Development and Technical Projects

Yandicoogina 2010 Regional Groundwater Modelling Report

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Executive Summary

The Yandicoogina Regional groundwater model, outlined herein, has been constructed for use in the prediction of dewatering scenarios for current and future Yandicoogina operations. In addition to future dewatering predictions, a critical driver for the model has been to create a regional tool, to be available to test closure waste and void management options and their impacts on water quality and quantity. Given the need for the model to represent the wider RTIO Yandicoogina region, pit scale geological complexity is not reflected. The groundwater model incorporates the latest conceptual hydrogeological model for the area (Kirkpatrick and Dogramaci, 2010a) – featuring permeable alluvium and weathered basement material adjacent to the Channel Iron Deposit.

The design, calibration and verification of this numerical model have been undertaken in accordance with the Murray Darling Basin Commission's Groundwater Flow Modelling Guidelines. While hydrological and hydrogeological data for the area is occasionally sparse, and often of variable quality, the numerical model is considered to be calibrated for the predictive purposes undertaken for this report.

Predictive dewatering simulations suggest that peak abstraction rates for the planned JSW-Oxbow expansion will be greater than 20GL/a; and that total mine dewatering will exceed 40GL/a, if the three planned new pits – JSW-A, JSW-C and Oxbow are mined concurrently. Further predictive scenarios have highlighted the direct link between dewatering rates in the expansion area and the rate of discharge of water to the overlying Marillana Creek; and the limited benefits of alternating mining sequences to reduce total dewatering volumes.

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1 Introduction

1.1 Context

Since 1978, numerous hydrogeological studies have investigated the Yandicoogina Channel Iron Deposit (CID) – a pisolitic iron ore deposit, infilling a palaeochannel incised into basement rocks of the Proterozoic Weeli Wolli and Brockman Formations. These studies indicated that the CID alone comprised the local aquifer system. Permeability had been associated with secondary porosity in the CID and creek-bed gravels immediately underlying the nearby Marillana and Weeli Wolli Creeks. A recent drilling and test pumping program (Kirkpatrick and Dogramaci, 2010a) has resulted in a new conceptual model of the hydrogeology of the Yandicoogina aquifer. The new model expands the domain of the principal CID aquifer to include overlying and abutting alluvium and colluvium, with additional transmissivity through hydraulically-connected, fractured and weathered basement rock in an envelope around the palaeochannel (Figure 3). The surrounding, unweathered basement is considered impermeable, with the exception of localised fracture flow.

The Yandicoogina CID has been mined by BHP Billiton Iron Ore (BHPBIO) since 1991, with the Rio Tinto Iron Ore (RTIO) Junction Central (JC) mine commissioned soon afterwards in 1997. Once the ore was depleted in the Initial Mining Area (IMA), mining at JC progressed in two directions, west into the Phil's Creek area and east into the Hairpin and Waterstand areas (Figure 9). Waste material from mining operations has been used to backfill the IMA, and the two pits are now separated. Distinct from operations at JC, a further pit was established in Junction South East (JSE) in 2006. The orebody is entirely below water table, and 14 separate dewatering borefields – each including between four and eight dewatering bores – have been commissioned to facilitate mining. Borefields are typically installed close to the centre of the orebody, in clusters, up- and down-gradient of active mining areas, to prevent the ingress of groundwater into the pits. As mining progresses towards the borefields, additional borefields are installed further along the channel to allow existing borefields to be mined-through. As mining approaches the bottom of the deposit, the effects of dewatering bores has been observed to diminish, and in-pit sumps and trenches have become necessary. A further borefield in the Billiard South area is used to re-inject surplus water back into the aquifer, in order to reduce the volume of water discharged at surface to creeks.

Variations in groundwater levels due to natural and anthropogenic stresses are immediate – highlighting the close connection between the aquifer and creek systems. Water level drawdown resulting from dewatering activities extends 12 km downstream of Junction Central (Kirkpatrick and Dogramaci, 2010b). Beyond this point, the water table elevation has remained stable since observations commenced in 1999.

Prior to the commencement of mining operation in the area, recharge to the aquifers principally occurred in the creek systems following high intensity rainfall events. In 2009, the total discharge of surplus mine water from dewatering of' BHPBIO Yandi, RTIO Yandicoogina and Hamersley HMS's Hope Downs 1 mine operations into Marillana and Weeli Wolli Creeks was over 45GL (Table 1). Permanent surface flows resulting from the continuous discharge to these creeks have resulted in increased leakage to the underlying aquifers. This is particularly significant where the creeks cross or flow adjacent to the CID.

Aquifer hydrochemistry has been the focus of recent studies to identify the long term impacts of mining operations on groundwater quality in the CID aquifer (Kirkpatrick and Dogramaci, 2010b). Analysis of the Cl concentration record and the results of groundwater and surface water sampling programs indicate that 20% of the water discharged to the creeks is lost to evaporation and evapotranspiration. The remaining 80% of the discharge has the potential to leak into the underlying alluvium and CID aquifers.

Observed increases in groundwater Cl concentrations – related to evapo-concentration, are limited to the 12 km stretch of creek, down gradient of Junction Central, beyond which no increase in Cl concentration is observed. The Cl concentration of CID groundwater beyond this point (45 mg/l), is less than that measured up gradient at JSE (150 mg/l) and JC (120 mg/l); suggesting a strong influence of mixing with much fresher surface water (i.e. recharge from intense rainfall and creek flow events that are characterised by very low Cl concentrations). This suggests that the aquifer system underlying the Weeli Wolli Creek is dominated by surface water recharge from intense rainfall events, rather than groundwater through-flow.

1.2 Numerical Groundwater Modelling Objectives

In response to the need for a numerical tool incorporating the new conceptualisation of groundwater flow in the area – a regional-scale, numerical groundwater model for the RTIO Yandicoogina Junction and Billiard deposits has been constructed. The objectives of this exercise were:

- To incorporate the new conceptual understanding of the local hydrogeology at Yandicoogina into a regional-scale, numerical groundwater model;
- To calibrate this model to accurately reflect regional trends in the groundwater domain;
- To keep the model as simple as possible, while honouring the conceptualisation and therefore the previous objective; and
- To use the calibrated model to run predictive dewatering scenarios for future mine plans.

2 Background

2.1 Yandicoogina

The Yandicoogina mine site is located approximately 85 km northwest of Newman and 145 km east of Tom Price in the Pilbara region of Western Australia. RTIO has operated a mine in the Junction Central (JC) area since 1998. Mining operations were extended to the Junction Southeast (JSE) area in 2006. The life of mine plan for Yandicoogina envisages mining the deposit in areas further up- and down-gradient of existing operations. The Yandicoogina deposit is concurrently mined by BHPBIO, upstream of current RTIO operations.

2.2 Physiography

The deposit lies in the mature drainage basin of the Marillana and Weeli Wolli Creeks (Figure 1), which has eroded into the keel of the broad, easterly trending, Yandicoogina Syncline (Macleod and de la Hunty, 1966). The Hamersley Range lies to the north and the Weeli Wolli 'Range' to the south; dominant landforms are mesas, peneplained ranges and broad, colluvium/alluvium filled valleys (Sullivan and Harmsworth, 1993).

2.3 Geology

The Yandicoogina deposit is an extensive, pisolitic, Channel Iron Deposit (CID), which infills an incised palaeodrainage channel, eroded into rocks of the Proterozoic Weeli Wolli Formation and Brockman Iron Formation (Figure 2). Tertiary and Quaternary alluvium and colluvium overlies and abuts the CID (Figure 3).

The Proterozoic basement comprises thick sequences of Banded Iron Formation (BIF), shale and chert. The Weeli Wolli Formation also includes many intrusive dolerite sills (Thorne and Tyler, 1997). The basement has been gently folded to form the Yandicoogina Syncline and is faulted and fractured at a regional, but more typically, local scale.

The CID consists of clasts of goethite/limonite pisoids, clays and fossilised wood fragments with an approximate average thickness of 80 m (Sullivan and Harmsworth, 1993). The CID clasts (peloids) are typically irregular or sub-angular to sub-rounded in shape. These iron rich peloids are interpreted to represent the end product of detrital weathering via sheet wash processes deposited in low lying areas (Ramanaidou, et al. 2003).

Alluvium and colluvium in the drainage channel chiefly comprise of valley fill and creek-bed gravels – which include fragments of the CID, and are restricted to areas close to present drainages (Sullivan and Harmsworth, 1993).

2.4 Climate and Hydrology

The climate of the Yandicoogina area is semi-arid with hot, wet summers from October to April and mild winters from May to September (Figure 4). Rainfall occurs from two climatic systems, with the larger events precipitating in the summer months from tropical systems, and moderate rainfalls from low pressure systems in winter.

The Marillana Creek catchment originates 20 km to the east of the Great Northern Highway and runs predominately east-west draining into the Weeli Wolli Creek system, downstream of RTIO's Yandicoogina mine operations (Figure 1). The Marillana Creek system has a total catchment area of 2230 km^2. The headwaters rise from high relief areas of the Hamersley Range where the creek drains in an east and north easterly direction into the Munjina Claypan. The claypan, an internally draining basin, has a total area of approximately 274 km^2. Surface water flows that exceed the internal holding capacity of the basin will spill southeast and return into Marillana Creek proper. The Lower Marillana Creek drains in an easterly direction through the existing BHPBIO and RTIO Yandicoogina operations; it continues its path downstream onto wide, flat plains before discharging into Weeli Wolli Creek. Major tributaries of the Marillana Creek catchment include Lamb Creek, Phil's Creek and Yandicoogina Creek. The creeks are ephemeral, with flow naturally occurring only after significant and intense rainfall events. Creek flows in the area have recently been supplemented by the more consistent, but lower intensity discharge of dewater from mining operations.

2.5 Hydrogeology

The conceptual model of the groundwater flow system underlying the flood plains of Marillana Creek and Weeli Wolli Creek was updated based on the results of a recent drilling and aquifer test pumping program (Kirkpatrick and Dogramaci, 2010a). The new conceptual model features a principal aquifer comprising the CID and overlying/abutting alluvium and colluvium, with additional transmissivity through hydraulically-connected, fractured and weathered basement rock in an envelope around the palaeochannel fill (Figure 3). The basement rocks of the Weeli Wolli Formation and Brockman Iron Formation are not interpreted to form an aquifer in and of themselves; however localised and regional fractures in these rocks may provide conduits for secondary groundwater flow. The hydraulic connection between the alluvium and the CID is consistent throughout the area; monitoring bores screened against in-situ, weathered bedrock also demonstrate hydraulic connection with the CID following dewatering abstraction.

The development of solution features has largely superseded the primary porosity of the interstitial pore spaces in the CID itself (MWH, 2006). The alluvial and colluvial deposits that overlie and abut the CID consist of mixtures of poorly-sorted gravels, sand, silt and clay which display hydraulic conductivities of the same order as the CID material (Kirkpatrick and Dogramaci, 2010a). Groundwater in the basement rocks occurs in secondary porosity of the weathered zone and within fractures in the bedrock.

A review of historical water levels in relation to rainfall activity and the hydrochemistry of ground and surface waters along the length of Marillana creek has shown there to be a direct connection between surface water and groundwater in the Yandicoogina CID aquifer (Kirkpatrick and Dogramaci, 2010b). The aquifer is typically recharged by the direct infiltration of surface water; predominantly via leakage through creek beds during creek-flow events following Cyclones and Tropical Storms (Figure 6). Due to the permanent presence of surface water discharge from mining operations, the alluvial and CID aquifers are constantly being recharged in the vicinity of discharge infrastructure (Figure 8). This discharge has resulted in greater recharge to and increased storage within the gravels and alluvium underlying the creeks. The current, natural depth to groundwater, away from the impacts of dewatering and discharge varies from 3 to 20 m below ground level (Kirkpatrick and Dogramaci, 2010b). The groundwater flow direction through the aquifer typically mirrors the direction of flow in overlying creeks (west to east). Groundwater can discharge from the aquifer to the creeks after flooding has subsided (Kirkpatrick and Dogramaci, 2010b).

2.6 Mining Operations

2.6.1 Mining Sequence

BHPBIO Yandi commenced mining activities in 1991, with the first surface water discharge to Marillana creek from their Anniversary Drive outlet (Figure 8) occurring the same year (Table 1). RTIO Yandicoogina subsequently became operational in 1998, with first ore from the Initial Mining Area (IMA) in Junction Central. Mining progressed into the Phil's Creek and Hairpin areas (Figure 9) in 2003, effectively splitting the Junction Central deposit into two separate pits as the IMA was backfilled with waste material. As mining has continued, the Hairpin pit progressed into the Waterstand area in 2008. As mining progresses in Waterstand, Hairpin is being gradually backfilled. Separate to the JC operations, mining commenced in the Union area of JSE (Figure 9) in 2006, progressing into the Marsh area in 2007. The inability to sufficiently dewater these areas has necessitated mining activities progressing horizontally toward the Ridge area, rather than vertically in the currently active areas.

In total 14 dewatering borefields have been installed to facilitate mining of the deposit (Figure 10). Replacement borefields for the initial Phil's Creek and Marillana Creek borefields were necessitated as pit boundaries expanded. The JSE Southern borefield was upgraded in 2009, in order to increase its effectiveness.

A proportion of the dewatering water is used on-site for dust-suppression and in the mine's wet processing plant (Table 1). Water not used on-site is either re-injected back into the aquifer via a re-injection borefield – constructed in the Billiard area in 2006, or released to Marillana and Weeli Wolli Creeks – via a series of discharge outlets.

2.6.2 Waste Fines Cell

A Waste Fines Cell was constructed in the area of the IMA in 2005. The cell receives slurry material from the mine's wet plant, chiefly comprising silt and clay. A scavenger pump removes water from a small lake that constantly pools atop the fines material. Four piezometers drilled in the cell wall adjacent to the Phil's Creek pit indicate that water does not flow directly through the wall material; however, sumps at the toe of the cell in both adjacent pits have consistently remained wet since the cell was established. It is postulated that the material in the cell hydraulically loads the underlying aquifer, creating pressure gradients which spread to the pits.

The construction of a second WFC in the Tributary area of Hairpin began in 2010.

3 Data Analysis

3.1 Previous Work

Extensive hydrogeological investigations have been ongoing at Yandicoogina since the late 1970s. Regional CID and Floodplain Alluvium water levels have been monitored by RTIO at select locations on a frequent basis since 1991. Since mining operations began, monthly groundwater abstraction and surplus discharge volumes have been monitored for compliance purposes.

The earliest hydrogeological investigation in the area concentrated on the feasibility of dewatering the CID to achieve dry mining conditions at JC (Rock Water, 1979). This work was followed by stage two and three of the investigation, which included long term test pumping and the prediction of the dewatering volumes required at JC (Australian Groundwater Consultants, 1980; Australian Groundwater Consultants, 1981). The results of these investigations indicated that Marillana Creek is hydraulically connected to the underlying aquifer and that recharge from the creek accounts for ~25% of the water budget of the CID aquifer (Australian Groundwater Consultants, 1981).

These studies were followed by an investigation of the potential effects of mining activities along Marillana Creek on the water balance of the CID aquifer - concluding that there is very little through flow in the CID within the Junction Central area (Peck and Associates, 1995). A water balance and the calibration of a numerical model that included the Junction Central pit and interaction between surface water and groundwater highlighted additional work was required to adequately represent Marillana Creek with a numerical model (Peck and Associates, 1997).

Following these works and due to the development of a new interface for the numerical modelling code MODFLOW, a new model was commissioned for Junction Central to predict long term dewatering volumes (Australian Bore Consultants, 1997). The model predicted that a total volume of 6.9GL of groundwater would need to be removed to lower the water level to RL 465m AHD within the initial mine footprint of JC. Dewatering to RL 465m AHD should be achieved after 125 days pumping at a cumulative rate of 38,000kL/d from ten bores (PPK, 1998).

An investigation into seepage from Marillana Creek into the CID aquifer, and a mine closure plan for JC were combined in the following study carried out by Peck (Peck and Associates, 1998). The dewatering of JC was the focus of two additional studies that included test pumping and aquifer hydraulic parameter estimation in the Hairpin and Phil's Creek borefields east and southwest of the IMA (Liquid Earth, 2002a, b; Liquid Earth, 2003). The results of these investigation highlighted that the installed borefields were unable to completely dewater the mining areas to a depth of 60m below ground level. The inability to dewater to plan was a result of under-estimating the dewatering capacity required. The dewatering design was under-estimated by the numerical modelling. In short, using an algorithm to represent dewatering bores as constant volume sinks resulted in drying of model cells which cut off further groundwater inflow in the model, resulting in the underestimation of the dewatering volumes.

3.2 Rainfall

Rainfall records since June 1972 are available from W.A. Department of Water (DoW) weather station ‘Flat Rocks’ (WRC number 505011), located approximately 27 km west and upstream along Marillana Creek from the current RTIO Yandicoogina mining operations. For the recording period 1973 - 2010 at Flat Rocks, the average rainfall is 395 mm per year.

Rainfall is episodic and highly variable between years (Figure 11). The majority of rainfall occurs during the hottest months, between December and March (Figure 4), resulting from cyclonic lows. Winters are dry and mild in comparison with lighter, winter rainfall expected in June/July each year. Due to the low rainfall and brief wet season, watercourses flow, if at all, for only brief periods. Rainfall is characterised by low intensity, frequent events related to localised thunder storms and tropical upper air disturbances, and occasional high intensity falls associated with tropical cyclones (Beckett, 2008).

3.3 Surface Flows

The DoW operates one flow gauging station on Marillana Creek at Flat Rocks (WRC number 708001). Daily flow data for the gauging station were available for the period August 1967 to September 2010, with occasional missing data (Figure 12). Weeli Wolli Creek contains several DoW flow gauging stations, including Tarina (WRC number 708014), approximately 10km southwest and upstream of the JSE mining operations. The Tarina gauging station is located downstream of Hamersley HMS’s Hope Downs 1 mine (an RTIO Joint Venture), which has discharged water into Weeli Wolli Creek since 2007. Data from the Tarina gauging station is available for the period May 1985 to September 2010 (Figure 12).

3.3.1 Cyclonic Activity

Five tropical cyclones (TC) passing within 100 km of the Flat Rocks gauging station were noted to produce flows in excess of 100 m^3/s:

- TC Sheila-Sophie in February 1971 (114 m^3/s),
- TC Kerry in January 1973 (255 m^3/s),
- TC Joan in December 1975 (839 m^3/s),
- TC John in December 1999 (141 m^3/s), and
- An unnamed tropical cyclone in January 2003 (161 m^3/s).

Nevertheless, more than five other cyclones have passed within 100 km of the catchment, including TC Wylva in February 2001 which passed over the catchment, and produced only minor flows (Beckett, 2008). In March 1984 and February 1995, flows greater than 100 m^3/s were also recorded as the result of rainfall from tropical lows.

During its period of operation, the Tarina gauging station has recorded flows exceeding 100 m^3/s concurrent with those recorded at Flat Rocks. In addition, ten more events have been recorded, including an event corresponding to TC Wylva. The highest recorded flow at Tarina was 2100 m^3/s in December 1999; believed to be equivalent to a 1 in 100 year Annual Recurrence Interval (ARI) flood event (Cheng, 2010).

3.3.2 Dewatering Discharge

Seven discharge outlets have been used to release water from dewatering operations at RTIO Yandicoogina into Marillana and Weeli Wolli Creeks since the commencement of mining operations in 1998 (Figure 8). BHPBIO have discharged water to Marillana creek, upstream of the Oxbow deposit, since 1991, first from their Anniversary Drive outlet and, subsequent to May 2007, from their Railway discharge outlet (Figure 8). Commencing in late 2006, water has been discharged to Weeli Wolli Creek from Hope Downs 1 operations; located 15km upstream of the JSE deposit (Figure 1).

A water balance featuring abstractions and discharges from RTIO Yandicoogina is presented in Table 1, along with flows from DoW gauging stations and external discharges and volumes of water used on-site for comparison. Total monthly discharge from RTIO's discharge outlets has varied from 200 to 2000ML/mth, since operations commenced (Figure 13). The volumes of water discharged are almost directly related to groundwater abstraction; on-site use of groundwater increased in 2005 in conjunction with the opening of a wet plant, and aquifer re-injection began in 2006, both removing water that would otherwise be discharged to creeks. For the period 1998 to 2006 discharge averaged 400ML/mth; the average discharge increased to over 1GL/mth in 2006 as JSE became operational and has occasionally exceeded 2GL/mth since (Figure 13). Discharge from Hope Downs began in December 2006 and has steadily increased since, to a current average of 2.5GL/mth, occasionally reaching 3GL/mth.

3.4 Evapotranspiration

Evapotranspiration is recognised as a key process affecting surface water and shallow groundwater in the region of the Marillana and Weeli Wolli. From an analysis of chloride concentrations, an estimated 20% of discharged surface water evaporates before it is able to recharge groundwater beneath the creeks (Kirkpatrick and Dogramaci, 2010b).

Specific uptake and transpiration rates of riparian vegetation in the Pilbara are not well established, but are likely to vary with vegetation type and distribution within the creek systems; evapotranspiration rates of the species found along the Marillana and Weeli Wolli creeks have been estimated to range between 500 and 1000mm/yr (Cheng, 2010). Riparian vegetation in Marillana Creek is dominated by woodlands of *Eucalyptus camaldulensis* (River Red Gum) and *E. victrix* (Coolibah) over low open woodlands of *Melaleuca argentea* (Cadjeput) and *M. glomerata* (Cheng, 2010). It has been suggested that the maximum rooting depth of *M. argentea* is less than 5 m and that of *E. camaldulensis* is less than 10 m (AGC Woodward-Clyde, 1992).

Pan evaporation rates have been measured at the Yandicoogina weather station since 2004. The maximum recorded evaporation on a single day is currently 17.7mm, corresponding to a rate of 6461mm/yr. A 30-day moving average of evaporation data follows a roughly annual trend between 1000mm/yr in the winter to 3000mm/yr in the summer.

3.5 Groundwater Monitoring

The earliest recorded water levels at RTIO Yandicoogina were measured in resource definition drill holes, drilled between 1974 and 1978 (Figure 14). The first purpose built monitoring bores were installed in the Junction Central area in 1979 (Rock Water, 1979), to measure aquifer responses to pump testing. Subsequent drilling programmes have installed groundwater monitoring bores in conjunction with the installation of dewatering and re-injection wellfields in the Junction Central, JSE and Billiards areas; and recent explorative work has seen the installation of monitoring bores at Junction South West (JSW) and Oxbow (Kirkpatrick and Dogramaci, 2010a). Further afield, a series of bores installed by BHPBIO prior to 1991, the YM series, although focused on their operations, stretched downstream to the confluence of Marillana and Weeli Wolli creeks. In 1999 RTIO installed four monitoring bores along Weeli Wolli creek, from the southern end of the JSE deposit, to the northern end of the Billiard deposit. In addition multiple probe holes have been monitored within the active mining pits.

Due to the practicalities of mining a channel iron deposit, dewatering and groundwater monitoring bores in the mining area are routinely destroyed to enable mining. As a consequence, continuous records of groundwater levels from individual bores in the mining areas are scarce. Accordingly, the database of water levels at Yandicoogina features numerous short records, focussed on the active pits, few records which are continuous since the onset of mining, and fewer records outside of the current mining areas.

After an exhaustive analysis of all water level data currently held by RTIO, a selection of 22 monitoring records were identified at roughly 2km intervals along a 35km long stretch of the CID (Figure 15). The chosen hydrographs together highlight the key events impacting on groundwater levels over the period of the groundwater model calibration and verification, at JC and JSW (Figure 5), Billiard (Figure 6) and JSE (Figure 7), including the impacts of cyclonic activity; the commencement and decommissioning of borefields; and the effects of dewatering discharge.

3.6 Groundwater Abstraction and Injection

The dewatering strategy for the Yandicoogina deposit is based on the constructive interference of drawdown impacts from multiple “cluster” borefields located up gradient and down gradient of active mining areas (Figure 10). In-pit dewatering from multiple sumps is utilised to remove groundwater drained from the lower sections of the CID aquifer. A timeline of borefield abstractions is outlined in Table 1.

3.6.1 Borefields

The initial dewatering infrastructure installed in 1997/98 consisted of a Sacrificial and a Permanent borefield. Eleven dewatering bores were installed; six bores (SP01-06) were installed in the active mining pit area (Sacrificial Borefield) and five dewatering bores (PP01-05) in the Permanent Borefield. Water levels in the vicinity of the Sacrificial Borefield located in the initial mining area were lowered 65.5 m (458.5 mRL) six months after abstraction commenced, then sustained with continuous pumping. The water table in the Permanent Borefield, located down gradient of the initial mining area, was lowered by 55 m (462 mRL) within the first six months, then continued to gradually decrease. As mining progressed to the southwest, the original Sacrificial Borefield was mined out and a Second Sacrificial Borefield installed in the Phil’s Creek area in early 2000.

In order to achieve dry mining conditions in advance of the progression of mining at JC, two permanent bore fields were commissioned in late 2002 (Phil’s Creek and Hairpin Borefields). The Phil’s Creek Borefield (PC001-008) was installed to replace the second Sacrificial Borefield and Hairpin Borefield (HP001-007) to replace the Permanent Borefield. Eight production bores were constructed, of which only five were commissioned in Phil’s Creek. Seven production bores were constructed in Hairpin of which only four were commissioned. Water levels in Phil’s Creek Borefield were lowered to 450 mRL (PC002) and remained constant. Water levels within the cluster of the Hairpin Borefield were lowered 79 m (445 mRL) then with continued abstraction, remained around 445 mRL. The water level at monitoring point HP30, 450 m away, was lowered by 13 m (467 mRL).

