205 | - | 67 | 580 | 1250 | 417 | 25 | | 9570 | 4502 | 2765 | 4125 | 7924 |
| **WEC-P069** | 10.4 | - | - | 890 | 3200 | 710 | 76 | | - | 4443 | 2671 | 3802 | 6746 |
| **WEC-P072** | 114.9 | - | - | 110 | 350 | 100 | 11 | | - | 5291 | 2742 | 3972 | 8748 |
| **WEC-P078** | 84.5 | - | - | 5.4 | 80 | 6.0 | dry | | - | 2158 | 510 | 1564 | - |
| **WEC-P084** | 3.0 | - | - | - | - | - | dam | | - | - | - | - | 94 |

*Table 7: Summary of relevant surface-water monitoring data for Hotham catchment from WIR database.*

| Site | WEC Site | Easting | Northing | Date range | TDS range (mg/L) |
|---|---|---|---|---|---|
| **6140696** | - | 451435 | 6374530 | 2004-2009 | 3350 - 7020 |
| **6140697** | - | 452757 | 6377939 | 2004-2009 | 2020 - 6320 |
| **6140698** | - | 453471 | 6379933 | 2004-2009 | 1420 - 5900 |
| **6140699** | - | 455036 | 6382061 | 2004-2009 | 3870 - 7020 |
| **6140700** | **WEC-P069** | 454892 | 6384275 | 2004-2009 | 4730 - 8320 |
| **6140710** | - | 455716 | 6394912 | 2004-2009 | 2240 - 9170 |
| **6140711** | **WEC-P072** | 458516 | 6395659 | 2004-2009 | 2190 - 9560 |
| **6140712** | - | 457340 | 6394668 | 2004-2009 | 3720 - 8260 |
| **6140713** | **WEC-P068** | 462779 | 6391567 | 2004-2009 | 3760 – 8710 |
| **6140871** | - | 451458 | 6374449 | 2001-2010 | 6390 - 13860 |
| **6141010** | - | 451253 | 6374720 | 1969-1976 | 450 - 11000 |
| **6141011** | **WEC-P069** | 454721 | 6384436 | 1969-1976 | 660 - 11840 |
| **6141012** | - | 462614 | 6390721 | 1969-1976 | 970 – 11800 |
| **6141377** | - | 438440 | 6386951 | 1976-1984 | 80 – 1020 |

There are plots of paired monitoring at three locations, shown in Figure 11. The salinity at WEC-P072 and WEC-P068 is similar to those observed at the nearby monitoring-locations between 2004 and 2010. At WEC-P069, the largest catchment, salinities are lower than those observed in 1976. This decline is similar to that noted at other sites, and is likely due to a reduction in groundwater contribution to flows due to the decline in precipitation. The salinities at the three locations are similar to each other, suggesting that there is a significant contribution from saline groundwater at all these locations in this agricultural catchment.

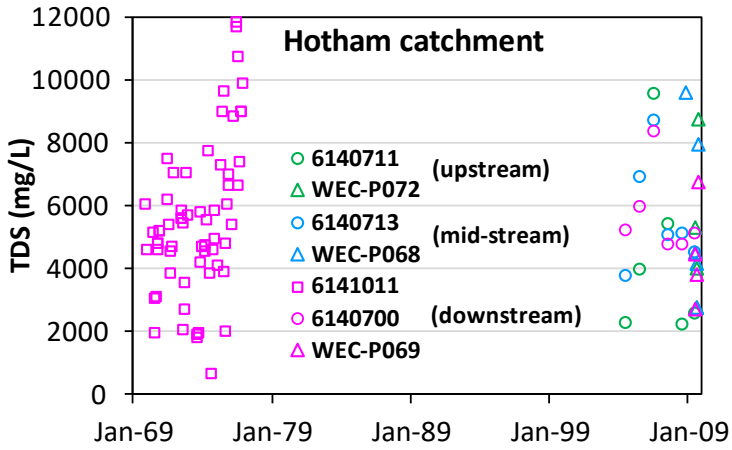


*Figure 11: Plots of paired surface-water monitoring locations in Hotham catchment.*