The Waterstand and Marillana Creek Borefields were constructed in late 2004. Water levels at Waterstand borefield were lowered to around 455 mRL (59 m drawdown) and have consistently remained at this level. Marillana Creek Borefield, located adjacent to Marillana Creek was commissioned in 2007 to phase out the Waterstand Borefield as mining progressed into this area. Water levels at the borefield were lowered 17.3 m (494 mRL), decreasing a further 30 m by January 2010. Due to changes in the final pit boundaries of Junction Central, a second dewatering borefield was installed at Marillana Creek in 2010, to replace those dewatering bores which will be lost to mining.

Dewatering borefields were constructed in JSE in 2004 and 2005 and commissioned in 2006. Concurrently five re-injection bores were constructed in Billiards (RB001-005). Thirteen production bores were constructed in the Central, Sacrificial and Southern JSE borefields. The water level in the Central JSE Borefield was 497 mRL at the commencement of the borefield in June 2006, decreasing to 468 mRL in 2008. Water level at the commencement of the Sacrificial JSE Borefield was 494 mRL and was lowered to 480 mRL in early 2010. Water level elevation at the commencement of the Southern JSE Borefield in June 2008 was 494 mRL decreasing to 480 mRL in February 2010. In 2009 three further bores were installed to complement the Southern Borefield. These additional bores were commissioned in early 2010 and the existing bores re-fitted with larger headworks and pumps, resulting in a three-fold increase in total borefield capacity.

The Re-injection Borefield (RB001-007) in Billiards was commissioned to re-inject surplus water from dewatering of JSE. Water levels slightly increased between August 2006 (490 mRL) and August 2007 (498 mRL).

The progression of mining in JSE northwards required the construction of the Northern Borefield (NB001-004) in 2007 which was commissioned in 2008. The water level in the borefield in June 2008 was 459 mRL decreasing to 439 mRL in February 2010. The Northern borefield was further supplemented by the construction of the Ridge North Borefield in 2010.

3.6.2 Sumps

The history of sumping at Yandicoogina has not been documented and reporting is inconsistent. As a part of this study, a partial history has been re-constructed, with the aid of archive aerial photographs and data from internal memos (Figure 16). Sumping in the Initial Mining Area (IMA) is not well understood, however a timeline has been pieced together for the Hairpin and Phil’s Creek pits largely from oral evidence from staff present during this period of mining.

Sumping has generally been required to aid dewatering of the bottom-most benches of the JC pits, where the underlying CID material becomes more clay-rich. Once this layer is reached, the effectiveness of the surrounding dewatering bores diminishes and sumping has typically been necessary. Although the volumes of water removed from the sumps are largely unknown, the bottom mining bench in JC reached a consistent depth of 460 mRL.

3.7 Aquifer Properties

Pump-testing analysis has been undertaken subsequent to the installation of each of the Yandicoogina borefields, and hydraulic parameters are now fairly-well established. The most recent round of pump-testing to take place analysed data from the JSW, Oxbow and JSE regions (Kirkpatrick and Dogramaci, 2010a).

3.7.1 Hydraulic Conductivity

The analysis of observed data in monitoring bores screened in CID material, to pumping tests, typically suggests hydraulic conductivities between 1 and 100 m/d, though most calculated values are in the range of 5 to10 m/d (Kirkpatrick and Dogramaci, 2010a). Calculated conductivities for a pumping bore installed into alluvial material and weathered bedrock produced conductivity values ranging between 3.6 and 16.2 m/d.

3.7.2 Storage

The aquifers in the Yandicoogina region are recognised to be unconfined. Calculated specific yields for the CID vary between 0.1 and 0.001, though most values are closer to the upper end of this range (Appendix A). The creek-bed gravels particularly, are recognised to have large storage values.

Table 1 – Yandicoogina Water Balance

Sources and Sinks Volumes in GL	Year																		
	1991	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**
Creek Flow + External Discharges																			
Tarina Flow Gauging Station	0.0	0.7	1.4	0.2	26.8	0.0	18.5	4.1	88.5	73.9	8.5	0.9	30.4	3.9	2.2	22.6	11.6	32.9	35.6
Hope Downs																0.08	17.6	20.8	24.7
Flat Rocks Flow Gauging Station	0.04	0.9	3.3	3.9	18.5	0.1	17.9	1.5	21.9	18.0	2.7	6.0	27.7	2.2	0.3	11.9	0.4	4.9	3.7
BHPB Anniversary Drive and Railway	0.1	0.1	0.09	0.08	0.3	0.8	6.6	6.1	8.1	13.4	8.3	5.9	5.4	4.7	2.5	7.0	7.9	5.2	4.7
Junction Central																			
Permanent								2.0	1.6	2.1	1.3	1.1	0.2						
Sacrificial								3.9	3.5	0.4									
Replacement Sacrificial										3.9	3.2	2.4							
Hairpin												0.3	1.4	1.3	1.3	0.2			
Phil's Creek												0.5	3.3	3.0	2.6	3.0	3.0	2.9	1.7
Waterstand															1.2	1.8	1.9	1.6	0.1
Marillana Creek																	0.4	3.9	3.8
Phil's Creek Cutback																			
Sumps										0.06	0.4	0.3	1.6	1.4	1.9	2.6	3.1	4.2	1.7
Total								**5.9**	**5.1**	**6.46**	**4.9**	**4.6**	**6.5**	**5.7**	**7.0**	**7.6**	**8.4**	**12.6**	**7.3**
Junction South East																			
Central																0.9	4.0	2.6	
Sacrificial																1.2	4.3	2.4	3.6
Southern																1.0	4.1	4.6	4.8
Northern																		1.3	2.2
Sump																		1.3	4.0
Total																**3.1**	**12.4**	**12.2**	**14.6**
Billiard																			
Re-Injection																**2.1**	**4.4**	**3.5**	**2.7**
Discharge Outlets																			
DO1								1.4	2.0	1.8	1.6	2.2	1.0	0.5	0.7	1.1			
DO2								4.4	2.8	0.3	0.3					0.2	0.07	1.1	1.3
DO3										3.8	1.9	2.9	3.3	3.0	1.5	2.5	1.6	1.9	0.9
DO4										0.06	0.5	0.3	1.6	1.4	2.1	2.7	3.1	3.2	3.1
DO5																0.5	6.2	7.2	5.9
DO6																	0.9	2.9	0.7
DO8																			4.2
Total Discharge through Outlets								**5.8**	**4.8**	**5.96**	**4.3**	**4.4**	**5.9**	**4.9**	**4.3**	**7**	**11.87**	**16.3**	**16.1**
Water Use on Site								**0.1**	**0.2**	**0.3**	**0.4**	**0.6**	**0.8**	**0.9**	**3.0**	**1.2**	**3.9**	**5.2**	**3.5**
Totals																			
Abstracted								**5.9**	**5.1**	**6.46**	**4.9**	**4.6**	**6.5**	**5.7**	**7.0**	**10.7**	**20.8**	**24.8**	**21.9**
Water Use + Discharge + Re-Injection								**5.9**	**5.0**	**6.26**	**4.7**	**5.0**	**6.7**	**5.8**	**7.3**	**10.3**	**20.17**	**25**	**22.3**
Discrepancy								**0**	**0.1**	**0.2**	**0.2**	**-0.4**	**-0.2**	**-0.1**	**-0.3**	**0.4**	**0.63**	**-0.2**	**-0.4**

4 Numerical Model Design

4.1 Conceptual Model

The Yandicoogina Regional Groundwater Model has been constructed following the recent conceptualisation of groundwater flow in the area (Kirkpatrick and Dogramaci, 2010a). This model proposes a primary, channel-shaped aquifer comprising the CID and surrounding alluvium and weathered bedrock, sitting within unweathered bedrock of the Weeli Wolli and Brockman formations, which may transmit water to and from the channel aquifer through discrete fractures and fissures.

A typical hydrogeological cycle for the aquifer comprises a major and nearly instantaneous recharge event associated with creek-flow following storm events; followed by a prolonged period of decline in groundwater levels, until the next creek-flow event (Figure 5 & Figure 6). During periods of low groundwater levels in this cycle, through-flow in the channel aquifer is minimal, in the order of 1500 – 2000m^3/d (Kirkpatrick and Dogramaci, 2010a).

4.2 Numerical Engine

For this numerical modelling exercise, the MODFLOW-SURFACT engine (HydroGeoLogic, 2001), an extension of the original MODFLOW code (McDonald and Harbaugh, 1988), was chosen due to its capability to simulate fluid flow in variably saturated media. Implicit in the use of the MODFLOW-SURFACT code is the assumption that flow in the aquifers is governed by Darcy's Law, as flow through porous media. As groundwater chemistry at Yandicoogina is consistently fresh (Kirkpatrick and Dogramaci, 2010a); groundwater density is not considered to affect flow. The model was constructed using Visual MODFLOW 4.2.

4.3 Temporal Discretisation

The availability and format of the temporal data for Yandicoogina constrains the length of the stress periods applied to the transient model. Monthly stress periods have been utilised for ease of data handling and to reduce model run times. During model runs, each stress period has been allotted ten time steps.

4.4 Spatial Parameters

4.4.1 Horizontal Discretisation

The Yandicoogina Regional Groundwater Model covers an area of 600km^2 (30 km x 20 km) as summarised in Table 2 and illustrated in Figure 1. The model domain has been chosen so as to include the majority of RTIO's Yandicoogina deposits (excluding Snooker and Meander). Prior to defining the boundaries of the model, an analysis of the likely effects of dewatering drawdown was undertaken. A simple Theis analysis determined that the effect of dewatering borefields would be minimal past a distance of 5km along the channel aquifer. Taking this into account, the model extent was chosen to extend upstream of the RTIO Oxbow deposit into land currently held by BHPBIO, in order that any dewatering infrastructure simulated at Oxbow, not be affected by Boundary effects.

The model has been constructed in the MGA94 co-ordinate system, a regular co-ordinate system prescribed by many government agencies. Use of this system allows ease of transfer of data between different software packages and databases. In accordance with the objective of keeping the model as simple as possible, the horizontal discretisation has been kept regular, with 100 m x 100 m grid cells across the model domain. A regular model grid should aid the numerical stability of the model.

Table 2 – Model Extent

	World Coordinates (m) **MGA94 Zone 50**		Model Coordinates (m)	
	Easting	Northing	X	Y
Bottom Left Corner	714000	7467000	0	0
Top Right Corner	744000	7487000	30000	20000

4.4.2 Vertical Discretisation

Groundwater through-flow in the channel aquifer is primarily horizontal (Kirkpatrick and Dogramaci, 2010a). With this in mind and in accordance with the objectives of this modelling exercise, individual geological units in the CID have been ignored, and the CID treated as a single hydrogeological unit. If possible it was intended to keep this unit as a single model layer.

Underlying the channel aquifer, the impermeable basement rock of the Weeli Wolli and Brockman formations is believed to transfer water to and from the channel aquifer through discrete fractures and fissures. The MODFLOW-SURFACT engine however, simulates flow in a porous medium. Information regarding the number and location of faults and fissures in the bedrock at Yandi is virtually non-existent, and the simulation of flow through fractured rock is considered to be beyond the scope of this work. To ensure that the bedrock is able to lose and receive groundwater from the channel aquifer, it has been decided to simulate the bedrock as a very low permeability porous medium. In this model, the bedrock is principally found in a separate model layer, beneath the channel aquifer.

After initially working with a two-layer model, the decision was made to split the channel aquifer into two layers, to better simulate recharge to the aquifer from surface water and to allow for greater evapotranspiration of water introduced to the model at surface. This upper layer of the model has a constant thickness of 5m below ground level.

All three layers have been assigned the MODFLOW LAYCON value 43; consisting of Interblock Transmissivity type 40 – a necessary setting for the MODFLOW-SURFACT engine; and Layer Type 3 – which allows a model layer to act as a confined or an unconfined aquifer, depending on the location of the water table. Layer Type 3 similarly affects whether Specific Storage or Specific Yield are the active methods of storage in a layer at any given time. The contents of each layer are summarised in Table 3.

4.4.3 Topography and Palaeochannel Definition

The top boundary of the model is defined by surface topography. The topographic surface was created by gridding the available 10m contour data for the region. The contour data was converted to a 50m x 50m grid, using Kriging. Errors in the topographic surface may be up to ±5m at any single grid point; however as the resolution of the model grid is lower than that of the gridded topography, little improvement would be possible for this exercise.

Table 3 – Model Layers

Model Layer	Geological Units	Top	Base	Thickness (m)	Aquifer Type
1	CID/Surrounding Alluvium/Fractured Bedrock/Creek-bed Alluvium	Topography	5m below topography	5	Confined/Unconfined Variable S, T
2	CID/Surrounding Alluvium/Fractured Bedrock	5m below topography	Base of weathered channel	Variable	Confined/Unconfined Variable S, T
3	Basement – Weeli Wolli/Brockman Formation	Base of weathered channel	300m RL	Variable	Confined/Unconfined Variable S, T

Critical to the success of this modelling exercise is the definition of the limits of the palaeochannel aquifer. Extensive Resource drilling to define the shape and extent of the CID has taken place between Oxbow and Southern JSE; less extensive drilling has been undertaken along the Billiard deposits; and very little drilling has been undertaken underneath or around the creeks, or outside the limits of the CID. Resource drilling data has been analysed and incorporated into at least eight separate 3D resource models for the area covered by this groundwater model. Each model has been developed to different degree and consistency between these models is poor. In addition, development of the resource models is heavily skewed towards the mineral deposit, and takes little account of the surrounding alluvium or bedrock material. Attempts to translate the resource data into a surface, suitable for use in this groundwater model, have resulted in channel shapes with highly undulating bases – leading to a large variability in aquifer transmissivity along the length of the channel.

With the intent of producing a channel surface with a more regular shape, while taking into account the alluvial and fractured bedrock material surrounding the CID, a surface was hand-drawn, based on geological cross-sections from resource drilling; but also ensuring that the channel base gradually decreased in elevation along its length, and kept a regular shape – tied to the break in slope of the palaeochannel valley (Figure 17). The hand-drawn surface was digitised to create a grid file, suitable for direct import into the modelling software.

4.5 Aquifer Parameters

The most recent round of test pumping and analysis at Yandicoogina (Kirkpatrick and Dogramaci, 2010a) has been used to inform the estimated range of aquifer parameters to be tested during model calibration (Table 4). Vertical hydraulic conductivities for each stratigraphy have been assumed to have one tenth of the value of horizontal hydraulic conductivity. The spatial distributions of aquifer parameters consist of zones, assigned according to geological and hydrogeological interpretation of the region, based on the conceptual hydrogeology outlined in Section 4.1. The horizontal hydraulic conductivities were varied during steady state calibration of the model. Calibrated spatial distributions of the aquifer parameters in layer one and layer two are shown in Figure 18 and Figure 19. Only one conductivity zone (Zone 3) is present in layer three.

Table 4 – Recommended Ranges of Aquifer Parameters

Conductivity Zone	Description / Stratigraphy	Horizontal Hydraulic Conductivity (m/d)	Specific Yield (-)
1	CID	5-50	0.001 – 0.1
2	Upstream alluvium/ weathered bedrock	5-50	0.001 – 0.1
3	Unweathered Bedrock	0.01-1	0.001 – 0.1
4	Creek-bed Gravel	10-100	0.001 – 0.1
5	Downstream alluvium/ weathered bedrock	5-50	0.001 – 0.1

4.6 Boundary Conditions

The northern, southern, eastern and western boundaries of the model, which dissect unweathered bedrock, have been set as no-flow boundaries; with the exception of sections of the northwest and northeast corners of the model, where the palaeochannel passes into and out of the model domain.

As the conceptual model for Yandicoogina considers only the palaeochannel to be a permeable aquifer, the fractured bedrock is not considered to gain or lose water from rainfall or evapotranspiration. For this reason, and to reduce the computation time for model runs – large portions of the topmost model layer which represent unweathered bedrock have been made inactive.

To represent the volumes of water introduced to the model through creek-flow events and via the Discharge Outlets, the MODFLOW Stream-Routing Package has been utilised. Effects of groundwater abstraction and injection of water to the aquifer have been simulated with the MODFLOW-SURFACT Fracture Well Package, and MODFLOW Drain Package.

4.6.1 Northeast and Northwest Boundaries

The Yandicoogina palaeochannel crosses the model boundary in its northwest and northeast corners. RTIO holds no data for either locality, with the northwest boundary lying within BHPBIO's operations and the northeast boundary lying 4km downstream of RTIO's closest observation bore. Continual discharge to Marillana Creek by BHPBIO attests to the company's active dewatering activities in the region of their operations; however, the magnitude and location of this activity is unknown. To ensure that the Marillana discharge is featured in model scenarios, the model boundary has been kept upstream of this point. Similarly, to ensure that monitoring point 99YJWB01 – the furthest downstream monitoring point at Yandicoogina – is included in model calibrations, the northeast boundary has been kept as far downstream as possible.

In the absence of any reliable monitoring data, Boundary Conditions have been specified to ensure that through-flow into and out of the palaeochannel aquifer is of the correct order of magnitude. Analytical estimates suggest that inflow to the model at the northwest boundary is in the order of 1500 m^3/d, and outflow to the northeast of around 2200 m^3/d.

Constant Head Boundaries have been defined across the width of the palaeochannel, in layer one and layer two, at these two locations. The Constant Heads were varied during steady state calibration, to best simulate the analytical estimates of through flow.

4.6.2 Recharge

Analysis of hydrograph responses to recharge events, and the current conceptual understanding of the hydrogeology at Yandicoogina, suggest that direct rainfall infiltration has little impact on groundwater levels.

Some direct rainfall recharge will be inevitable over the area of the permeable, palaeochannel aquifer, and the MODFLOW Recharge package applies this to the model as a prescribed flux. Recharge has been zoned spatially, mirroring the conductivity zones of layer 1 (Figure 18). The prescribed flux is calculated as the product of net monthly rainfall and a variable recharge coefficient. The recharge coefficient was varied during steady state calibration of the model.

4.6.3 Evapotranspiration

Evapotranspiration (ET) is only applied to the creek-bed gravels, at a varying rate throughout the year. ET has been zoned according to vegetation density. Six active zones have been defined, representing separate reaches of the creeks (Figure 20). A synthetic ET sequence has been created, based on measured pan evaporation from the Yandicoogina weather station. This sequence is applied to all ET zones in the model. Extinction depths for each zone have been varied as a part of the transient calibration of the model, up to a maximum of 5m.

4.6.4 Streamflow-Routing Package

The conceptual hydrogeology and analysis of historical water levels in the area indicate that areas inundated during creek flow act as the primary recharge mechanism for the aquifer.

MODFLOW includes two packages designed to simulate watercourses – the River package and the Streamflow-Routing package. A River boundary is able to transfer water to or from the model, depending on the relative heights of the water table and a river stage specified for each cell. A Stream boundary, conversely, takes volumes of water entering individual stream segments as inputs. From the Visual MODFLOW User Manual:

"The function of the Streamflow-Routing Package is to account for the amount of flow in-stream, and to simulate the interaction between surface streams and groundwater. Streams are divided into segments and reaches. Each reach corresponds to individual grid cells, while segments consist of a group of grid cells connected in downstream order. Streamflow is accounted for by specifying a stream inflow for the first reach in each segment, and then calculating the stream flow to adjacent downstream reaches in each segment as equal to inflow in the upstream reach plus/minus leakage from/to the aquifer in the upstream reach."

Creek flow at Yandicoogina has typically been ephemeral and creek stages have not been recorded in any meaningful way. Compounding this, the coarse horizontal discretisation of grid used in this model does not replicate the nuanced creek-bed topography that would be essential input for the effective working of a River boundary in this model. Additionally, discrete reaches of the creeks at Yandi are now permanently inundated by the water released from Discharge Outlets. The length of these inundated areas has varied according to the volumes of water discharged and background conditions. However, volumes of water released from all discharge Outlets on Marillana and Weeli Wolli creeks, along with measured creek flows from DoW gauging stations, provide sufficient data to apply Stream boundaries to the model.

Stream boundaries have been included in the model as 27 inter-connected segments. Segments have been used to represent Weeli Wolli, Marillana, Phil's Yandicoogina and an unnamed creek crossing the Oxbow deposit, as well as nine separate Discharge Outlets. Inputs required for the Stream package include nominal values for Stage, Streambed Top, Streambed Bottom, Stream Width and Streambed Conductivity, in addition to Segment Inflow. Segments with no inflow of their own have been flagged to receive any surplus flow from preceding segments. No flow data is held for Phil's, Yandicoogina or the unnamed creek and these segments have had no inflow assigned. Streambed Top has been fixed as the top of each cell containing a stream boundary. Likewise Streambed Bottom has been fixed as 0.5m below, and Stream Stage 0.5m above the top of each relevant cell. Stream width has been fixed at 5m and Streambed conductance has been set to reference the vertical hydraulic conductivity assigned to each cell containing a stream boundary.

The product of Streambed Top, Bottom, Width and Conductivity defines a Streambed Conductance term, which affects the rate of leakage between the Stream and the aquifer. Streambed Conductance has been varied during the transient calibration of the model, mainly by varying the Streambed Width term.

4.6.5 Wells and Drains

Fifty-six pumping wells and five re-injection wells have been represented in the transient model calibration and validation. Monthly abstraction and injection volumes are well documented and have been used here. Where recorded screened intervals do not correspond with the appropriate aquifer material in the model, due to the smoothing of the channel shape, screen elevations have been adjusted to ensure water is only abstracted from the appropriate aquifer layer.

In-pit sumps have been represented by Drain boundaries. Significant volumes of water have been abstracted from the sumps, but reporting of the volumes removed from individual sumps is scant. The sumps are also susceptible to sudden changes in location and size, also poorly documented. In order to apply the Drain boundaries to the model, historical sump locations were traced from archive aerial photos (Figure 16). Drain boundaries have been created for each individual sump in the Phil's Creek and Hairpin pits. The elevation of each drain has been specified as the final elevation of the pit floors in the Phil's Creek and hairpin Pits (460 mRL). Drains have only been flagged as active during periods when they were known to be in operation.

5 Model Calibration and Verification

5.1 Steady State Calibration

A steady state calibration has been undertaken to develop a broad hydraulic conductivity distribution and boundary conditions, best-matching a measured head distribution and estimated through-flow fluxes, considered representative of average hydrological conditions. The calibration was further undertaken to produce a head distribution, suitable for use as an initial condition for the transient calibration.

Defining a period of average hydrological conditions at Yandicoogina has been found to be problematic. Analysis of hydrographs (Figure 5 & Figure 6) and the conceptual hydrogeology indicate that the hydrological conditions are highly cyclical, with large increases in groundwater levels following storm-related creek flow events, and linear decays in levels thereafter. For the purposes of this calibration, a measured head distribution prior to the commencement of discharge to Marillana Creek by BHPBIO in 1991 was sought. Water level data for Yandicoogina held by RTIO prior to 1991 is scant, and after thorough investigation, the widest distribution of measured heads was found to be data recorded in 1972 and 1978 during early reconnaissance of the deposit (Figure 14).

To add confidence to the calibrated head distribution, and to improve non-uniqueness of the calibration, groundwater through-flow has been used as a second calibration parameter. Analytical estimates suggest that inflow to the model through the CID/alluvial channel should be in the region of 1500 m^3/d, and outflow around 2200 m^3/d.

The Steady State model was calibrated via the iterative adjustment of selected aquifer parameters. Aquifer parameters varied for this exercise included hydraulic conductivity, the rainfall recharge coefficient and constant head values at the northeast and northwest boundaries. As surface flow in the area is recognised as solely a transient stress, surface flow is not a component of the steady state model.

5.1.1 Calibration Performance Criteria

Nationally recognised performance criteria for groundwater model calibrations have been laid out in the Murray-Darling Basin Commission (MDBC) Groundwater Flow Modelling Guideline (Aquaterra, 2000). The guideline specifies four measures, critical to calibration acceptance:

- Water balance error;
- Iteration residual error;
- Qualitative measures; and
- Quantitative measures.

For complex models, the water balance error is widely accepted to be acceptable if a value of less than 1% is obtained.

Iteration residual error may be satisfied by setting a convergence criterion for model time-steps, of one or two orders of magnitude less than the accuracy required in model heads. For this steady state simulation, calculated heads were desired to be within tens of centimetres of observed heads.

Qualitative measures considered during the steady state calibration included:

- an assessment of the fit between modelled and observed groundwater level contour plans;
- the number of observation points used for comparison of modelled and observed heads; and
- the distribution of model aquifer properties adopted.

Quantitative measures considered during steady state calibration include:

- residual head statistics;
- consistency between modelled and observed heads at discrete monitoring points; and
- a comparison of simulated and estimated components of the groundwater budget.

For this simulation, the residual head statistics of importance have been agreed on as Scaled RMS and the coefficient of determination. A scaled RMS of less than 10% and a coefficient of determination greater than 0.9, will be considered acceptable for model calibration.

5.1.2 Calibration Results

The steady state model was calibrated until the agreed performance criteria were met. Calibrated aquifer parameters are presented in Table 5.

Table 5 – Calibrated Steady State Hydraulic Conductivities

Zone	Description/Stratigraphy	Kh (m/d)	Kv (m/d)
1	CID	10.0	1.0
2	Upstream alluvium/ weathered bedrock	5.0	0.5
3	Unweathered bedrock	0.1	0.01
4	Creek-bed gravels	10.0	1.0
5	Downstream alluvium/ weathered bedrock	10.0	1.0

The calibrated solution features inflow to the model at the northwest boundary of 1121 m^3/d and outflow through the northeast boundary of 2588 m^3/d (Table 6). To achieve this result, a recharge coefficient of 1.5% was applied across all active recharge zones. No evidence was available to support greater or lesser recharge through any particular zone.

Table 6 – Comparison of Estimated and Modelled Water Budgets (All volumes in m^3)

	CH In	CH Out	Recharge In	Discrepancy
Estimated	1500	2200	700	0
Modelled	1121	2588	1466	1

To produce the calibrated head distribution and through-flow results presented here, a Constant Head of 540 mRL was specified at the northwest boundary and 435 mRL at the northeast boundary.

5.1.3 Calibration Performance

Water Balance error for the steady state solution was 0.03%, well within the accepted limit.

An Iteration residual error of 0.1 mm was used for the calibration; significantly less than the desired range of residual heads.

Table 7 – Steady Sate Calibration Residual Head Errors

Well	Measured (m RL)	Modelled (m RL)	Residual (m)	Absolute Residual (m)	Residual ^2	Fraction	Fraction ^2
YJ-P1	513.72	511.97	-1.75	1.75	3.0713	-0.00341	0.00001
YJ-P12	506.19	500.64	-5.55	5.55	30.8579	-0.01097	0.00012
YJ-P18	486.94	488.47	1.53	1.53	2.3470	0.00315	0.00001
YJ-P20	482.771	486.48	3.71	3.71	13.7620	0.00768	0.00006
YJ-P26	488.55	491.35	2.80	2.80	7.8529	0.00574	0.00003
YJ-P31	503	497.50	-5.50	5.50	30.2158	-0.01093	0.00012
YJ-P32	501.09	497.38	-3.71	3.71	13.7618	-0.00740	0.00005
YJ-P41	510.85	509.87	-0.98	0.98	0.9614	-0.00192	0.00000
YJ-P45	516.23	514.55	-1.68	1.68	2.8309	-0.00326	0.00001
YJ-P51	520.01	518.63	-1.38	1.38	1.8987	-0.00265	0.00001
YJ-P55	476.513	482.88	6.37	6.37	40.5780	0.01337	0.00018
YJ-P56	496.12	497.11	0.99	0.99	0.9813	0.00200	0.00000
YJ-P7	509.22	508.14	-1.08	1.08	1.1720	-0.00213	0.00000
YJ-P8	508.44	505.38	-3.06	3.06	9.3735	-0.00602	0.00004
YW-P15	477.74	481.95	4.21	4.21	17.6913	0.00880	0.00008
YW-P20	459.66	475.55	15.89	15.89	252.4889	0.03457	0.00120
Min	459.66	475.55	-5.55				
Max	520.01	518.63	15.89				
Range	60.35	43.08	21.44				
Mean	497.04	497.84					

A comparison plot of modelled and measured steady state heads is displayed in Figure 21. There is significant similarity between the plots. Both plots show groundwater levels decreasing gradually along the length of the palaeochannel at similar gradients; gradients increase along those sections of alluvial material where Marillana Creek diverges from the CID in both modelled and observed plots. The monitoring points chosen for statistical comparisons (Figure 14) have been chosen to represent the greatest spatial distribution of available head observations. The aquifer properties adopted are all within the measured ranges suggested by test pumping analyses.

Table 8 – Steady State Calibration Performance Measures

Calibration Performance Measure	Result
Root Mean Square (m)	5.18
Scaled Root Mean Square (%)	8.59
Root Mean Fraction Square (%)	4.39
Scaled Root Mean Fraction Square (%)	36.14
Mean Sum of Residuals (%)	3.76
Scaled Mean Sum of Residuals (%)	6.23
Coefficient of Determination (tends to unity)	0.98

Residual head statistics for individual monitoring points are presented in Table 7 and a variety of calibration performance measures are presented in Table 8. The Scaled RMS for the selected points was 8.59%; below the desired target. The corresponding coefficient of determination was 0.98, well above the desired target. A spatial plot of the discrepancy between modelled and observed heads is presented in Figure 22. The minimum residual head is 0.98 m at YJ-P41 in JSW; the maximum residual head is 15.89 m at YW-P20 in Billiard South. The absolute mean of residual heads is 3.76 m. The model areas which show the best calibration are the stretches of palaeochannel between Oxbow and Phil's Creek, and between Hairpin and Northern JSE (Figure 22). The area of worst calibration is Billiard South, though only one monitoring point was available for this region. No monitoring points were available for the area upstream of Oxbow, held by BHPBIO, or the area downstream of YW-P20, where no drilling had been undertaken at this time. The estimated and simulated components of the steady state groundwater budget are outlined in Table 6. The values reveal modelled recharge to be over double that estimated; however inflow and outflow are of the correct order of magnitude. This level of error in the water budget was a result of reducing error in the residual heads to produce a head distribution suitable for use in the transient model.

5.2 Transient Model Calibration

A transient calibration has been undertaken to develop a broad storage distribution and define time-dependant boundary conditions, to best-match measured variations in observed heads and estimated fluxes. A calibrated and verified transient model will be the basis for predictive groundwater simulations.

The transient model was calibrated over the period January 1991 to December 2007. The transient model included 204 monthly stress periods. As the model period involves prolonged periods of abstraction from multiple wellfields (Table 1) – and therefore a series of quantifiable stress on the groundwater system – no calibration to individual aquifer tests has been deemed necessary.

Aquifer parameters calibrated during the steady state calibration have been kept constant during the transient calibration. The final head distribution from the steady state calibration has been used to define initial heads for the transient simulations.

The transient model was calibrated via the iterative adjustment of selected aquifer parameters. Aquifer parameters varied for this exercise included specific yield, evapotranspiration extinction depths and streambed conductances.

5.2.1 Calibration Performance Criteria

The MDBC Guidelines (Aquaterra, 2000) are the basis of the transient model performance criteria.

A water balance error of less than 1% for each stress period and less than 1% over the model duration will be acceptable for model calibration.

Calculated heads from the transient calibration are desired to be within tens of centimetres of observed heads. The iteration residual error for an acceptable calibration must be at least one or two orders of magnitude less than this accuracy.

Qualitative measures considered during the transient calibration included an assessment of the fit between modelled and observed groundwater level contour plans; the number of observation points used for comparison of modelled and observed heads; and the distribution of model aquifer properties adopted.

Quantitative measures considered during steady state calibration include consistency between modelled and observed head variations at discrete monitoring points; and a comparison of simulated and estimated components of the groundwater budget.

5.2.2 Calibration Results

Storage parameters for the final transient calibration are detailed in Table 9.

Table 9 – Calibrated Transient Aquifer Parameters

Zone	Description/Stratigraphy	Sy (-)	Sc (-)
1	CID	0.05	$1x10^{-5}$
2	Upstream alluvium/ weathered bedrock	0.1	$1x10^{-5}$
3	Unweathered bedrock	0.05	$1x10^{-5}$
4	Creek-bed gravels	0.1	$1x10^{-5}$
5	Downstream alluvium/ weathered bedrock	0.1	$1x10^{-5}$

Calibrated evapotranspiration extinction depths are detailed in Table 10.

During the transient calibration, streambed conductances for the major creeks have not been varied from their initial settings (Section 4.6.4). To improve the model calibration in the area of the Hairpin and Waterstand pits, the conductance of the stream segment connecting Discharge Outlet 4 to Marillana Creek has been reduced by an order of magnitude. To achieve this, the relevant streambed conductivity term was set to 0.1, and no longer reflects the vertical hydraulic conductivity of the underlying aquifer.

5.2.3 Calibration Performance

For the chosen calibration, the water balance error for stress periods eight to twelve was 0.01%. For all other stress periods and for the total model duration the water balance error was effectively 0%.

The iteration residual error for the final transient calibration was 1 cm; one order of magnitude less than the desired model accuracy.

Modelled and observed groundwater level contour plans for significant periods throughout the calibration duration indicate a good fit between modelled and observed groundwater flow patterns (Figure 23, Figure 24 and Figure 25). Visible in these plots are the build-up of a groundwater mound under the BHPBIO Anniversary Drive Discharge Outlet (Figure 23); the build-up of a similar mound under RTIO's Discharge Outlets to Marillana Creek between Phil's Creek and Yandicoogina Creek (Figure 24); the development of a dewatering cone of depression in the JC pit beginning in 1998 (Figure 25); the development of a similar cone of depression in the JSE pit in 2006; and the correct representation of groundwater flow around the CID meander in the Pocket area at all model times.

Table 10 – Calibrated Evapotranspiration Extinction Depths

Zone	Creek-bed Reach	Extinction Depth (m)
1	Marillana – Flat Rocks to Phil's Creek	5
2	Marillana – Phil's Creek to Yandicoogina Creek	5
3	Yandicoogina Creek	5
4	Marillana – Yandicoogina Creek to Weeli Wolli Creek	1
5	Weeli Wolli – Tarina to Marillana Creek	1
6	Weeli Wolli – Marillana Creek to Fortescue Valley	2

The distribution of storage adopted for the transient calibration is consistent with the objectives of this exercise. The storage values adopted for the calibration are within the acceptable range defined by test pumping analysis (Appendix A). The spatial extent of the model over which evapotranspiration is applied is consistent with the current distribution of braided creeks and associated vegetation, delimited from aerial photos. The maximum extinction depths applied are consistent with the estimated extent of rooting by the recognised tree species in the area. Where reduced extinction depths have been applied, the spatial extent of the applicable evapotranspiration zones covers the maximum extent of creek-beds, which feature reduced vegetation density. The impact of the increased spatial extent is therefore limited by the reduced extinction depth. Where streambed conductance has been lowered along the channel from Discharge Outlet 4 to Marillana Creek, anecdotal evidence has implied that most flow along this channel reached the creek, supporting the decision to lower the leakage rate here.

The observation points used for comparison of modelled and observed head variations were chosen as a suite providing the best spatial and temporal coverage, after a thorough QA/QC was undertaken of all available groundwater monitoring data. As previously stated in Section 3.5, twenty-two hydrographs were selected in total. The hydrographs cover an area extending from JSW-C to the downstream end of Billiard North. No suitable long-term monitoring records are available for the JSW-A or Oxbow areas, and no data is held for the area upstream of Oxbow held by BHPBIO. Nonetheless, the chosen hydrographs cover 75% of the modelled channel area and capture all the regional trends and events that were planned to be mirrored by the model.

Modelled and observed head variations at the chosen monitoring points, along with residual errors are provided in Appendix B. The majority of these hydrographs display a suitable fit between measured and modelled heads, although some trends have not been replicated, and in some instances residual head errors are greater than 10 m.

At JSW monitoring point YJ-P99 shows a near-perfect fit to measured values. YJ-P92, 2km upstream does not match the measured absolute heads as well, but captures the significant trends.

In Junction Central, S10 and D01YJ937 feature good comparisons between the modelled and observed heads, though at S10 drawdown is slightly over-predicted and at D01YJ937, drawdown is slightly under-predicted. Monitoring point YJ-DD119 is not well calibrated, although some later-time trends are replicated. Modelled heads for YM117 do respond to creek flow events, to the same degree as measured heads, although timings are synchronous.

Virtually all of the monitoring points from JSE are well calibrated over the period of the transient calibration. However, modelled heads at D03YJ1653 are slightly higher than those measured, while modelled heads at D04YJ2026 and JSE 25 appear to over-predict the effects of dewatering this area.

Via a visual comparison of the observed and modelled groundwater trends, five of the six monitoring points in Billiard can be considered to be well calibrated, reflecting virtually every trend evident in the measured data. The furthest downstream monitoring point, 99YJWB01 cannot be considered to be well-calibrated. Although the modelled heads for this point reflect all of the observed events, the model responses are not of the same scale, and the residual head error is constantly greater than 20m.

Analysis of the model mass balance reveals that both in terms of rates, and of cumulative volumes, water enters the model via the MODFLOW Stream-routing package in far larger quantities than it does via the Recharge package. By the final model stress period, the volume of water entering the model from Streams is fully forty times greater than the volume of water entering from direct rainfall recharge (Figure 26). Analysis of the rates of stream leakance reveals that leakance is highly episodic during the early stress periods, with an increased average rate during the later stress periods (Figure 27). The increased average rate reflects the commencement of discharge to creeks from mining operations, although noticeably, these volumes are still dwarfed by storm-related creek flow events.

Comparing the volumes of water removed from the whole model by the MODFLOW Evapotranspiration package against the volumes of water entering the model via the Stream-routing package, it is apparent that the relationship is highly variable, but that the average ratio increases gradually with time (Figure 28). As a percentage of total stream leakance rate, the total evapotranspiration rate tends to vary between 20% and 80%, though in certain stress periods, the total volume of water removed from the model via evapotranspiration is greater than that entering the model through the streams (Figure

28). During the early stress periods, the average ratio of total evapotranspiration to total stream leakance is below 20%. By the final stress periods of the model, this ratio has increased to 40%.

5.3 Model Assumptions

The following assumptions have been made while calibrating the numerical groundwater model:

- that the model cannot account for the removal of material from pits;
- no simulation of the current or any future Waste Fines Cells; and
- that any dewatering undertaken by BHPBIO, upstream of RTIO Yandicoogina, will have no impact groundwater levels in the area of interest during calibration.

5.4 Model Verification

Verification of groundwater models is encouraged, to test whether the calibrated model may be reliably used as a predictive tool. From the MDBC guideline (Aquaterra, 2000):

> “[verification involves] running the model in predictive mode to check whether the simulation reasonably matches observations from a data set, deliberately excluded from consideration during calibration.”

For this exercise, the verification data set is a continuation of the calibration set. Of the 22 monitoring points selected for the model calibration over the period Jan-1991 to Dec-2007, 17 points feature observations that continue into the chosen verification period, Jan-2008 to Dec-2009. Although the verification data set is not from a separate suite of monitoring points, it is still distinct from the calibration data set. Model stresses applied during the verification period are consistent with stresses to be applied during predictive simulations – these stresses include groundwater abstraction and injection via wells, dewatering via sumps, rainfall recharge, evapotranspiration, and stream flow.

Hydrographs depicting modelled and observed groundwater levels, and residual head errors, from the verification period are presented in Appendix C. At JSW, simulated heads for monitoring point YJ-P99 displays the same trends in groundwater levels, though with a slight time lag in rising heads. The residual head error here is around 3m. Residual head errors for monitoring point YJ-P92 vary between 1m and 5m. A downward then upward trend in groundwater heads is simulated here, but not observed in the measured data. No hydrographs from Junction Central, used during the model calibration, continue into the verification period. For the purposes of the predictions carried out here, this is of little consequence.

Along JSE, verification varies from very good to average. Modelled and measured heads for monitoring points JSEB2 and D04YJ1948 fit particularly well. Across the other monitoring points used for verification in JSE, average residual errors varied between 1m and 8m. In general, trends in groundwater levels are well represented during the verification, even if absolute levels are not correct, i.e. JSE6. The worst match between modelled and measured heads in JSE is perhaps at D03YJ1653, close to Marillana Creek.

In the Billiard area, verification can be seen as good to poor. At monitoring point JSE30, modelled heads are rising while measured heads are falling, although the average residual head error here is relatively low. 99YJWB03, 99YJWB04 and YM119 have particularly small residual head errors (<1m), although minor trends in groundwater levels are not all captured. Modelled and measured heads from 99YJWB01 and 99YJWB02 reflect the same, relatively static, trends; however modelled heads are consistently 30m above measured heads at 99YJWB01 and 10m higher at 99YJWB02.

Following the previous analysis, JSW, JSE and a stretch of the Billiard area – between JSE30 and YM119, can be considered to be verified for predictive purposes. The areas of Billiard south of JSE30 and north of YM119; the Junction Central area and the Oxbow and BHPBIO areas of the model cannot be considered to be verified.

The poor calibration south of JSE30 is likely due to the effects of stream leakage from Weeli Wolli creek. By the time of the verification period, discharge has begun from the Hope Downs mine site and Weeli Wolli creek has become a permanent, rather than an ephemeral creek. Downstream of YM119, including monitoring point 99YJWB01 is still poorly understood in terms of geology and hydrogeology. Before a numerical model can be accurately calibrated in this area, an improved conceptual model will have to be formed.

6 Model Uncertainty

A degree of uncertainty is inherent in every numerical groundwater model. Uncertainties arise from our limited knowledge of factors as diverse as the aquifer parameter distributions used in the model, to the conceptual hydrogeology of the aquifer system itself. An analysis of these uncertainties is critical in determining the ability of the model to function as a predictive tool.

There is currently no standard practise for uncertainty analysis in Australia. Limitations on time and available resources during this study have ruled out any quantitative analysis of uncertainties. In order to highlight those areas of the model with the greatest degree of uncertainty, a sensitivity analysis and a qualitative analysis of model uncertainties have been completed.

6.1 Sensitivity Analysis

The purpose of a sensitivity analysis is to identify the aquifer parameters which are most important in determining aquifer behaviour. These analyses are typically undertaken by incrementally varying model parameters or stresses, and observing how these impact the aquifer's response. However, as the MDBC Groundwater Flow Modelling Guideline highlights:

> "For a high complexity numerical model, a sensitivity analysis conducted by perturbation is extremely demanding computationally. A full sensitivity analysis is an unreasonable expectation when there are too many model parameters. Only a limited selective analysis is justified, perhaps for anticipated key parameters in critical areas only."

ASTM Guide D5611-94 (ASTM, 1994) categorises sensitivity results into four types (Type I – IV). Of these four, the only type of any note in terms of model performance is Type IV – classified as a sensitivity in which perturbations in model parameters produce little change in the model calibration, but large changes in predictive results. In order to identify sensitivities of this type, a partial sensitivity analysis was completed during steady state calibration, focussing on hydraulic conductivity and rainfall recharge rates. A further, limited sensitivity analysis was completed post-calibration, covering hydraulic conductivity, specific yield, rainfall recharge rates and stream conductance. Constant Head boundary conditions and evapotranspiration rates were not included in the post-calibration sensitivity analysis – the Constant Head boundaries are considered to be too distant from areas of interest in model predictions to be worthwhile analysing; while evapotranspiration was considered to be too arduous to appropriately analyse.

Sensitivity analysis undertaken during the model calibration highlights those parameters of key significance to properly representing the aquifer's behaviour, and can greatly aid the calibration process when calibrating by trial-and-error. During steady state calibration, aquifer hydraulic conductivities were found to have significant impacts on residual head errors and water balances. While the rainfall recharge coefficient was seen to have an impact on steady state water budgets, its impact on residual heads was insignificant.

Post-calibration sensitivity analysis was undertaken by running model simulations with chosen aquifer parameters varied by up to an order of magnitude (considered suitably intensive) from a calibrated base case simulation. As seen during the calibration, varying the aquifer hydraulic conductivity had a significant effect on residual head errors. Varying the specific yield of individual model zones had an insignificant impact on residual head errors, as did varying the rainfall recharge coefficient, while the stream conductance had significant impacts on residual heads in some areas of the model, and insignificant effects in other areas.

No sensitivity analysis has currently been undertaken on predictive simulations, so it is impossible to classify the sensitivities into one of the four Types. However the sensitivity analysis which has been undertaken would indicate that were a Type IV sensitivity exist in the model, it would likely correspond to either specific yield or the rainfall recharge coefficient. Any predictive sensitivity analysis should focus primarily on these two parameters.

Considering the objectives lain out at the start of this study and the results of the limited sensitivity analysis completed, the groundwater model is considered to be suitably calibrated. Residual head errors have been kept to minimum and those aquifer parameters which have been shown to be insensitive to change during the post-calibration analysis have been kept within the range determined by aquifer pump testing and by the steady state calibration.

Given the conditions outlined in the previous paragraph, the model predictions are considered to be fit for purpose. The model has been calibrated, as best it can, given the data available; while fulfilling the objective of remaining as simple as possible. The aquifer parameters which the sensitivity analysis has revealed may be of Type IV – specific yield and the rainfall recharge coefficient, are limited by prior knowledge. Qualitative analysis of the effects of evapotranspiration in the model, reveal that it has most effects in the area of Marillana Creek downstream of the discharge outlets and in the vicinity of Weeli Wolli Creek. Neither of these areas are key to the predictive simulations carried out for this study.

6.2 Uncertainties

A quantitative analysis of model uncertainty is not within the scope of this study. In lieu of this a qualitative analysis of model parameters has been undertaken.

During calibration the aquifer properties of hydraulic conductivity and specific yield have been adjusted, to produce a model that best-represents observed aquifer behaviours. Following the study objective of keeping the model as simple as possible, as few conductivity and storage zones as feasible have been used. Within these zones, aquifer parameters have been kept within the ranges suggested by aquifer tests. The results of the completed sensitivity analysis reveal that varying hydraulic conductivity has a significant effect on residual head errors. During the analysis, individual zone conductivities were varied by up to an order of magnitude. In some instances, raising or lowering the hydraulic conductivity of a zone produced lower residuals than the base calibration; however across the model as a whole, the base case still provides the best calibration. These findings highlight that a more refined model could provide a better calibration by introducing more complexity; while uncertainty in conductivity has been minimised as far as possible given the study objectives. Further analysis of the uncertainties in specific yield would require sensitivity analyses to be carried out on model predictive simulations.

Calibration stress data sets are sourced from RTIO databases and DoW Gauging Stations. The DoW data is considered to be reliable, with few data gaps. RTIO data for groundwater abstraction, injection and surface discharge has been thoroughly QA/QC process. An analysis of this data and the associated discrepancies is presented in Table 1. Data on the volumes of water abstracted from individual sumps has been poorly recorded, and has not been used during model calibration. Predictive scenarios have used historical DoW rainfall and creek-flow data to ensure similar patterns of events are simulated in predictions. It is recognised that while this approach will produce suitable results over the total length of model predictions, it will not provide a set of satisfactory stresses for thoroughly investigating questions of mine sequencing.

The model has been calibrated to observed groundwater levels and fluxes calculated with analytical models. A thorough QA/QC of observed heads was undertaken prior to commencing numerical modelling.

The previously reported sensitivity analysis and the uncertainties outlined here, have the potential to affect the outcome of predictive scenarios undertaken with the calibrated groundwater model. The chief uncertainties will be whether different values of specific yield and the rainfall recharge coefficient will affect predictive outcomes, and whether different rainfall sequences affect the outcomes of scenarios which focus on determining between scenarios which differ only in timing.

6.3 Model Limitations

During model calibration and verification it has been noted that the residual head errors in the northeast corner of the model, downstream of monitoring point YM119 are continually large. This area of the model is not considered to be calibrated at present and further work is suggested to improve on the conceptual hydrogeology of this region. Evidence from previous hydrogeological investigations, where hydraulic gradients along the palaeochannel appear to change significantly, suggests that the CID channel shape in this area has not been fully captured by Resource Drilling. Further to this, a neighbouring area in this region is currently held by Iron Ore Holdings Pty. Ltd. Anecdotal evidence suggests that there is a significantly different hydrological regime here.

The simulation of the bedrock as a low conductivity permeable aquifer is a broad assumption, which may be applicable in some areas of the model more than others. During the sensitivity analysis, it was noted that increasing the bedrock conductivity had a beneficial effect on the calibration of the southern portion of JSE. Other areas of the model tended to show adverse effects to this change.

The width and depth of the palaeochannel simulated in these scenarios is recognised to be artificial, aiding in simplifying the various sources of topographical data that are available for this surface. The surface is believed to represent the transmissive palaeochannel aquifer, to the best of our current knowledge; but could well be improved upon in future.

External sources of surface water are recognised as a key stress affecting dewatering rates within the model. The effect of varying these stresses has been analysed in the following predictive simulations.

The hydrological regime upstream of the Oxbow deposit is largely unknown to us. Further hydrogeological data would improve model calibration and predictive ability in this area.

Evapotranspiration has been handled in an embryonic fashion. While it's affects are largely seen downstream of mining operations, and inconsequential to the following predictive scenarios; a more nuanced approach could be developed to improve its representation in the model.

7 Prediction

7.1 Dewatering simulations

The calibrated transient model has been used to undertake a series of predictive dewatering simulations based on current mine plans, supplied by the RTIO Resource Development Mine Planning department. The objectives of these simulations have been to:

- determine cumulative and peak dewatering volumes and rates for input to the Yandicoogina JSW & Oxbow Public Environmental Review (PER) and pre-feasibility study (PFS);
- determine the extent of dewatering impacts from drawdown, discharge and re-injection along the channel from actively dewatered areas to help predict impacts to Stygofauna and Troglofauna habitats;
- determine whether the sequence of mining three new pits will affect the dewatering requirements; and
- analyse how much influence external sources of water, such as the BHPBIO discharge outlet, have on dewatering volumes.

7.1.1 Mine Plans

To determine the necessary water levels for mining, the elevation of mining benches through the life of mine were extracted from the supplied mine plans for selected points in each pit (Figure 29). An extra 5m was subtracted from these elevations to create the target water levels for the simulations.

Six separate mine plans illustrate the mining of three proposed pits – JSWA, JSWC and Oxbow in each possible sequence, outlined in Table 11. Both the commencement date for mining in each pit and the rates of bench progression vary between mine plans. In each mine plan, final bench elevations in all three pits have been reached by the year 2022. Final mining benches for each pit are consistent between mine plans.

Table 11 – Six Mining sequences for JSW - Oxbow

Option	Order of Mining
1	JSWA - JSWC - Oxbow
2	JSWA - Oxbow - JSWC
3	JSWC - JSWA - Oxbow
4	JSWC - Oxbow - JSWA
5	Oxbow - JSWA - JSWC
6	Oxbow - JSWC - JSWA

7.1.2 Predictive Model Design

Dewatering bores have been added to the model at locations suitable to best dewater the prospective pits, and where possible, outside of the pit boundaries (Figure 30). A number of dewatering bores were drilled in the JSW – Oxbow area in 2008 and 2009 in order to conduct aquifer pumping tests. These dewatering bores have been incorporated into the model, although not all are used in the simulations. Due to the shape and length of the Oxbow pit, in-pit bores have been required in the dewatering simulations. Pumping wells have been assumed to be able to abstract groundwater at the established maximum pumping rates for existing bores in the area. Total abstraction volumes and rates have been determined with MODFLOW's Zone Budget tool and reconciled with the volume of water re-introduced to the model through RTIO's discharge outlets and re-injection bores.