# 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 12, 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.

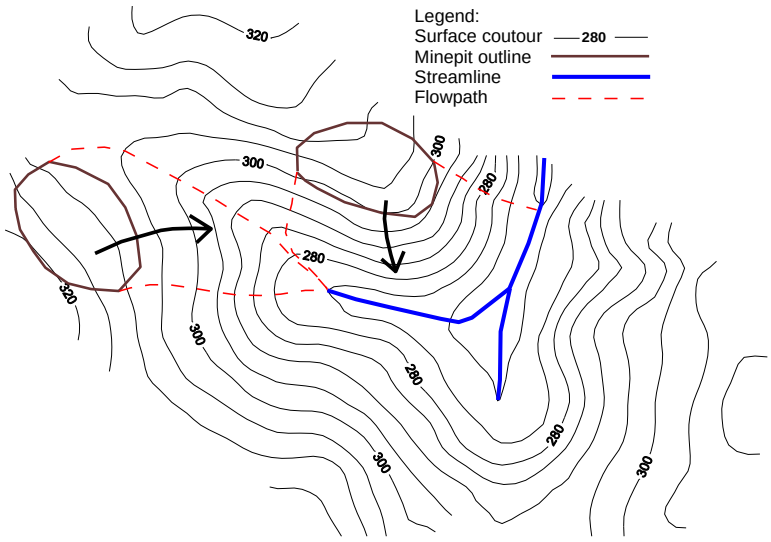


*Figure 12: A theoretical landscape with two minepits illustrating the application of FDA.*

The FDA concept discussed above is applied to the CMA and HNEMA through computational analysis of a digital elevation model (DEM). The DEM is created with a 25 m square grid-cell, consisting of 3,120,000 cells for the CMA and HNEMA study areas. 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). The relationship from the Hotham North area will be used to estimate the flux density in the CMA and HNEMA as there is insufficient data to develop a local relationship and Hotham North is closest to these two areas. The CMA and HNEMA cover a large area; the southern areas have similar rainfall and forest density to Hotham North, but these decrease to the north and east. 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 is a large plantation area in HNEMA (see Figure 3); 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 plantation becomes established. The net effect is likely to be a water-level decline; accurate modelling of these plantations would require annual land-use mapping. There are currently only small areas of bauxite identified within the planation area catchment, it was decided that treatment of these areas as equivalent to other forested areas, as a conservative approximation, would be sufficient for this study. The estimated valley-floor groundwater-level rise due to current land-use is shown in Figure 13. There are significant rises in Dale and Hotham River catchments due to agricultural clearing.