Boundary conditions are recognised as a limiting factor in the accuracy of these predictive simulations. Evapotranspiration has been applied to the model in the same manner as during the transient calibration. The sensitivity analysis described in Section 6, has shown that the model is largely non-responsive to changes in the rainfall recharge coefficient, however, the volumes of water introduced to the aquifer via streambed leakage following storm events area are a critical component of the water balance. To ensure that realistic volumes of water are introduced to the aquifers, over the total duration of the predictive simulations, historical stream flow data for the period June 1991 to December 2004 has been used as an analogue for the predictive period June 2009 to December 2022. Although this approach will ensure that the total volume of water added to the model over the duration of the predictions is of the correct order of magnitude, the use of only one stream flow sequence does not allow for the occurrence of large stream flow events at varying times throughout the predictions. For predictive simulations that feature any analysis of the variation in timing of events, such as the analysis of the merits of mining pits in different orders, this limitation will have an adverse impact on simulations.

7.1.3 Predictive Model Assumptions

The following assumptions have been made while performing the predictive simulations outlined here, including:

- that the model cannot account for the removal of material from pits;
- no simulation of the current or any future Waste Fines Cells;
- that rainfall, evapotranspiration and creek-flow for the duration of the simulations are analogous to historical records;
- that any dewatering undertaken by BHPBIO upstream of the Oxbow pit which will not impact on RTIO dewatering activities; and
- that pits which have been mined out will not be backfilled during the model period and shall be assumed to remain dry.

While performing the Whole Mine Dewatering predictions, a number of additional assumptions were made, specifically:

- that mining Option 3 will be chosen as the preferred mine plan;
- that BHPBIO's discharge to Marillana Creek shall remain at a constant rate of 5GL/a, and is discharged evenly throughout the year; and
- that lacking any firm information to the contrary, the discharge of surplus water from RTIO's dewatering activities will take place at existing discharge points, namely DO2, DO3, DO5, DO6 and DO8 (Figure 8).

7.2 Simulation results

The results of three rounds of dewatering simulations have been presented in a series of memos; the memos cover:

- Dewatering volumes and rates necessary to achieve dry mining conditions in the JSW and Oxbow pits for the six possible mining sequences (Inverarity, 2010a);
- The effect of varying the volume of BHPBIO's discharge to JSW on dewatering volumes and rates for the JSW and Oxbow pits (Inverarity, 2010b); and
- Dewatering volumes for the entire RTIO Yandicoogina Operations over the life of mine (Inverarity 2010c).

7.2.1 Sequence of Mining

Simulation results suggest that the order of mining at JSW-Oxbow will have little impact on peak abstraction volumes, and hence, discharge rates to creeks (Figure 31). The cumulative dewatering volumes for the 12 year period until 2022 (Table 12) indicate that Option 5, which envisages mining the three pits in the opposite order to the expected scenario – Option 3; would require dewatering as much as 20GL less than Option 3, roughly equivalent to the total volume of water currently dewatered at Yandi in a single year (Table 12).

Table 12 – Cumulative Dewatering Volumes 2010 - 2022

Option	Volume (GL)
1	161
2	155
3	165
4	165
5	142
6	161

7.2.2 BHPBIO Discharge

Over the period 1998-2009, BHPBIO have discharged a mode 5GL of water into Marillana Creek at one of two discharge points in the vicinity of the Oxbow pit (Figure 32). BHPBIO's current discharge license allows discharge up to 15GL/a; a volume which has been approached once over the same period (13.4GL in 2000, Table 1). To determine what effect any change in BHPBIO's discharge rate would have on dewatering volumes at JSW and Oxbow, simulations were run with this rate fixed at 0, 5, 10 and 15GL/a. The results of these simulations (Figure 33) reveal an almost linear relationship between discharge and dewatering volumes, once an initial period of storage has been dewatered.

7.2.3 Whole Mine Dewatering

Dewatering simulations for the whole Yandicoogina mine operations have been undertaken to determine total abstraction and discharge volumes for the site over the life of mine. The results of the whole mine simulations suggest that dewatering volumes will rise to over 40GL/a if the three pits – JSW-A, JSW-C and Oxbow are mined concurrently (Figure 34). Assuming at least a 10% error in these results, peak annual dewatering volumes could exceed 45GL/a.

8 Summary and Recommendations

8.1 Summary

The Yandicoogina steady state ground water model has been conceptualised and constructed as a three layer model, incorporating a thin surface layer, underlain by a layer of variable thickness – representing the bulk of the channel material; and a low permeability layer underneath, approximating the fractured bedrock. With the objective of keeping model complexity to a minimum, while still attaining a satisfactory calibration to both measured heads, and also to estimates of groundwater through flow in the aquifer; as few aquifer parameter zones as possible have been used, with the result that a total of five hydraulic conductivity and storage zones were delineated.

While it is still uncertain whether or not the aquifers of the Yandicoogina region are ever in steady state in terms of groundwater – the best efforts have been made to calibrate the model to a set of largely contemporaneous, pre-mining head observations. Throughflow in the calibrated steady state numerical model is comparable to the rates estimated analytically. The greatest discrepancy in the calibrated heads is found in the Billiard south region, where measured heads were only available from 1978 (four years later than all other head observations used for the calibration).

All model properties from the steady state calibration have been kept constant for the transient calibration. Fundamental to the calibration of the transient model has been the correct application of storm-related creek-flow events to the model. These brief, high intensity events provide the majority of recharge to the aquifers, vastly exceeding the volumes of water entering the aquifers via direct rainfall recharge. The sensitivity analysis undertaken on the calibrated transient model has re-enforced the importance of this fact.

Predictive dewatering simulations have been undertaken to provide insight into:

- the future dewatering demands of the JSW-Oxbow expansion;
- the demands of the whole Yandicoogina operations over the life of mine;
- the difference in dewatering demands of six different mine plans; and
- the potential impacts of varied discharge to Marillana Creek by BHPBIO.

The predictive simulations indicate that peak dewatering rates for each of the six mine plans simulated will exceed 20GL/a during at least one year of mining operations. Total mine dewatering volumes are likely to exceed 40GL/a while the three proposed pits are mined concurrently. Furthermore, the impact of increased discharge to Marillana Creek by BHPBIO appears to have a linear impact on the dewatering rates required for the proposed new pits.

Further optimisation is possible for any chosen mine plan, to optimise borefield designs, reduce interference between bores and potentially reduce peak and cumulative discharge rates. Future dewatering scenarios could also investigate the potential effects of the varied timings of storm-related creek flow events on peak dewatering and discharge rates.

8.2 Recommendations

The following further work is recommended to improve the understanding of the hydrogeology and at Yandicoogina:

- explorative hydrogeological work in the Billiard North region to determine the nature of groundwater flow in the area;
- further investigation into the contribution of groundwater to the Yandicoogina aquifers from fractured bedrock;
- testing the alluvium along Yandicoogina and Marillana creek to better understand groundwater inputs and outputs and the potential impacts of mining;
- optimisation of the location of surplus water discharge points; and
- a thorough and detailed sensitivity and uncertainty analysis.

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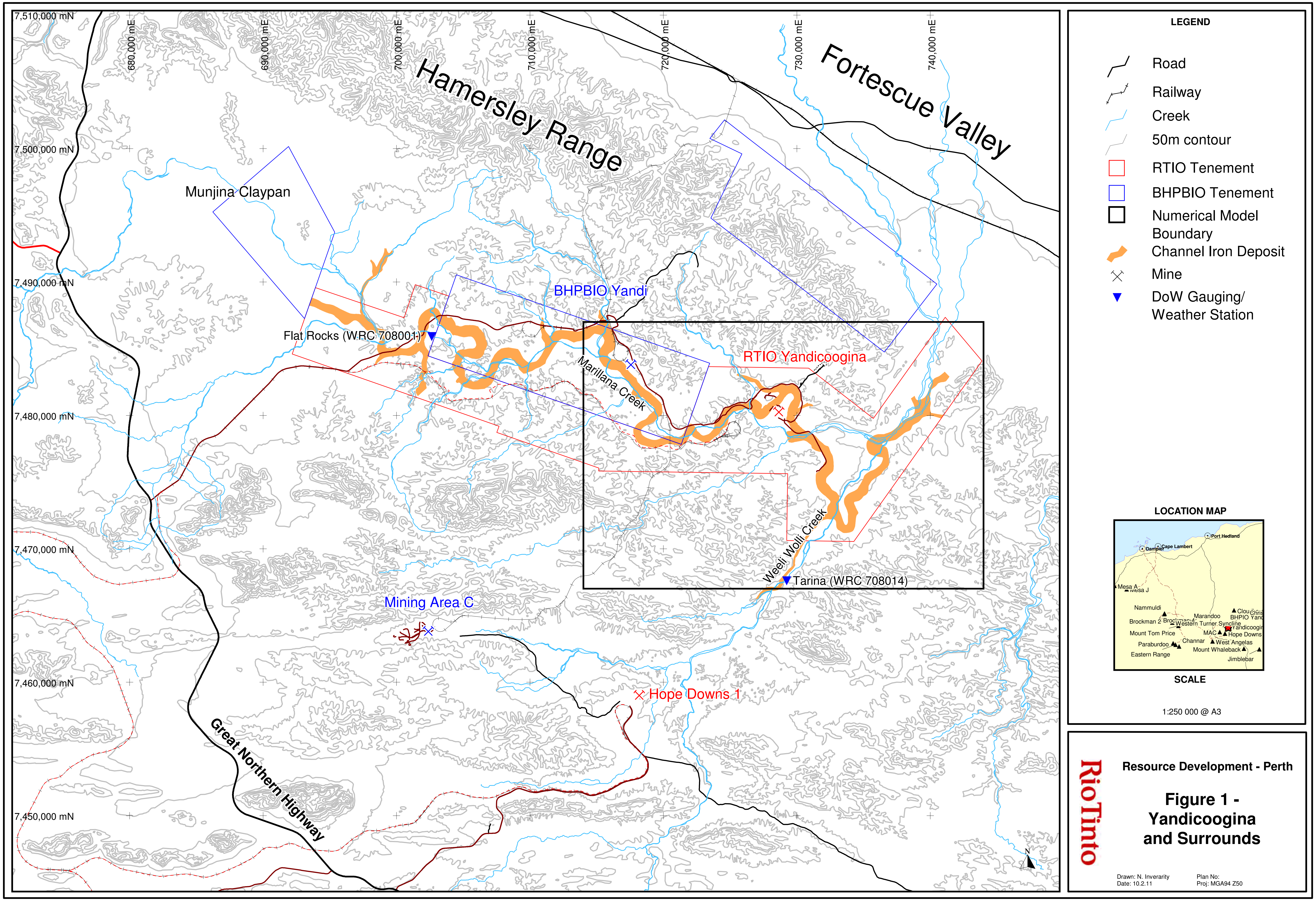

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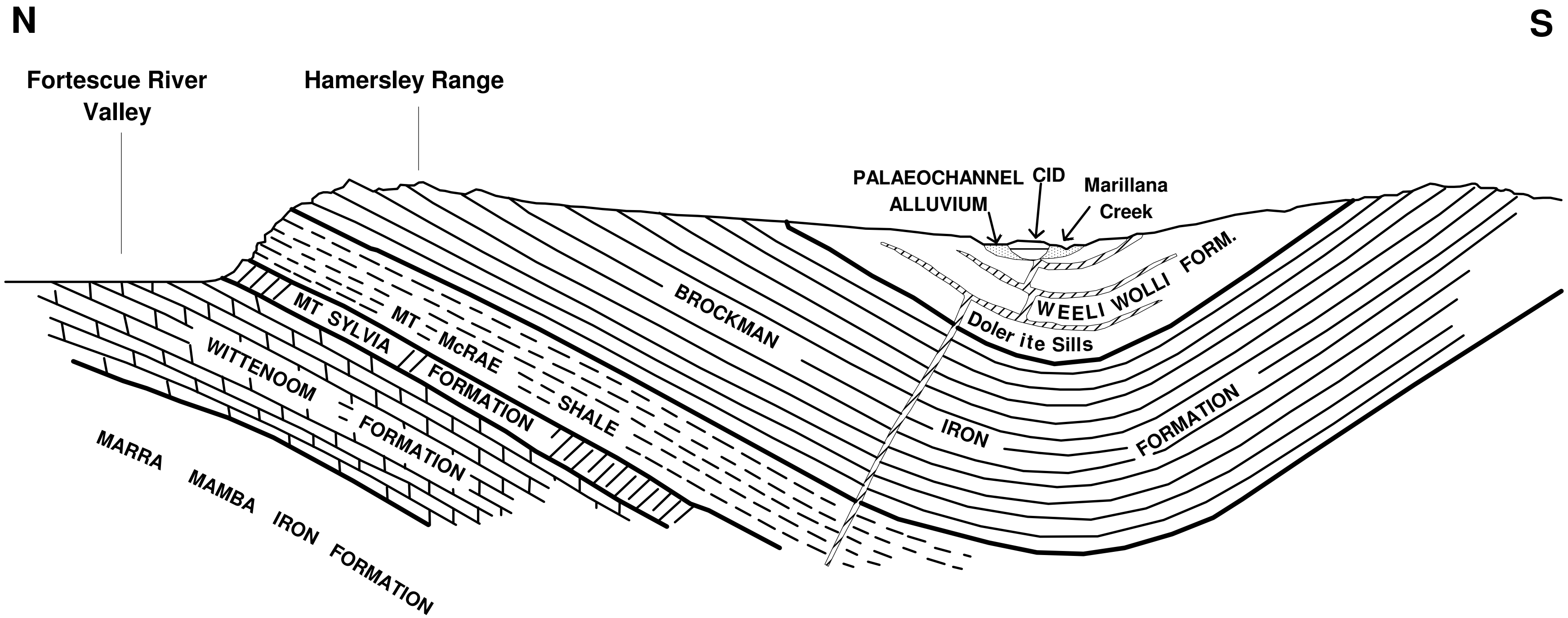
Figure 1 - Yandicoogina and Surrounds

Drawn: N. Inverarity
Date: 10.2.11
Plan No:
Proj: MGA94 Z50



(After Sullivan and Harmsworth, 1993)

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Figure 2 - Schematic Cross-Section of the Yandicoogina Syncline

Drawn: N. Inverarity
Date: 15.2.11

Figure 3 – Yandicoogina Palaeochannel Hydrogeological Cross-section

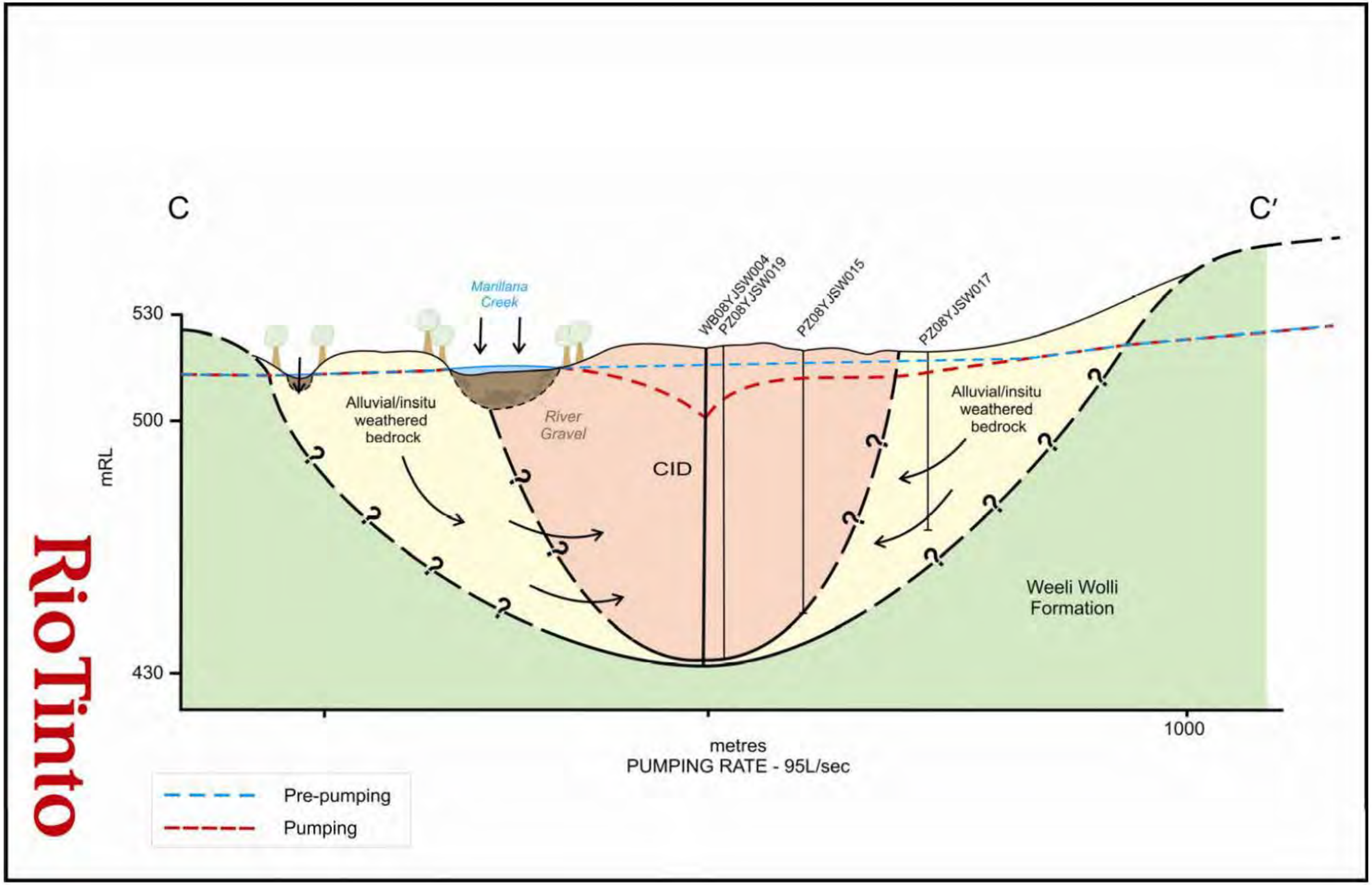


Figure 4 – Average Climate at Yandicoogina

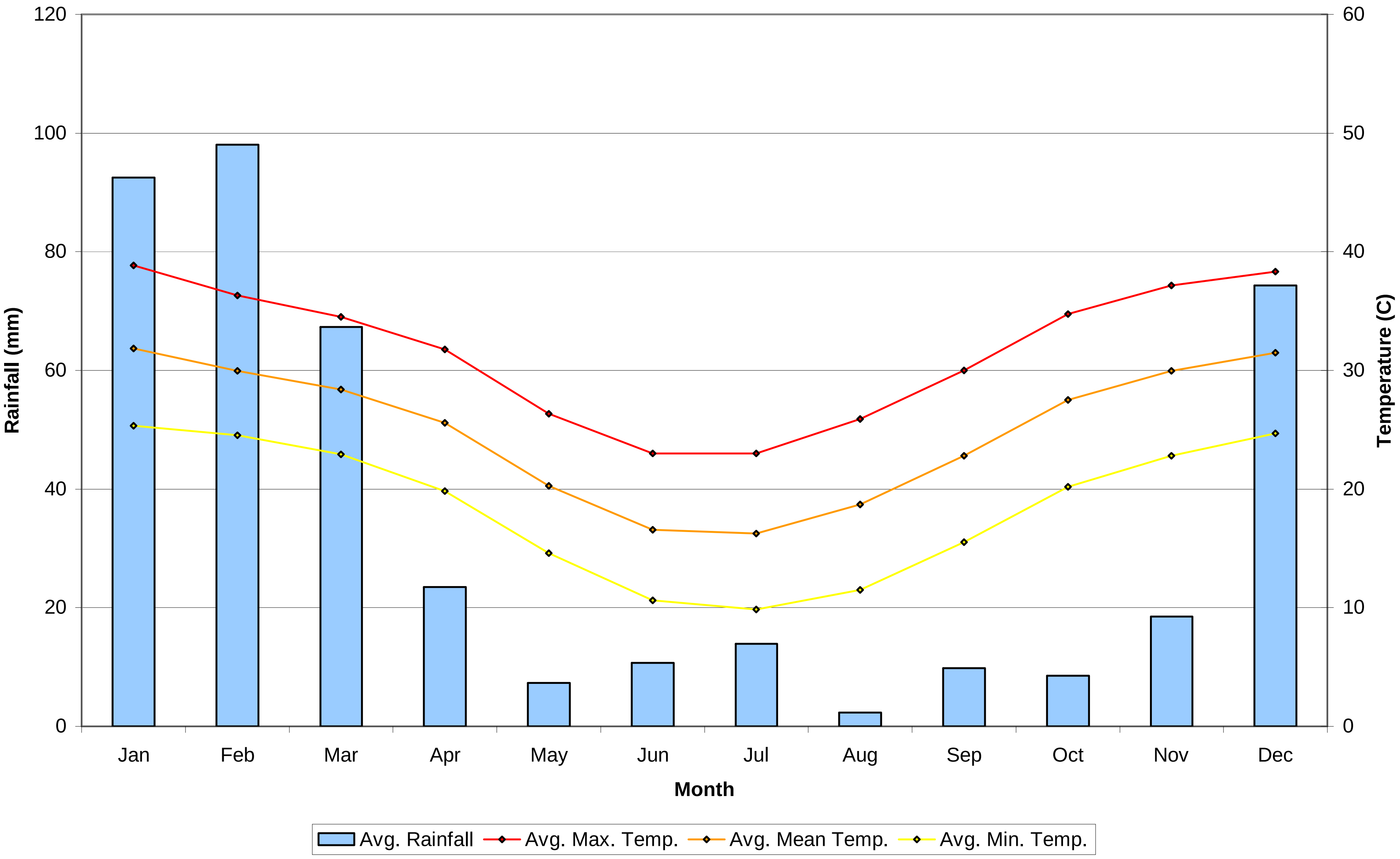


Figure 5 – Junction Central and Junction South West Hydrographs

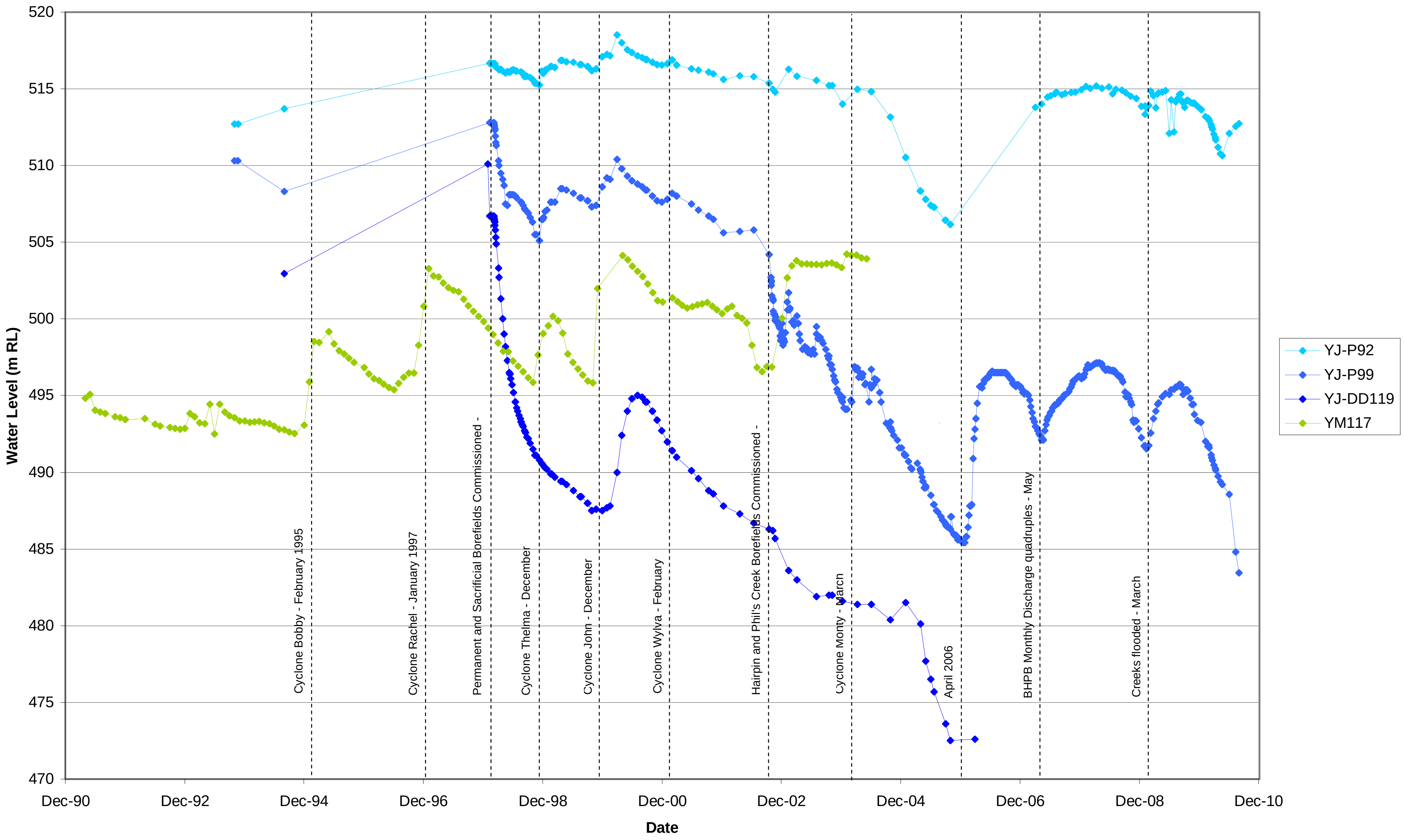


Figure 6 – Billiard Hydrographs

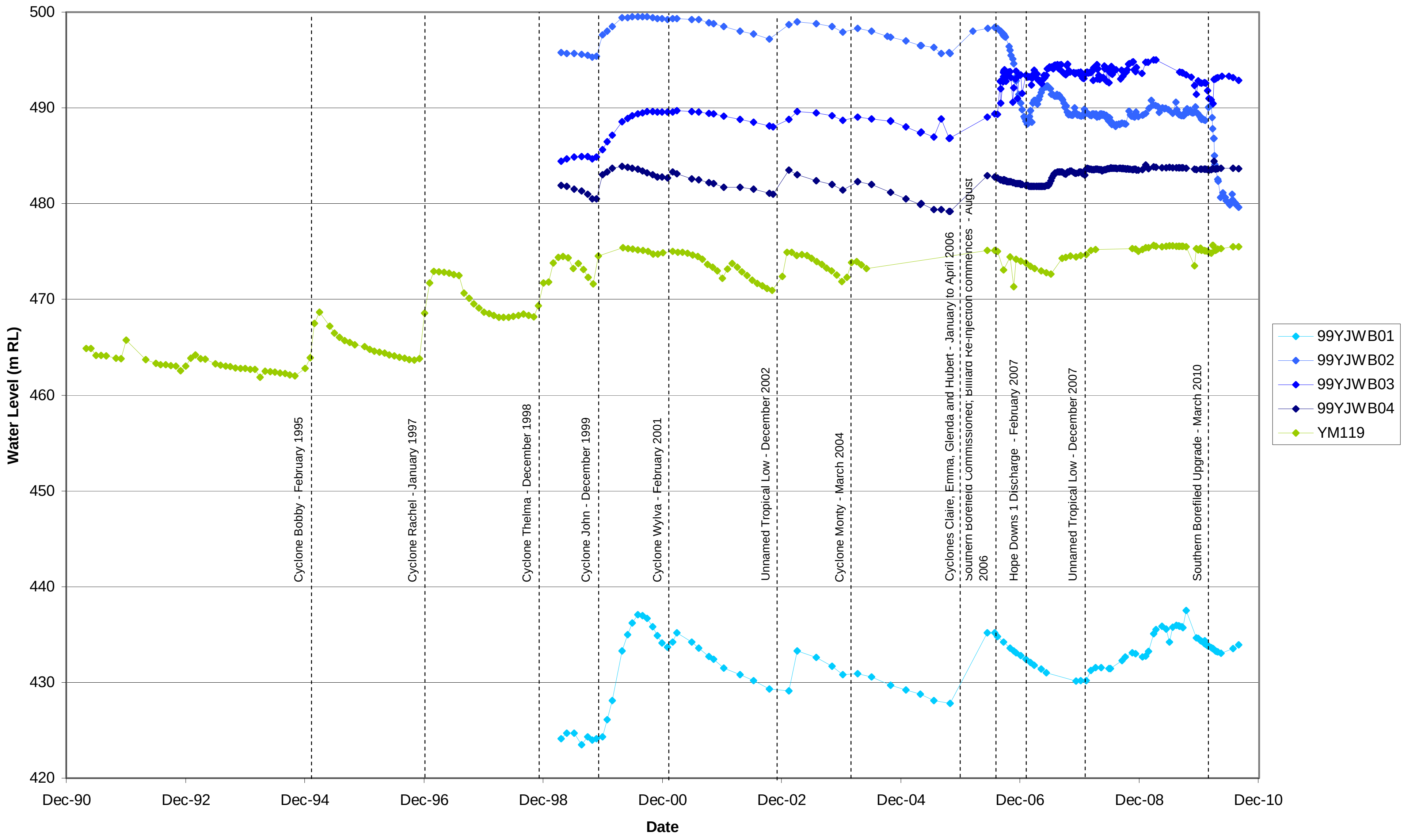
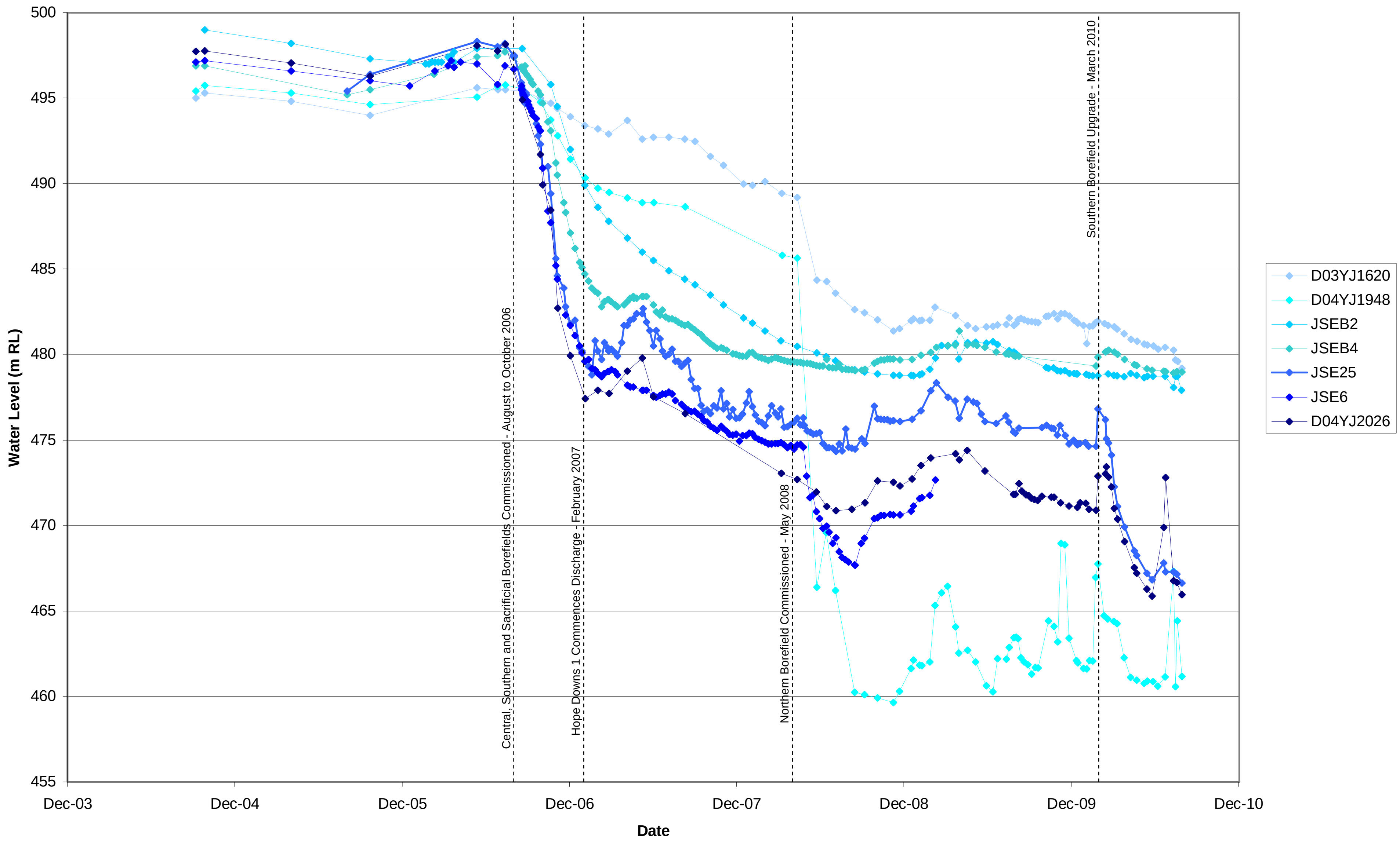
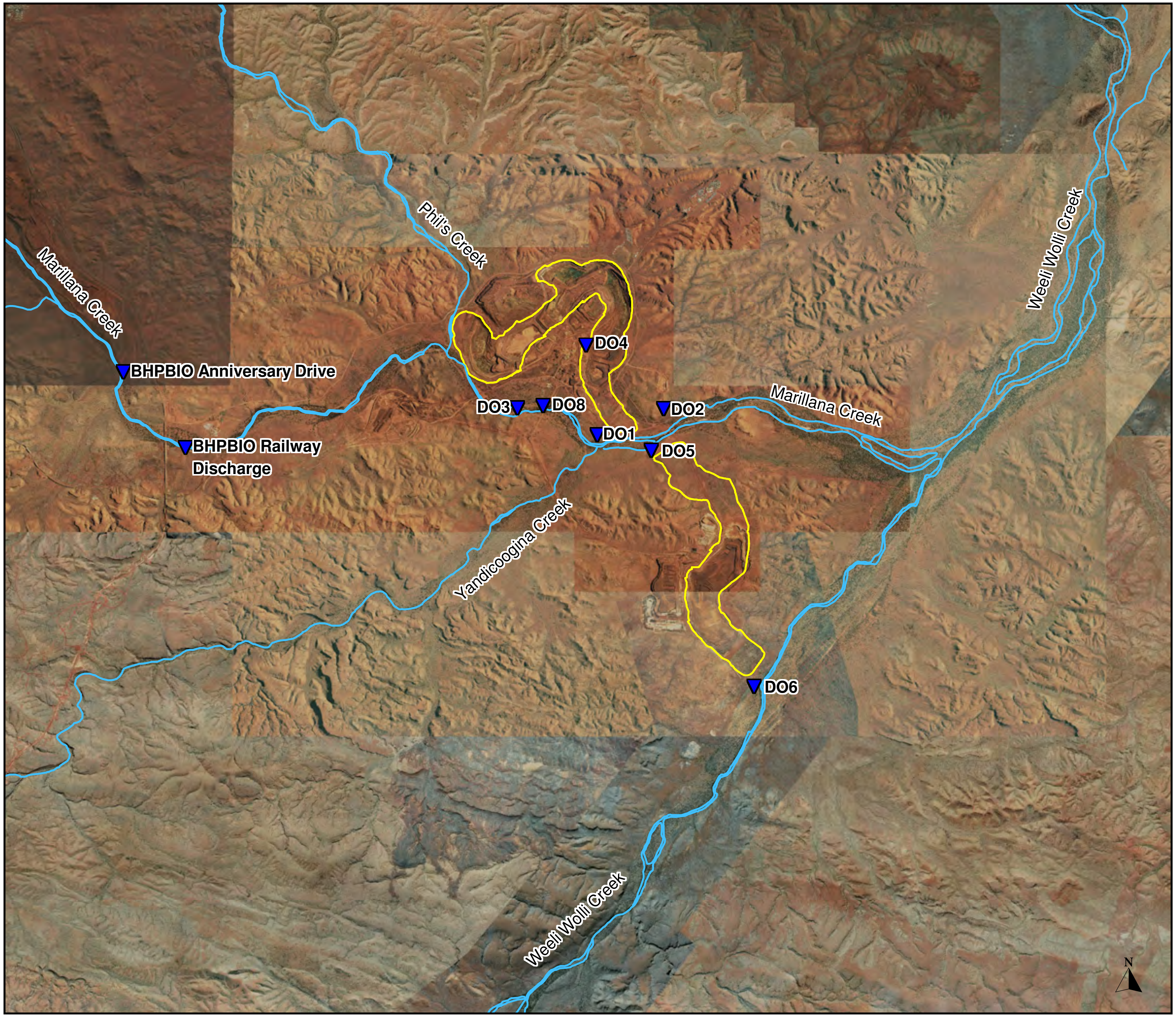


Figure 7 – Junction South East Hydrographs





LEGEND

Discharge Outlet

Final Boundaries of Existing Pits

Creek Bed

SCALE

1:80 000 @ A4

RioTinto

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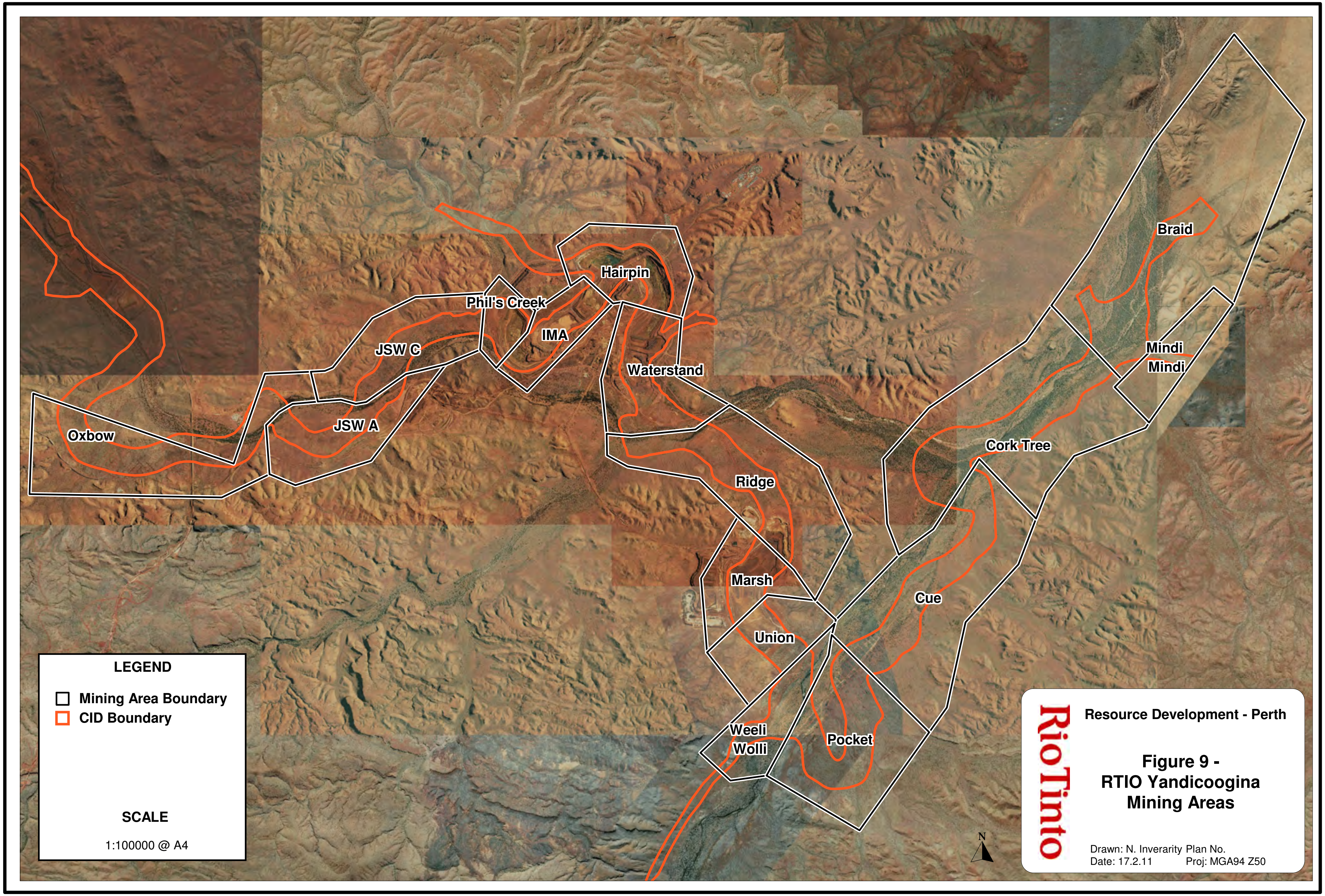
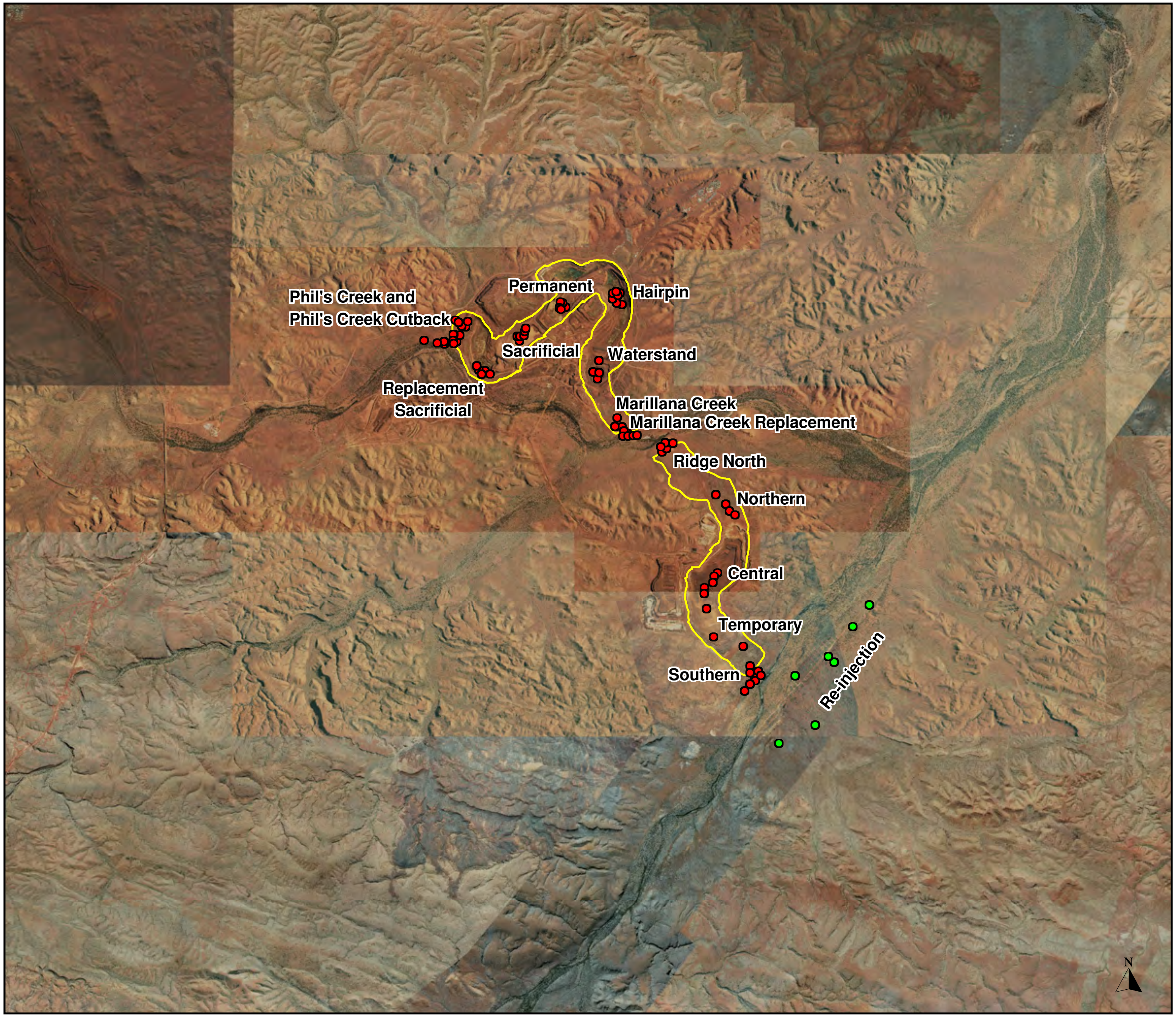
Figure 8 - Discharge Outlets in the Yandicoogina Region

Drawn: N. Inverarity Plan No.
Date: 13.9.10 Proj: MGA94 Z50


Hairpin
Phil's Creek
IMA
JSW C
Waterstand
JSW A
Oxbow
Ridge
Marsh
Union
Weeli
Wolli
Pocket
Cue
Cork Tree
Braid
Mindi
Mindi
LEGEND
Mining Area Boundary
CID Boundary
SCALE
1:100000 @ A4
N
RioTinto
Resource Development - Perth
Figure 9 -
RTIO Yandicoogina
Mining Areas
Drawn: N. Inverarity Plan No.
Date: 17.2.11 Proj: MGA94 Z50



LEGEND

- Dewatering Bore
- Re-injection Bore
- Final Boundaries of Existing Pits

SCALE

1:80 000 @ A4

Rio Tinto

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Figure 10 - RTIO Yandicoogina Borefields