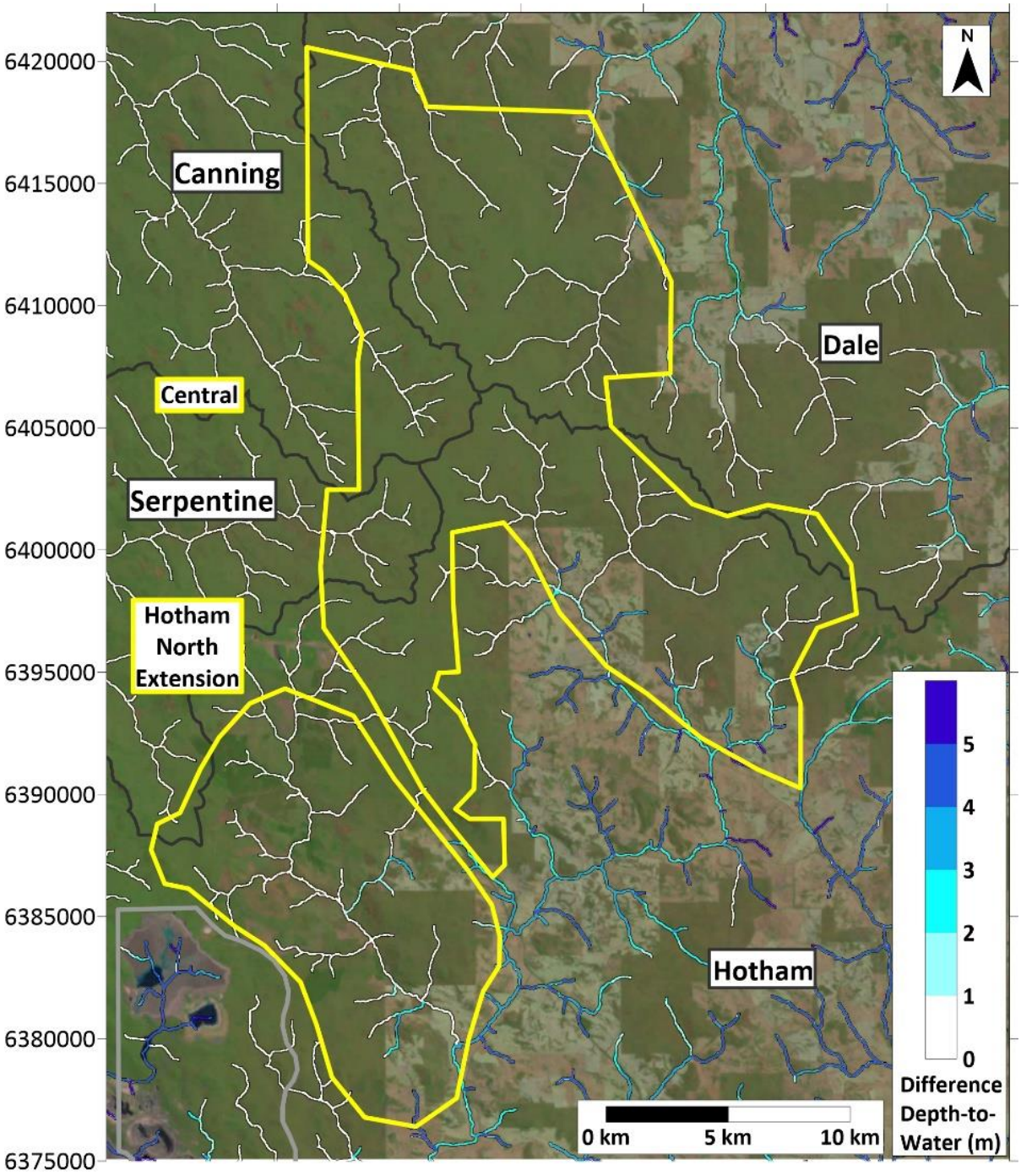


*Figure 13: Map of the FDA-estimated changes in valley-floor groundwater levels due to existing agricultural clearing.*

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 14. There are rises in the groundwater in catchments with bauxite, but these are limited to the tributaries with no significant rises along the main waterways.