Drawn: N. Inverarity Plan No.
Date: 13.9.10 Proj: MGA94 Z50

Figure 11 – Monthly Rainfall Recorded at DoW Flat Rocks Weather Station

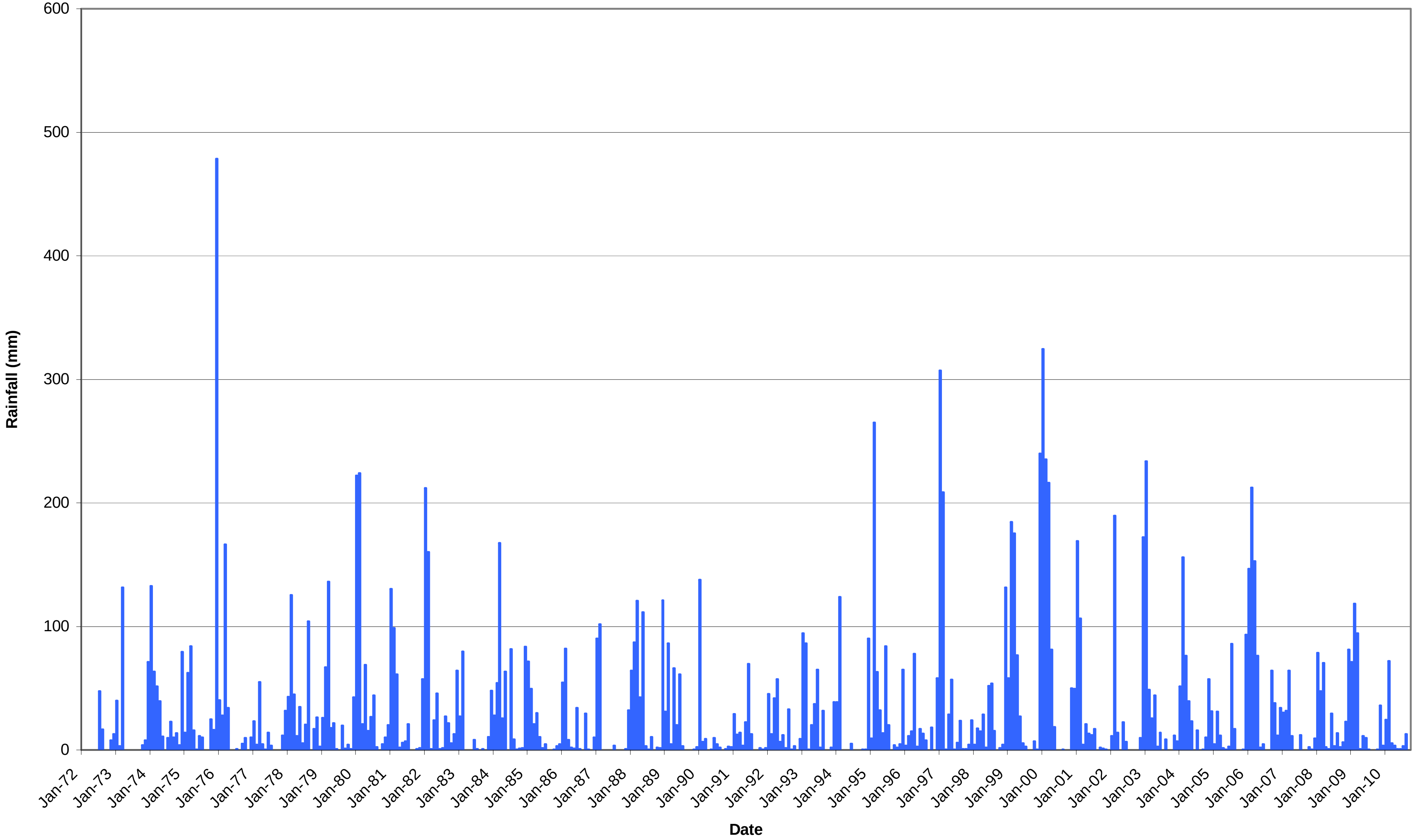


Figure 12 – Monthly Stream Flow Recorded at DoW Flat Rocks Gauging Station

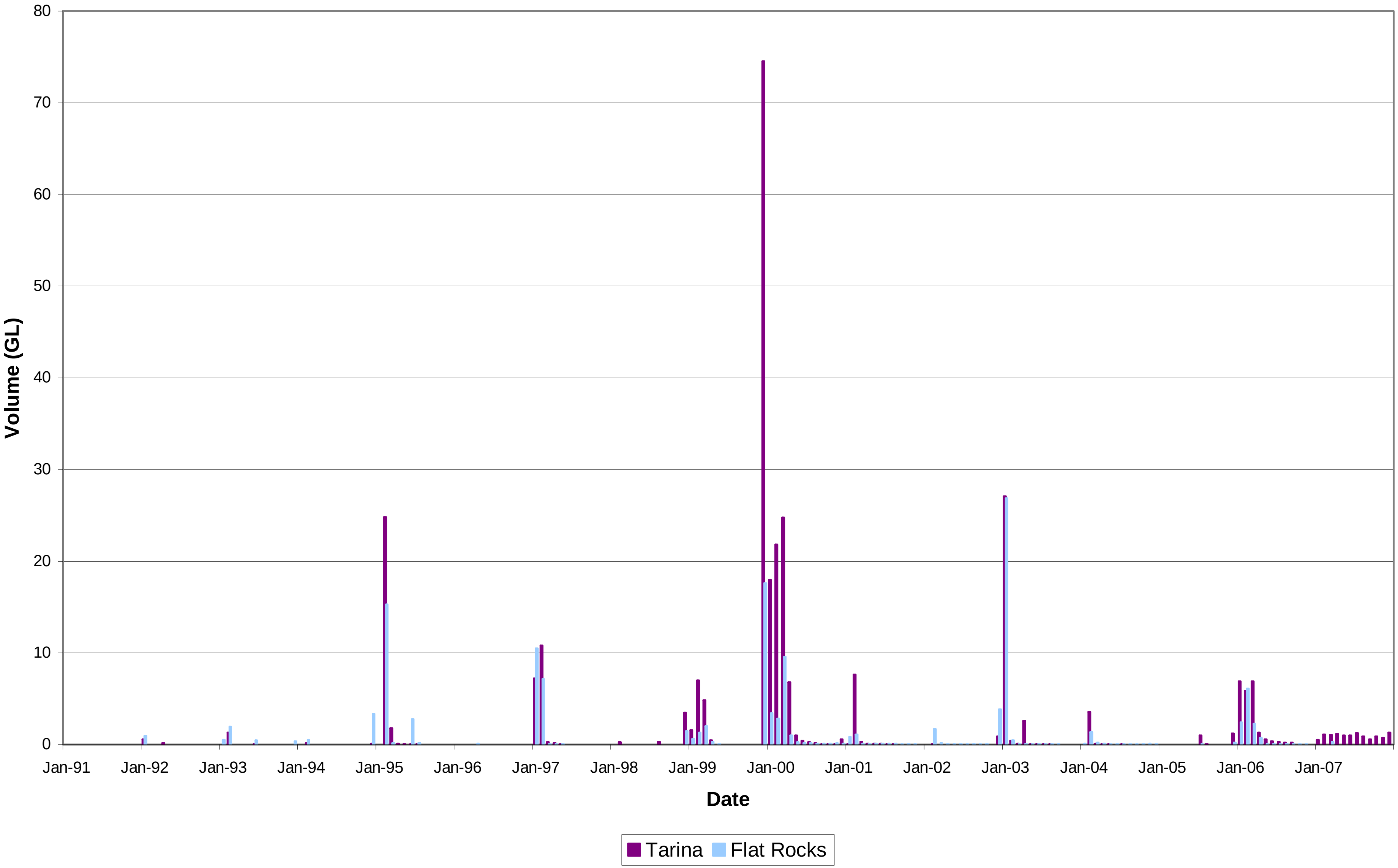
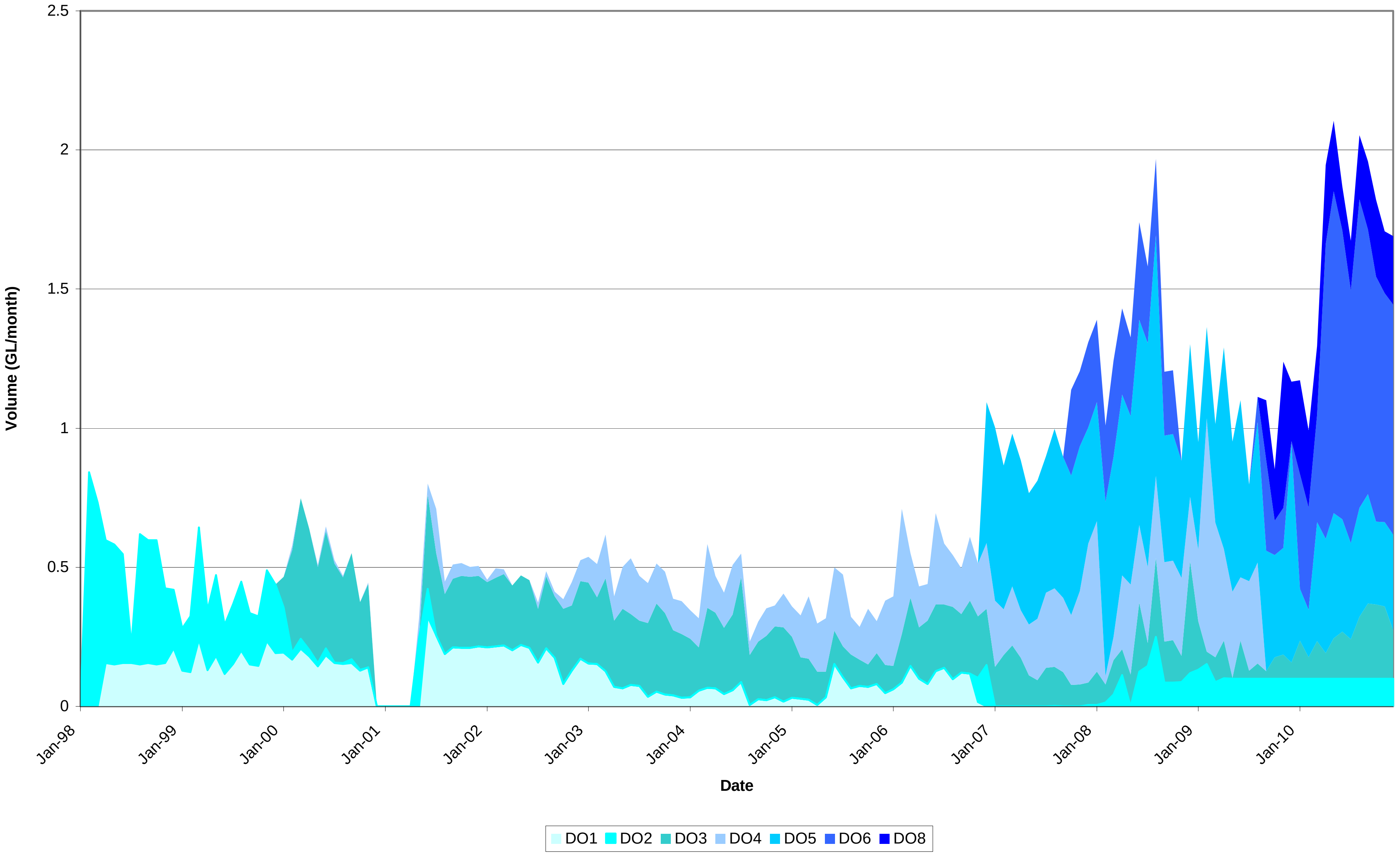
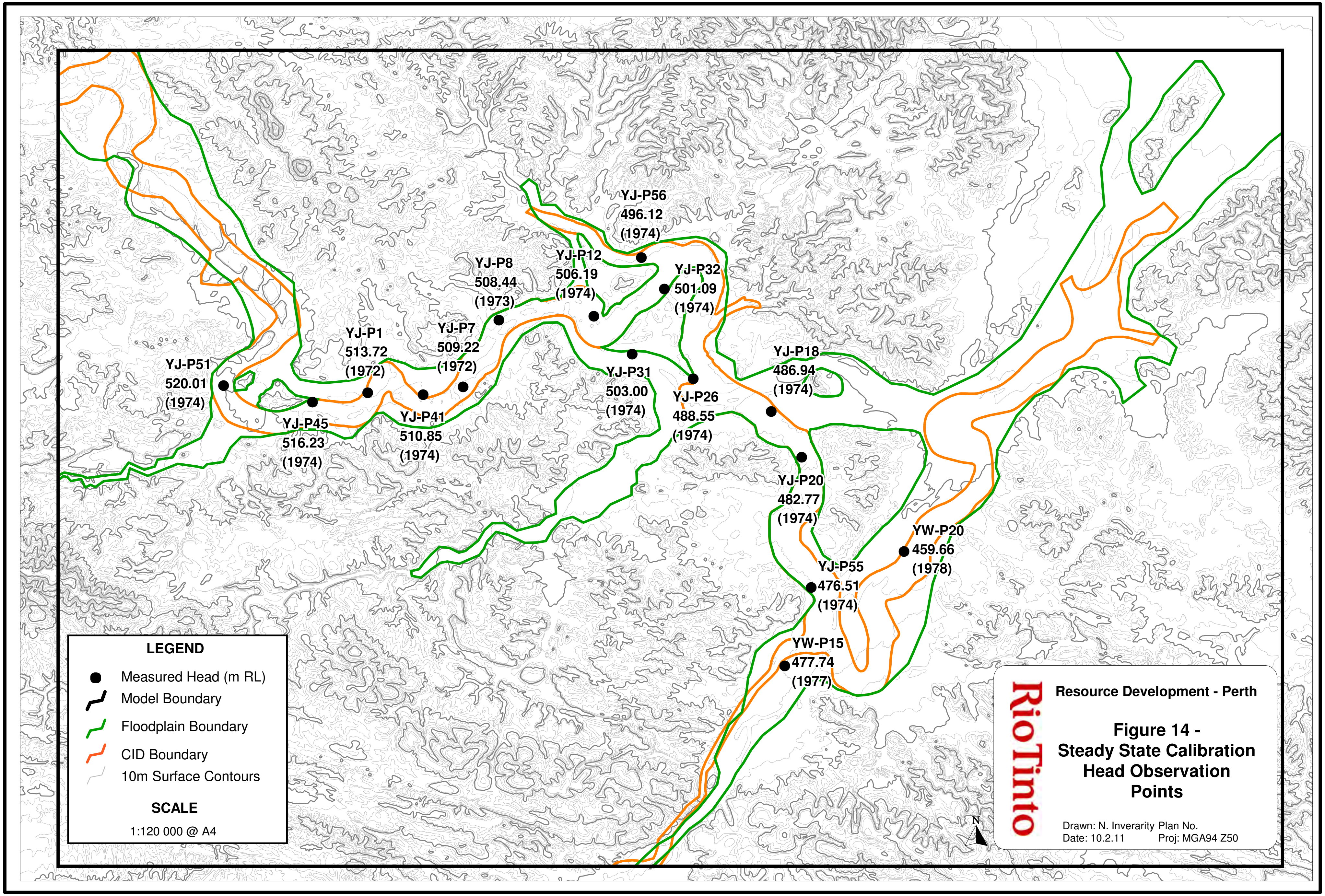
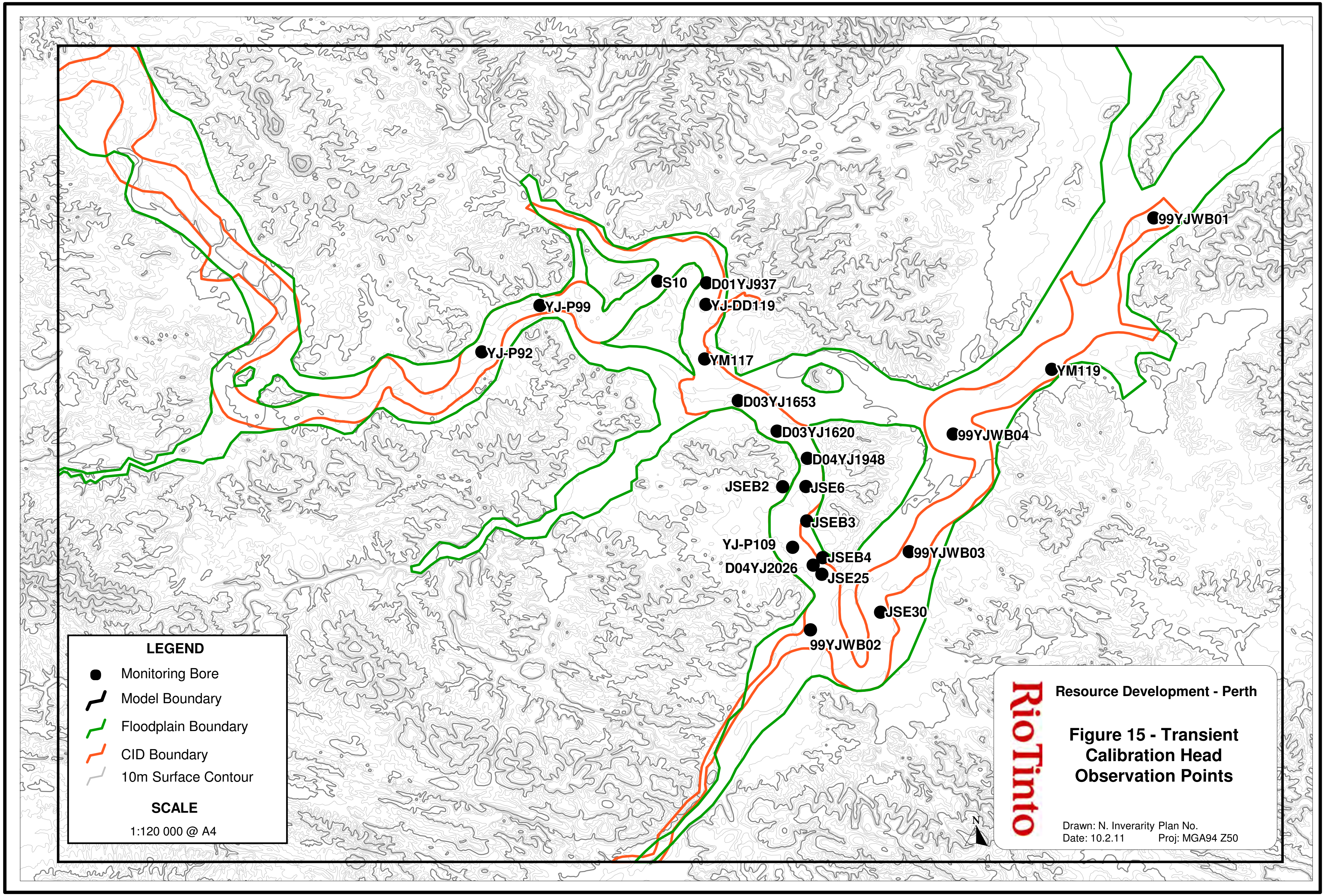


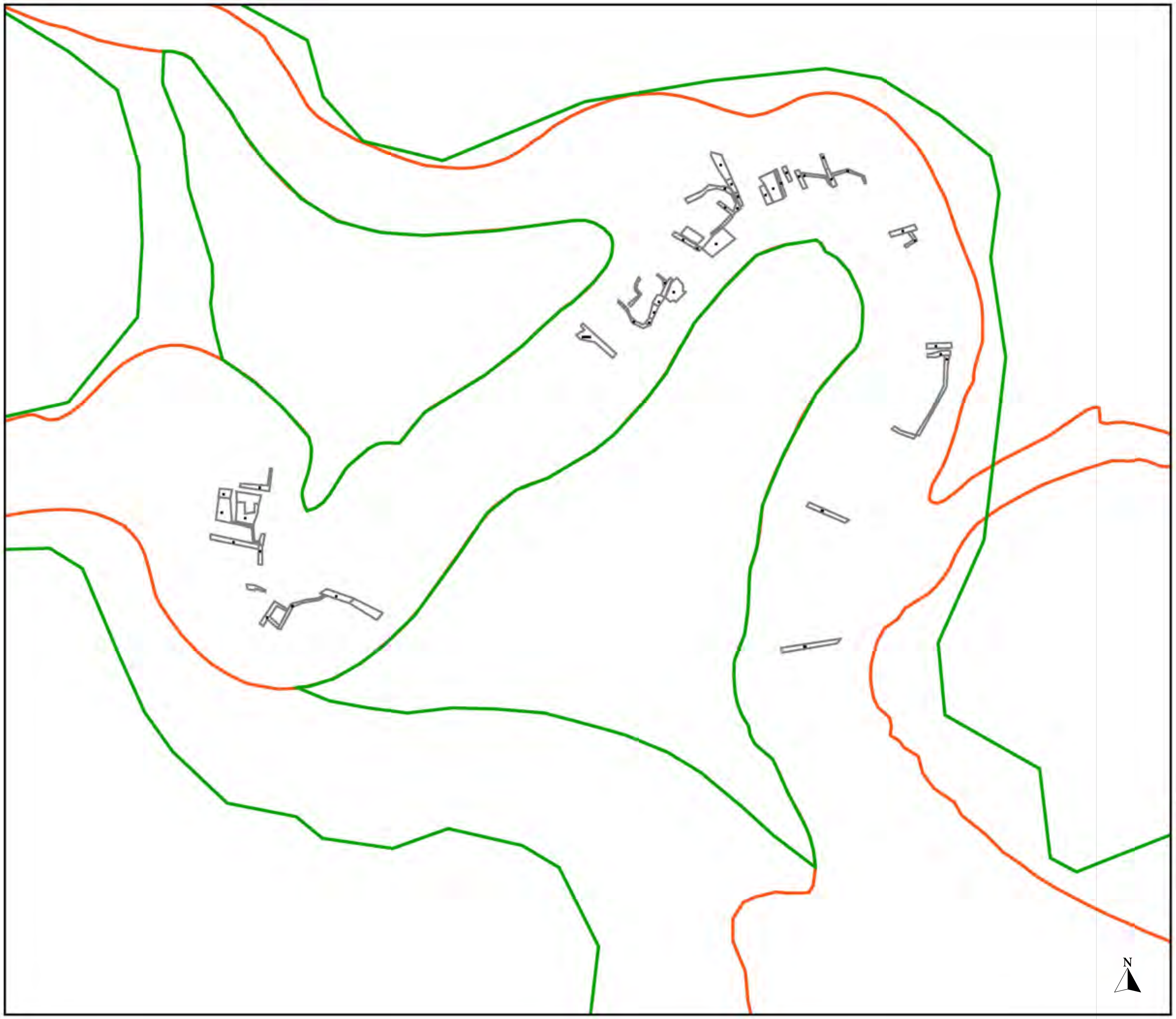
Figure 13 – Monthly Discharge Volumes from RTIO Yandicoogina Discharge Outlets





YJ-P56
496.12
(1974)
YJ-P12
506.19
(1974)
YJ-P32
501.09
(1974)
YJ-P8
508.44
(1973)
YJ-P1
513.72
(1972)
YJ-P7
509.22
(1972)
YJ-P51
520.01
(1974)
YJ-P45
516.23
(1974)
YJ-P41
510.85
(1974)
YJ-P31
503.00
(1974)
YJ-P26
488.55
(1974)
YJ-P18
486.94
(1974)
YJ-P20
482.77
(1974)
YW-P20
459.66
(1978)
YJ-P55
476.51
(1974)
YW-P15
477.74
(1977)
LEGEND
Measured Head (m RL)
Model Boundary
Floodplain Boundary
CID Boundary
10m Surface Contours
SCALE
1:120 000 @ A4
N
RioTinto
Resource Development - Perth
Figure 14 -
Steady State Calibration
Head Observation
Points
Drawn: N. Inverarity Plan No.
Date: 10.2.11 Proj: MGA94 Z50


99YJWB01
S10
D01YJ937
YJ-DD119
YJ-P99
YJ-P92
YM117
YM119
D03YJ1653
D03YJ1620
99YJWB04
D04YJ1948
JSEB2
JSE6
JSEB3
YJ-P109
JSEB4
99YJWB03
D04YJ2026
JSE25
JSE30
99YJWB02
LEGEND
Monitoring Bore
Model Boundary
Floodplain Boundary
CID Boundary
10m Surface Contour
SCALE
1:120 000 @ A4
N
Rio Tinto
Resource Development - Perth
Figure 15 - Transient Calibration Head Observation Points
Drawn: N. Inverarity Plan No.
Date: 10.2.11 Proj: MGA94 Z50



LEGEND

- Sump and Trench Boundaries
- Floodplain Boundary
- CID Boundary

SCALE

1:25 000 @ A4

Rio Tinto

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Figure 16 - Location of Sumps in the Junction Central Pits

Drawn: N. Inverarity Plan No.
Date: 10.2.11 Proj: MGA94 Z50

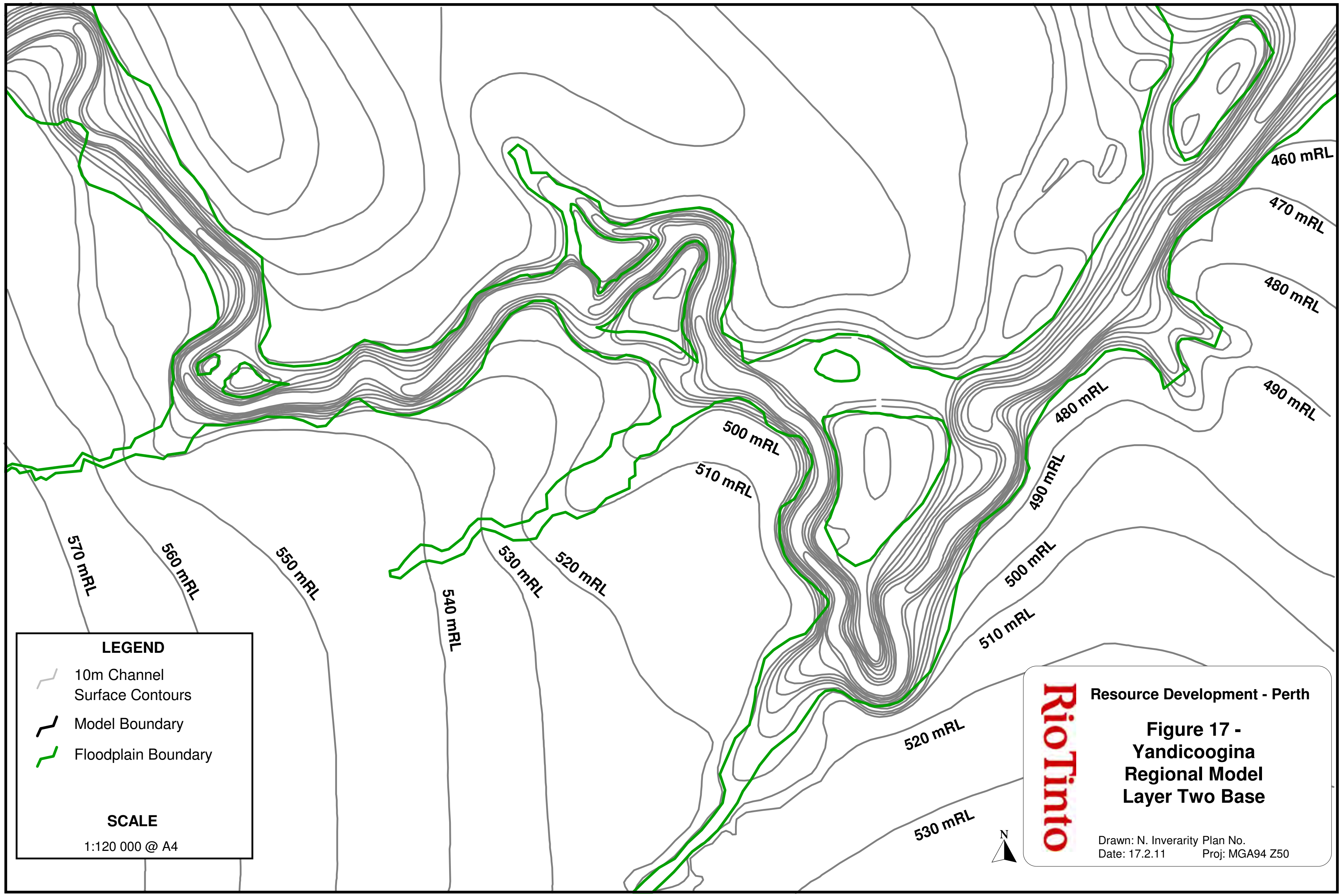


Figure 17 - Yandicoogina Regional Model Layer Two Base

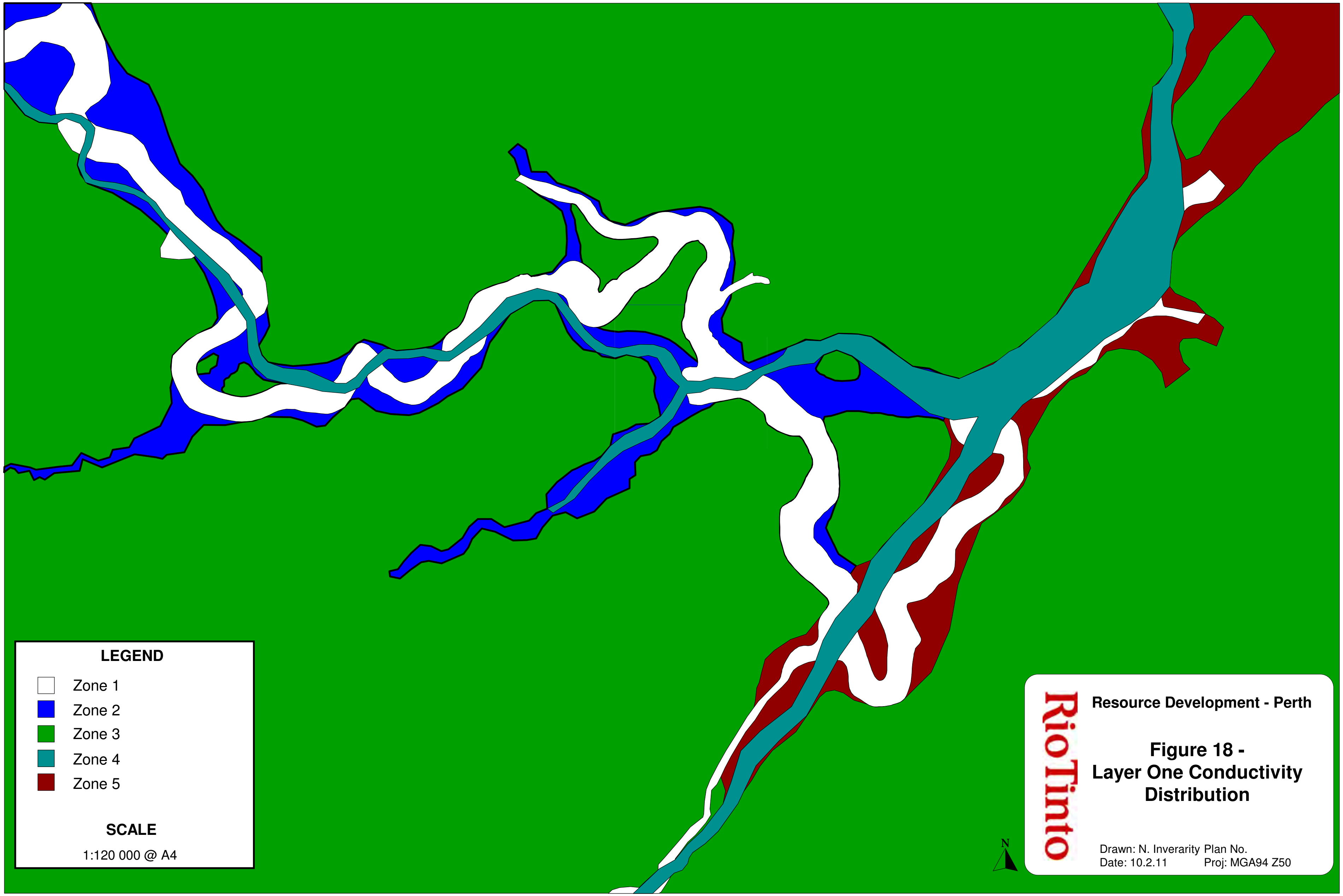
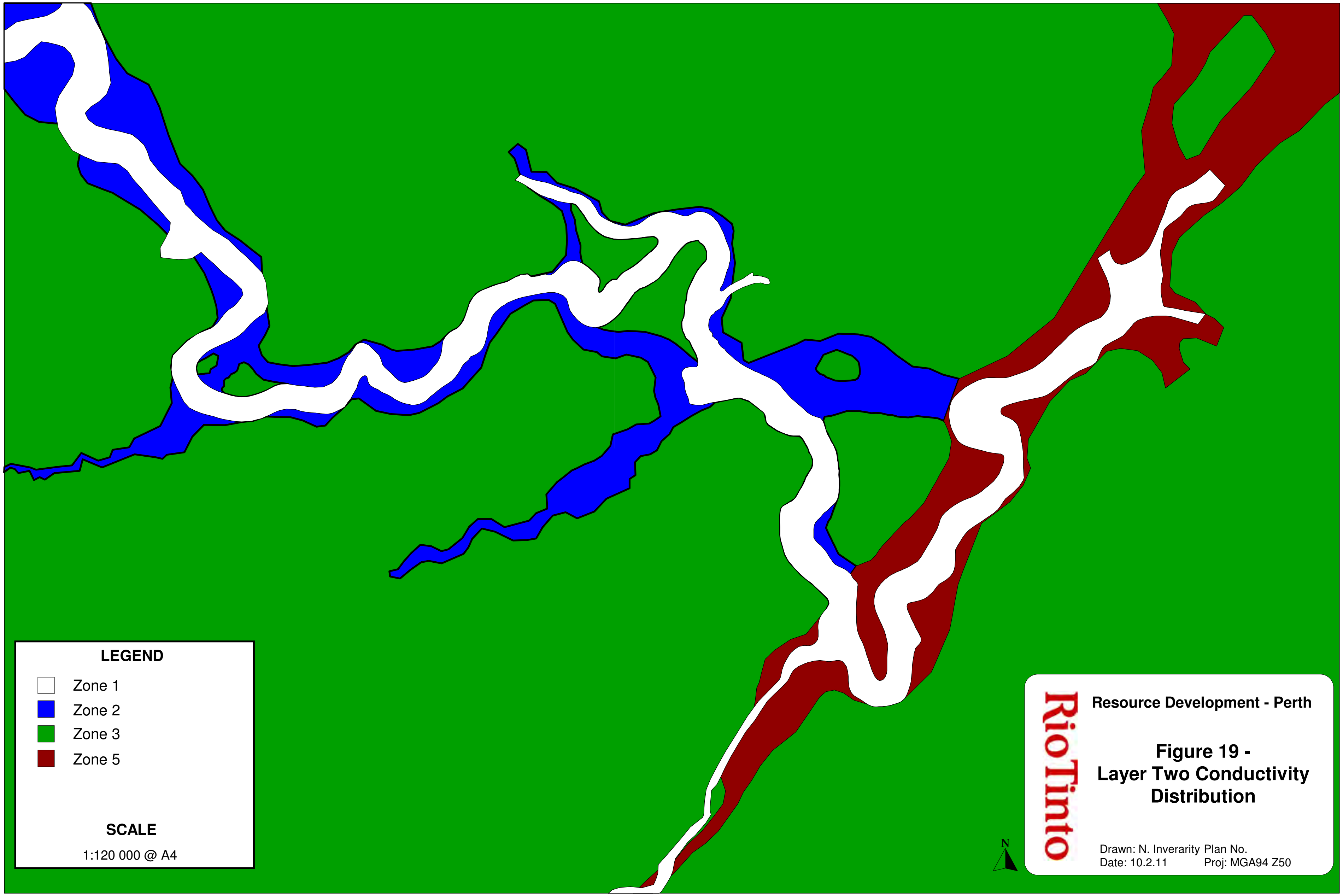


Figure 18 - Layer One Conductivity Distribution


LEGEND
Zone 1
Zone 2
Zone 3
Zone 5
SCALE
1:120 000 @ A4
N
RioTinto
Resource Development - Perth
Figure 19 -
Layer Two Conductivity
Distribution
Drawn: N. Inverarity Plan No.
Date: 10.2.11 Proj: MGA94 Z50

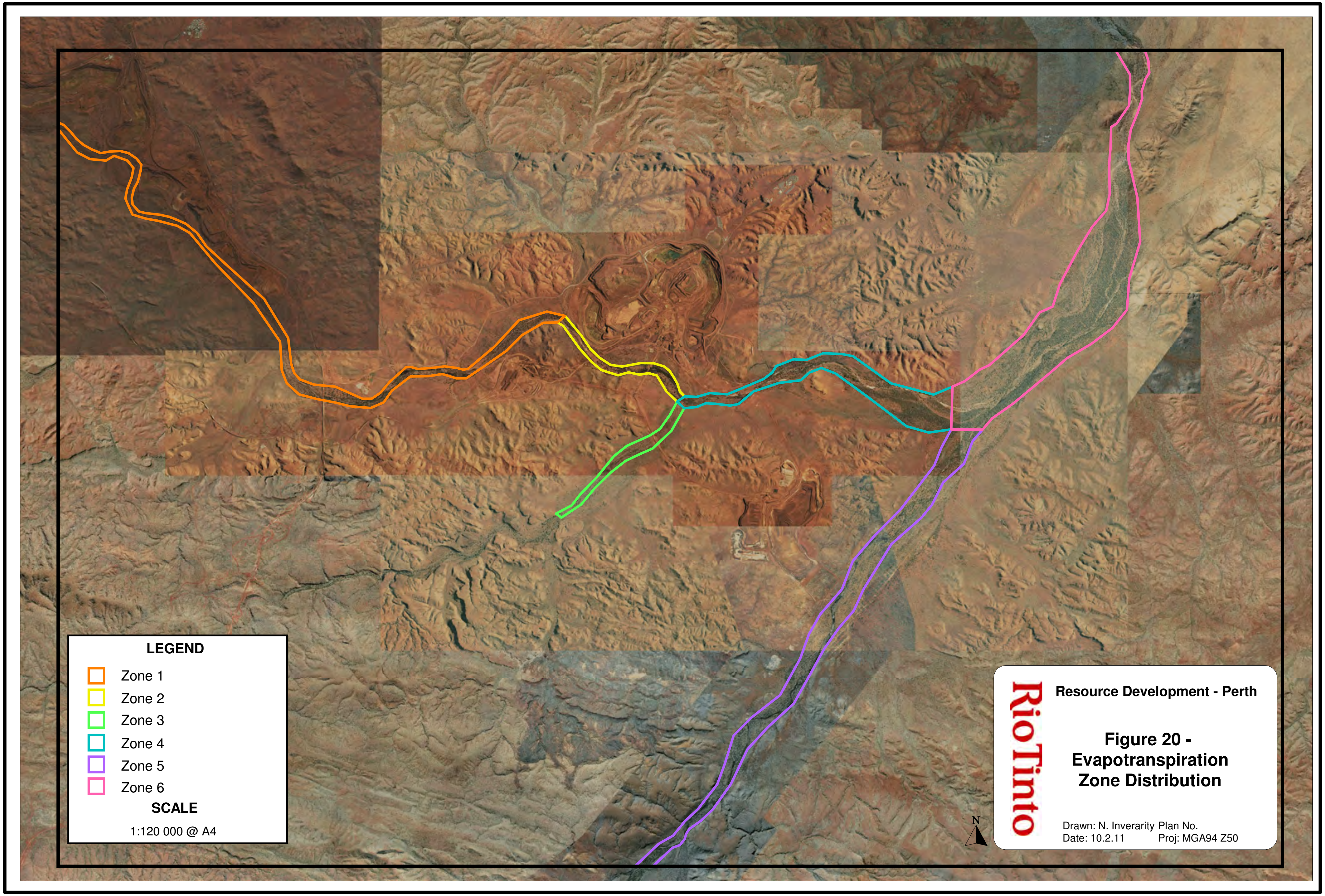
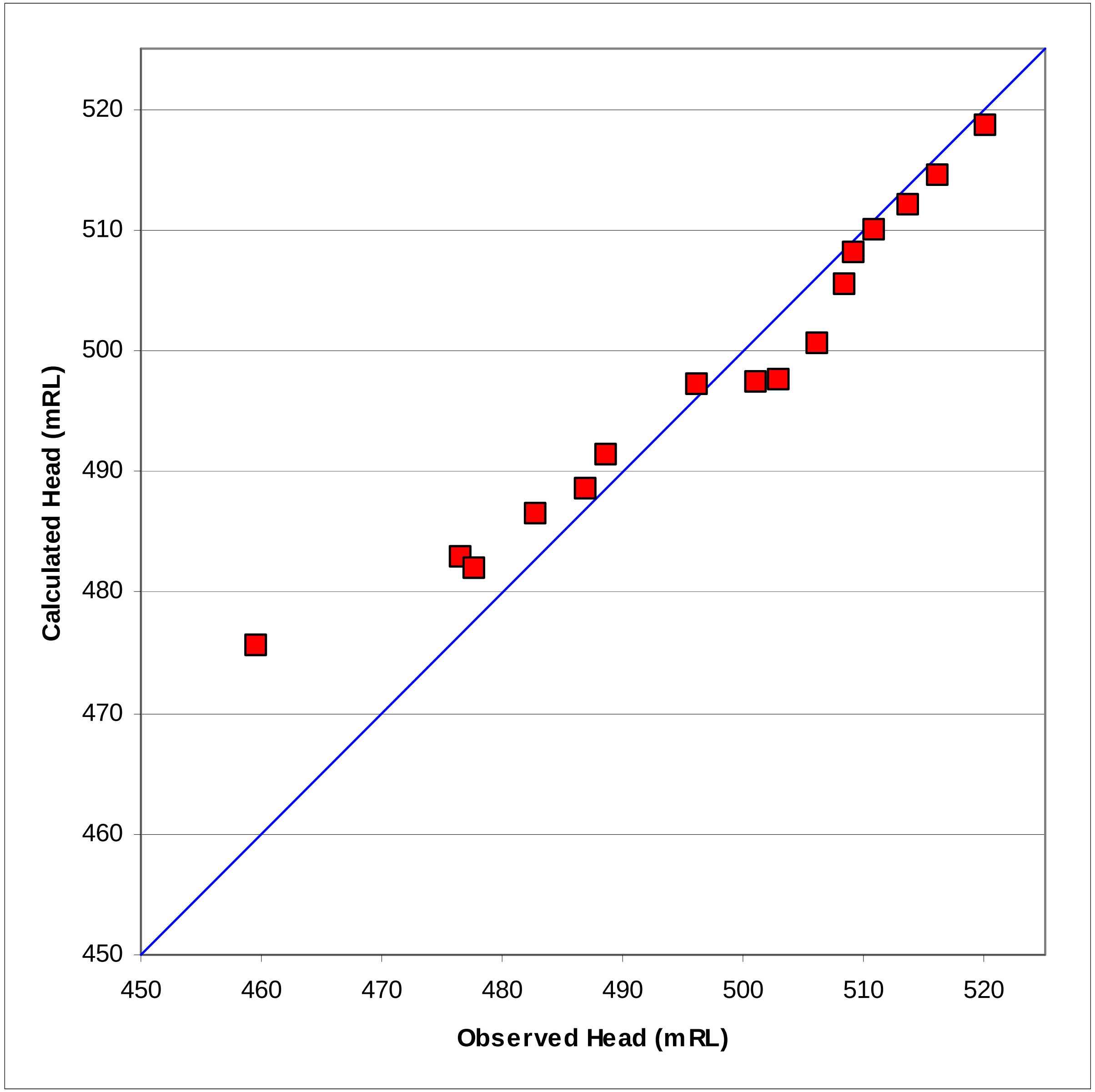

LEGEND
Zone 1
Zone 2
Zone 3
Zone 4
Zone 5
Zone 6
SCALE
1:120 000 @ A4
N
Rio Tinto
Resource Development - Perth
Figure 20 -
Evapotranspiration
Zone Distribution
Drawn: N. Inverarity Plan No.
Date: 10.2.11 Proj: MGA94 Z50

Figure 21 – Calculated Vs. Observed Steady State Heads



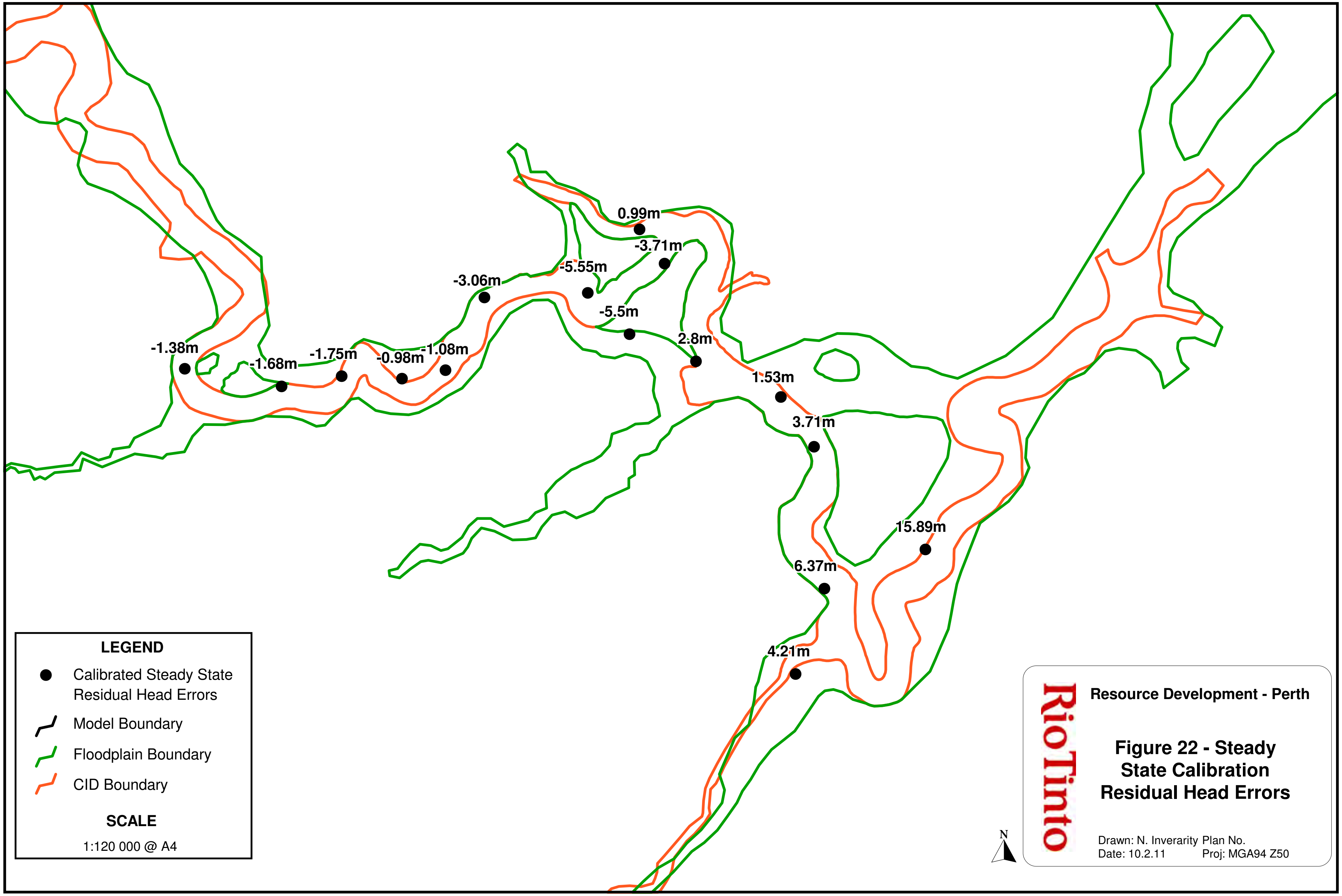


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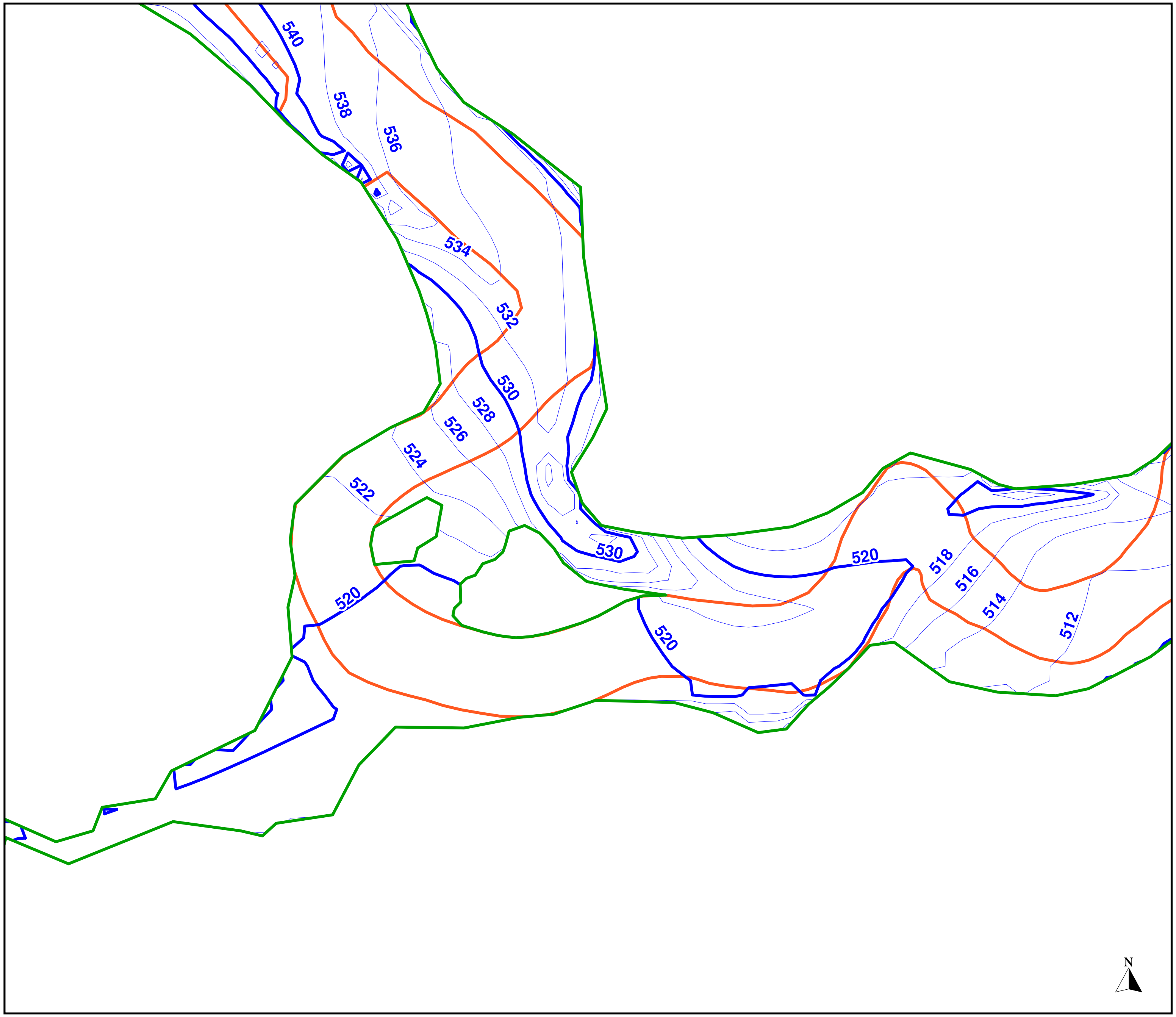
Figure 22 - Steady State Calibration Residual Head Errors

Drawn: N. Inverarity Plan No.
Date: 10.2.11 Proj: MGA94 Z50



LEGEND

2m Head Equipotential (mRL)
10m Head Equipotential (mRL)
Floodplain Boundary
CID Boundary

SCALE

1:40 000 @ A4

RioTinto

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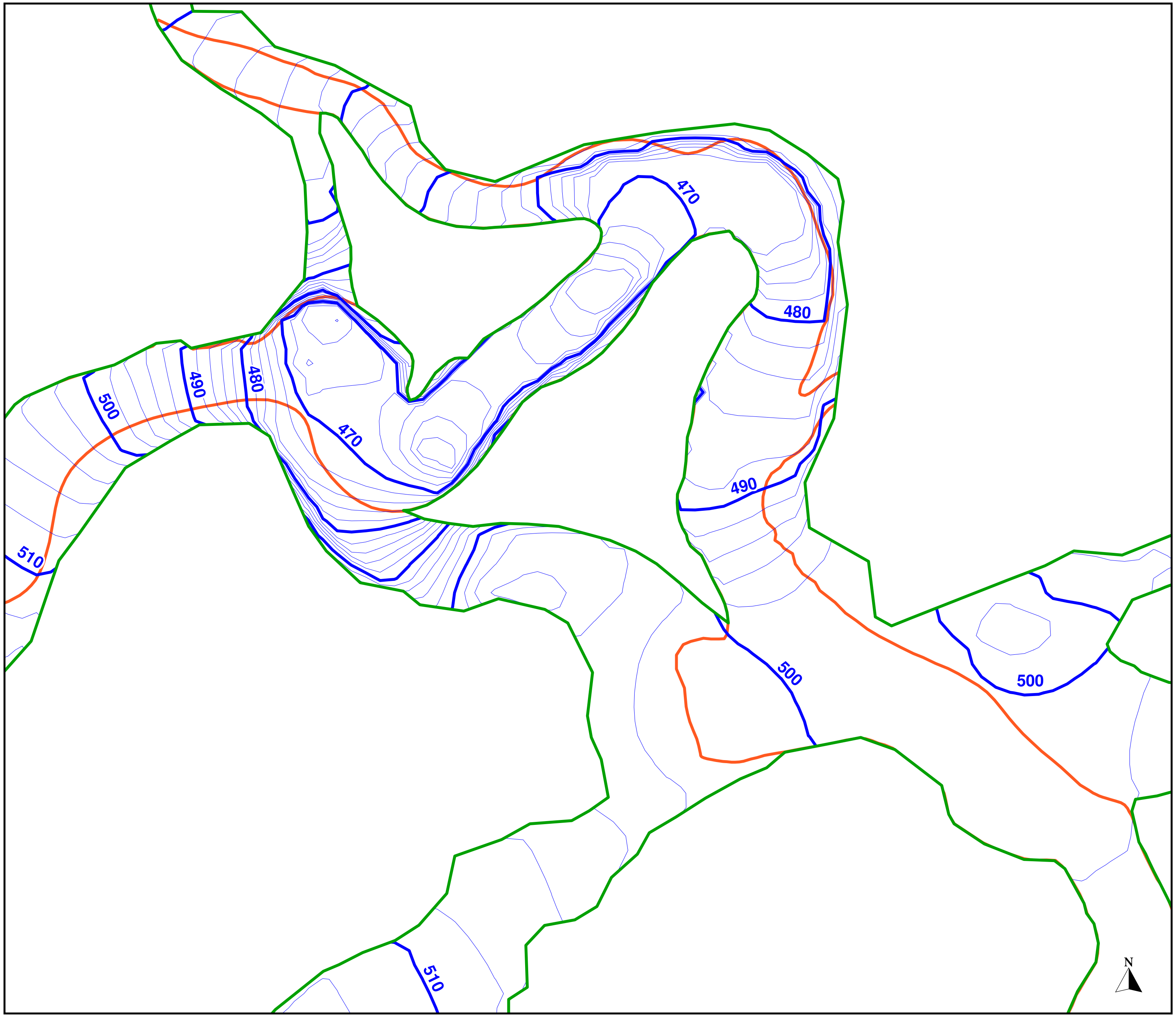
Figure 23 - Modelled February 1995 Water Table Elevation

Drawn: N. Inverarity Plan No.
Date: 10.2.11 Proj: MGA94 Z50



LEGEND

- 2m Head Equipotential (mRL)
- 10m Head Equipotential (mRL)
- Floodplain Boundary
- CID Boundary

SCALE

1:40 000 @ A4

Rio Tinto

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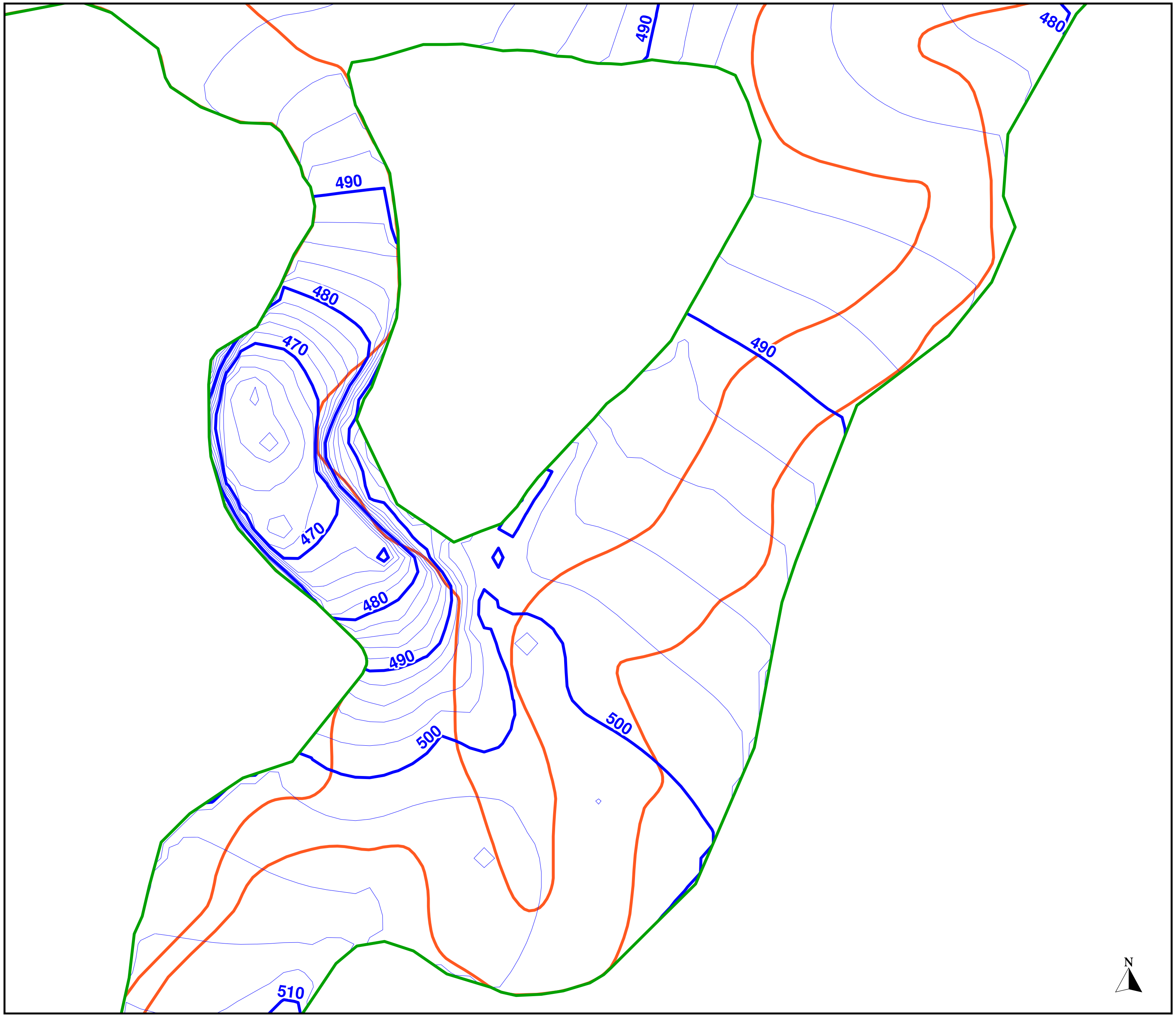
Figure 24 - Modelled December 2005 Water Table Elevation