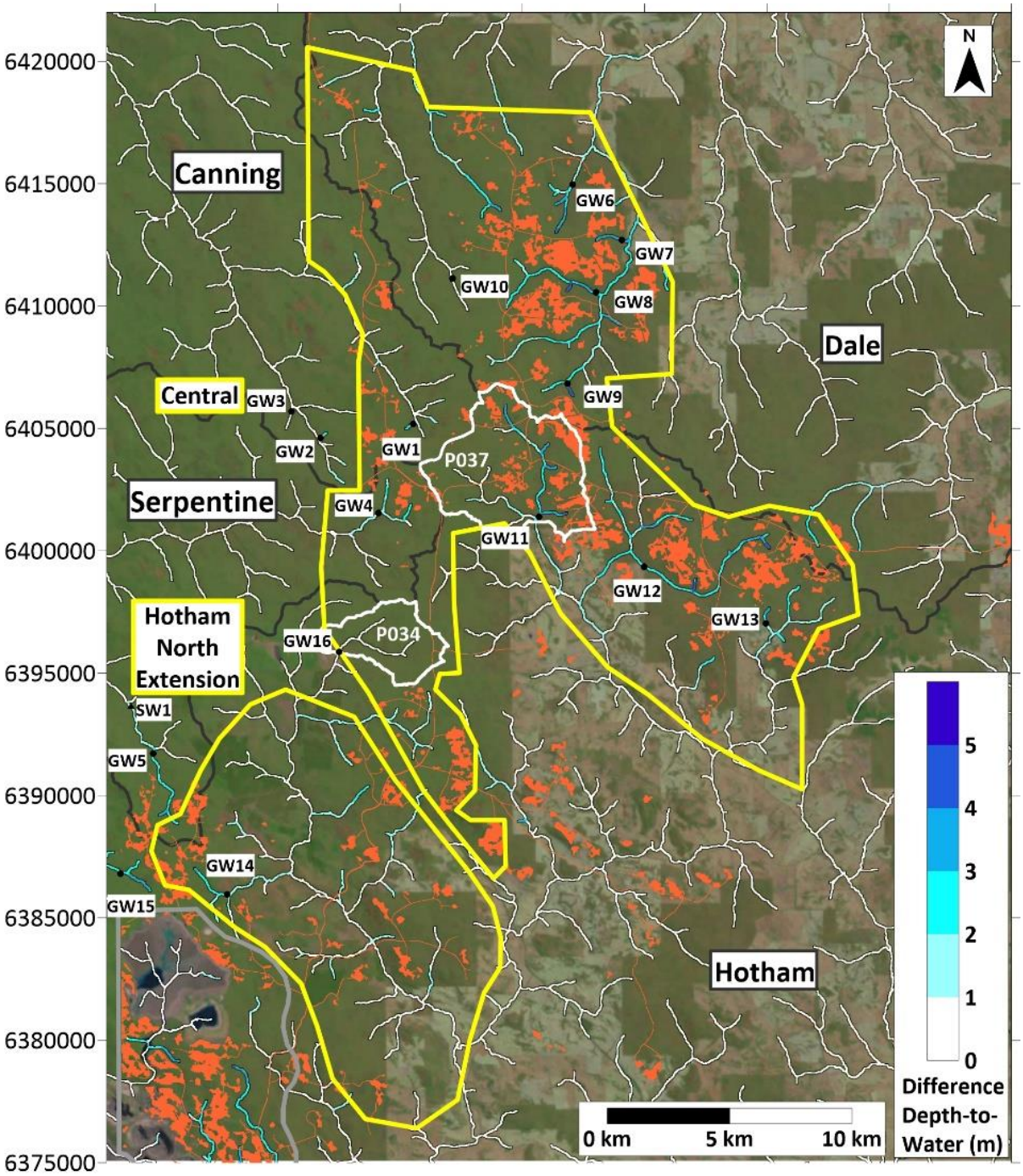


*Figure 14: Map of FDA-estimated change in groundwater-level along the valley floor due to proposed mining activities.*

In the Canning catchment groundwater rises are limited to minor tributaries and have a maximum rise of 2.4 meters along the valley floor. Given the limited area of bauxite it is unlikely that mining activities will increase the salinity of the Canning PDWSA. However renewed monitoring of existing surface-water sites is recommended, along with the installation of two monitoring-bores in the most affected tributaries, (GW1 & GW2) and a control bore (GW3) in an undisturbed valley.

Groundwater rises in the Serpentine catchment are limited to the headwater, with rises up to 3.3 meters in the southern tributary. As the area of mining is small compared to the overall catchment area it is not expected that mining activities will affect the salinity of Serpentine PDWSA. Renewed monitoring of existing surface water monitoring sites and the inclusion of a new monitoring location, SW1, on the southern tributary is recommended, as well as two bores in mining areas (GW4 & GW5).

The Dale catchment has the largest expected groundwater-rise due to mining activities, rises of up to 4.8 meters are expected in some tributaries but rises are below one meter along the main channels. Four groundwater monitoring-bores are proposed in mining sub-catchments (GW6 to GW9), and a control bore (GW10) in an unmined sub-catchment; renewed monitoring at the WEC surface monitoring sites is also recommended.

Expected groundwater-rises along the valley floor of Hotham catchment are up to 4.1 meters in minor tributaries but fall to below one meter along the main channels. Hotham catchment includes two surface-water monitoring sites in forested catchments with high salinity measurements in the 2007-09 studies, WEC-P034 and P037 (catchments are shown in Figure 14), which suggest there may be some deep groundwater discharge. Catchment P037 has significant mining within the catchment, whereas P034 has only haul roads traversing the eastern section. Renewed monitoring of these two sites is recommended with monthly visits and monitoring further upstream when flow allows to understand the source of the salinity within the sub-catchments. The P037 catchment is just above agricultural land, the potential increase in saline discharge may have a localised effect on the utility of the downslope land along the valley floor, but this will be negligible below the confluence of the three tributaries. Renewed monitoring of all other WEC surface water sites in Hotham catchment is also recommended. Groundwater bores in P034 (GW16) and P037 (GW11) are recommended, to both understand the current groundwater table and monitor any changes. Four other groundwater bores in mining areas within Hotham catchment are also recommended (GW12 to GW15).

While the monitoring by WEC in 2007-09 was solely based on manual sampling, it may be worthwhile considering employing data loggers, at least for some of the sites, particularly those within the Serpentine and Canning catchments. WEC has extensively used In-Situ AquaTROLL 200 units for water-level and EC monitoring and WEC has a custom housing and mounting system that is quick to deploy and easy to maintain. If additional data is required, then a one-shot sampler or a sonde could be considered. The three sets of WEC installs are shown in Figure 15. Baseline monitoring prior to mining should be undertaken for at least three years that cover a flow range (low-rainfall year, average year and high-rainfall year). Because it isn't possible to know what the rainfalls will be during the baseline period, it is best to make the period of five years duration.



*Figure 15: WEC monitoring site showing In-Situ logger-housing (foreground), custom one-shot sampler intake (middle-ground), and sonde housing (background).*

# 6. CONCLUSIONS

The majority of CMA and HNEMA identified bauxite bodies are in forested upslope areas of the Dale and Hotham River catchments. While surface-water in these forested upslope areas is mostly fresh, downslope samples have very high salinity suggesting that there is significant saline groundwater discharge in the agricultural areas. Mining activities may raise the groundwater table in the valleys directly below bauxite bodies, potentially affect the land utility along the valley floor, but there is not likely to be any significant increase in salinity in the main waterways. In Hotham catchment there are two forested sub-catchments with high salinity; further investigation into the source of this salinity from both upstream sampling and groundwater monitoring is recommended. There are small bodies of bauxite identified in the Canning and Serpentine PDWSAs; the areas of disturbance are small compared to the catchment size. Surface water salinity has declined since the 1970's in the highest flow monitoring points near the bauxite bodies of both these catchments suggesting that the groundwater table has been falling, so small localised rises are unlikely to affect the drinking water quality but will still have a significant profile given they are within water-supply catchments.

Sixteen new groundwater-monitoring locations have been identified to both gain a better understanding of the catchments and monitor any potential effects of mining activities. There should be two nested bores at each location, screening the shallow superficial-aquifer, and the saprolite aquifer. One new surface-water monitoring site has been identified in the south-east of Serpentine catchment; renewed monitoring is recommended for relevant surface monitoring sites from the 2007-9 surface-water studies. Monitoring should precede mining activities by at least three years to collect baseline data and should continue until mining activities and rehabilitation have been completed in the monitored catchment. It would be advisable to install automated monitoring (In-Situ loggers) at some of the Serpentine and Canning sites.

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