Drawn: N. Inverarity Plan No.
Date: 10.2.11 Proj: MGA94 Z50



LEGEND

- 2m Head Equipotential (mRL)
- 10m Head Equipotential (mRL)
- Floodplain Boundary
- CID Boundary

SCALE

1:40 000 @ A4

Rio Tinto

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Figure 25 - Modelled April 2007 Water Table Elevation

Drawn: N. Inverarity Plan No.
Date: 10.2.11 Proj: MGA94 Z50

Figure 26 – Selected Cumulative Components of the Calibrated Numerical Model Mass Balance

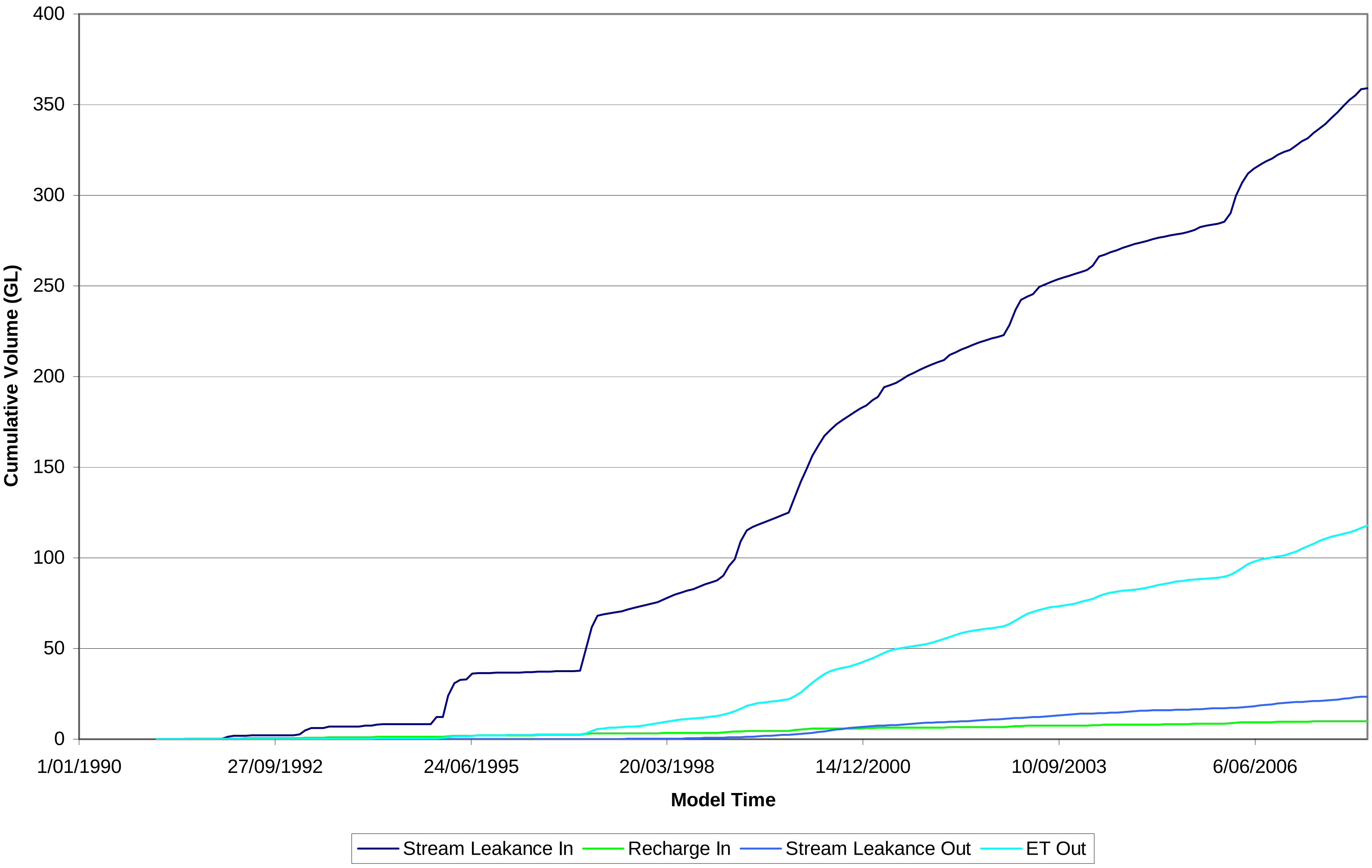


Figure 27 – Selected Rate Components of the Calibrated Numerical Model Mass Balance

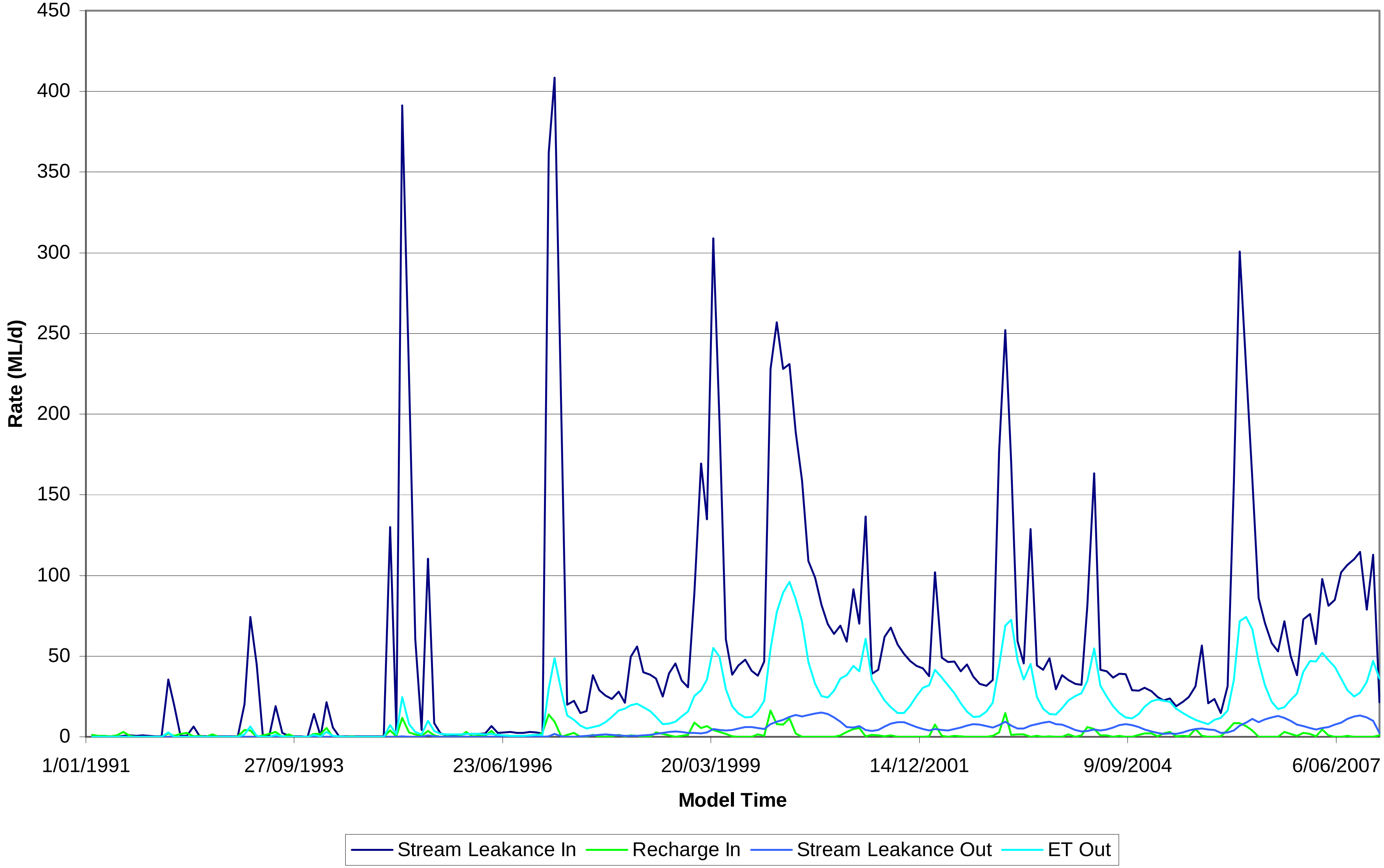
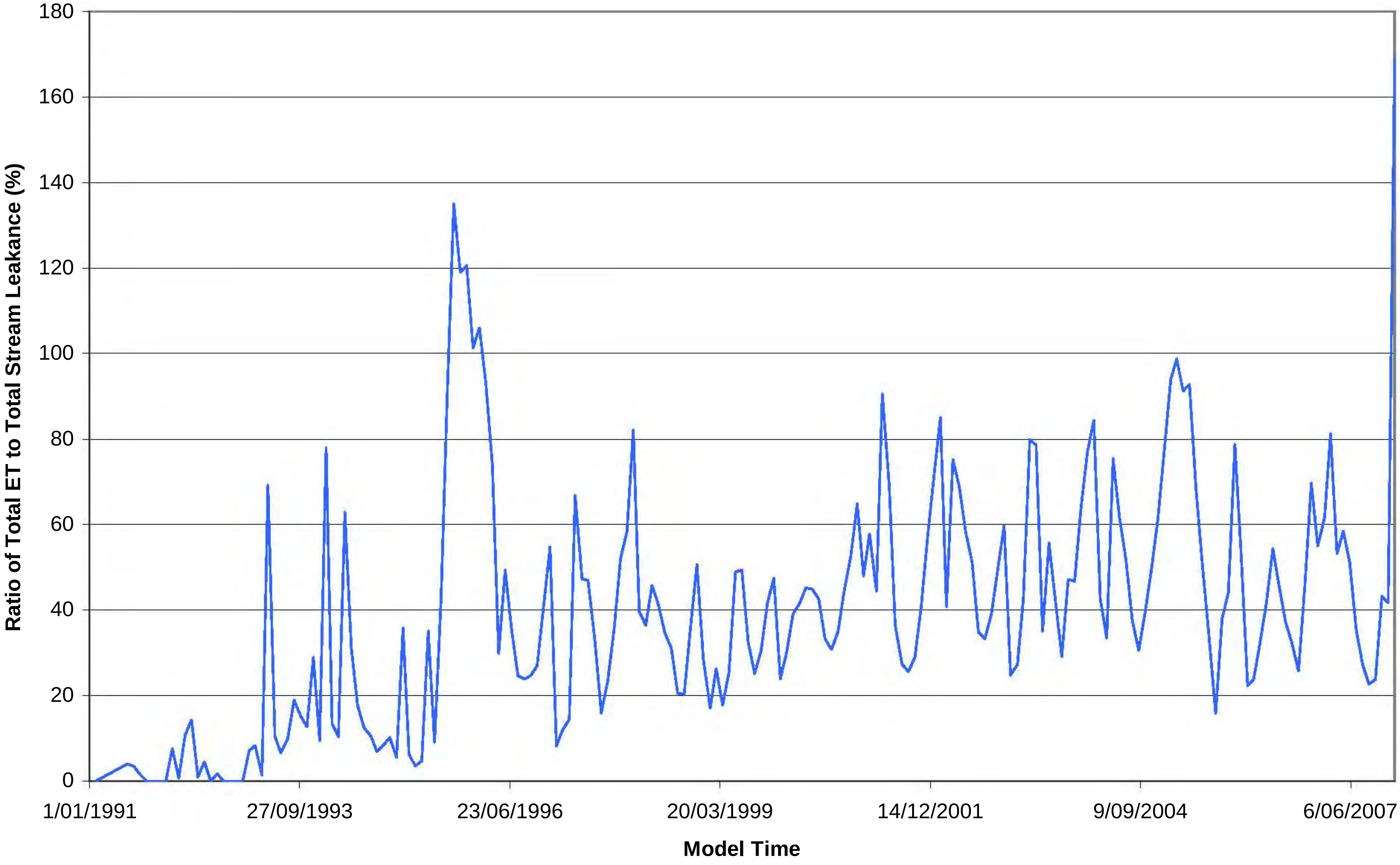
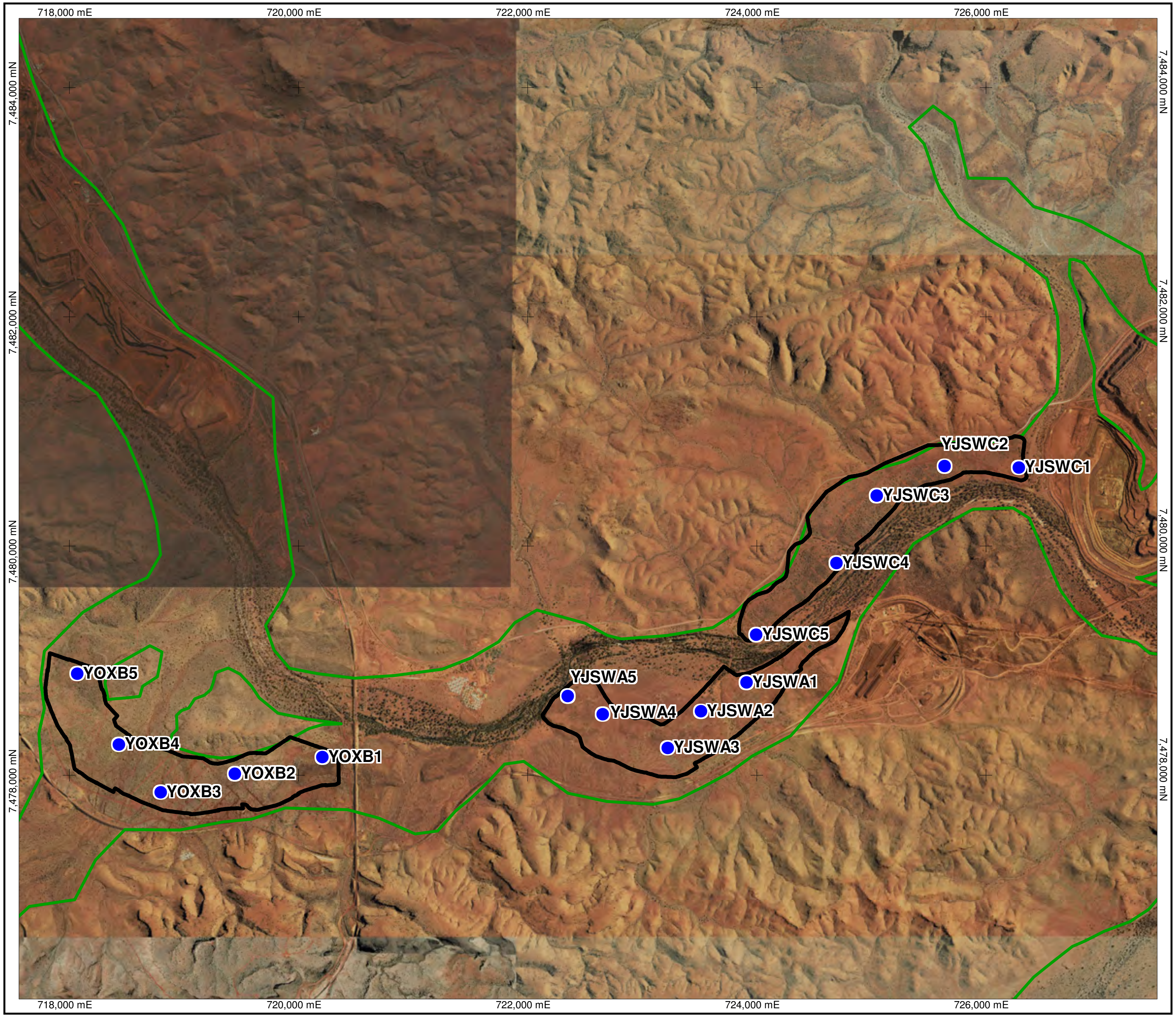


Figure 28 – Ratio of Total Rate of Evaptranspiration to Total Rate of Stream Leakance into Model





LEGEND

- Head Obs. Point
- Pit Outline
- Floodplain boundary

SCALE

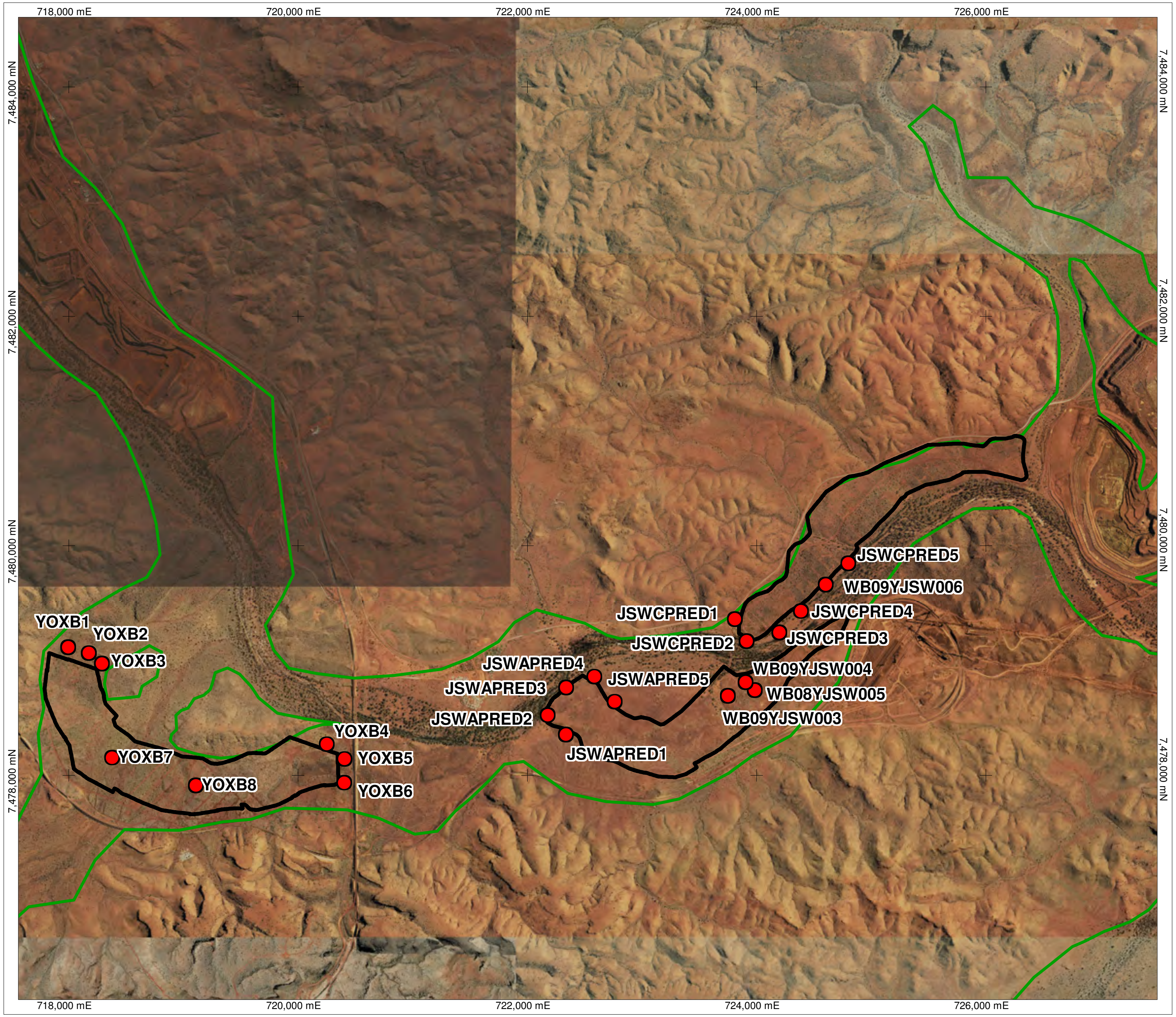
1:50 000 @ A4

RioTinto

Resource Development - Perth

Figure 29 - Predictive Simulation Head Observation Locations

Drawn: N. Inverarity Plan No.
Date: 15.6.10 Proj: MGA94 Z50



LEGEND

- Dewatering Bore
- Pit Outline
- Floodplain boundary

SCALE

1:50 000 @ A4

Rio Tinto

Resource Development - Perth

Figure 30 - Predictive Simulation Dewatering Bores Locations

Drawn: N. Inverarity Plan No.
Date: 18.2.11 Proj: MGA94 Z50

Figure 31 – Predicted Annual Dewatering Volumes for Six Mining Scenarios

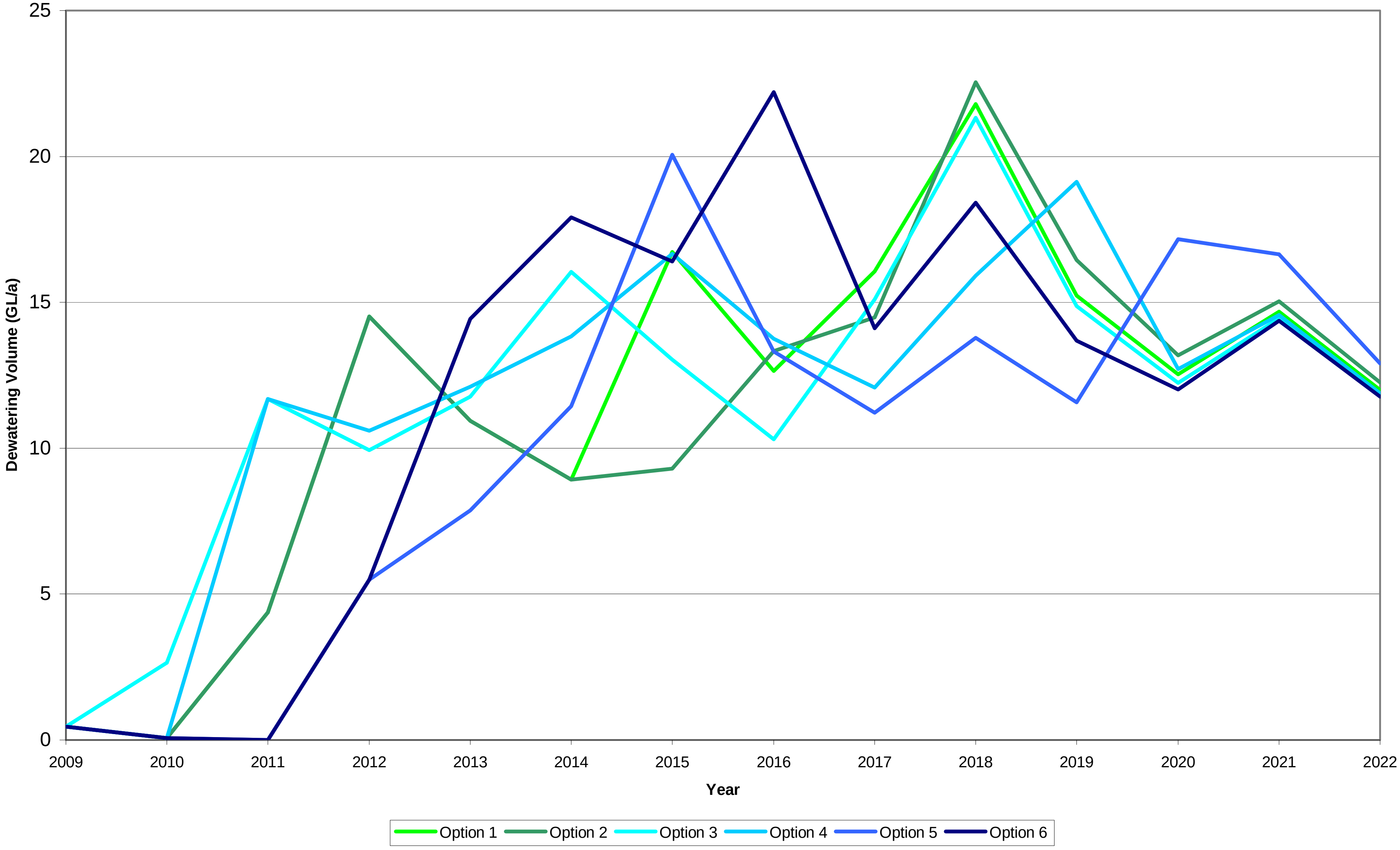


Figure 32 – Annual Volume of Water Discharged to Marillana Creek by BHPBIO

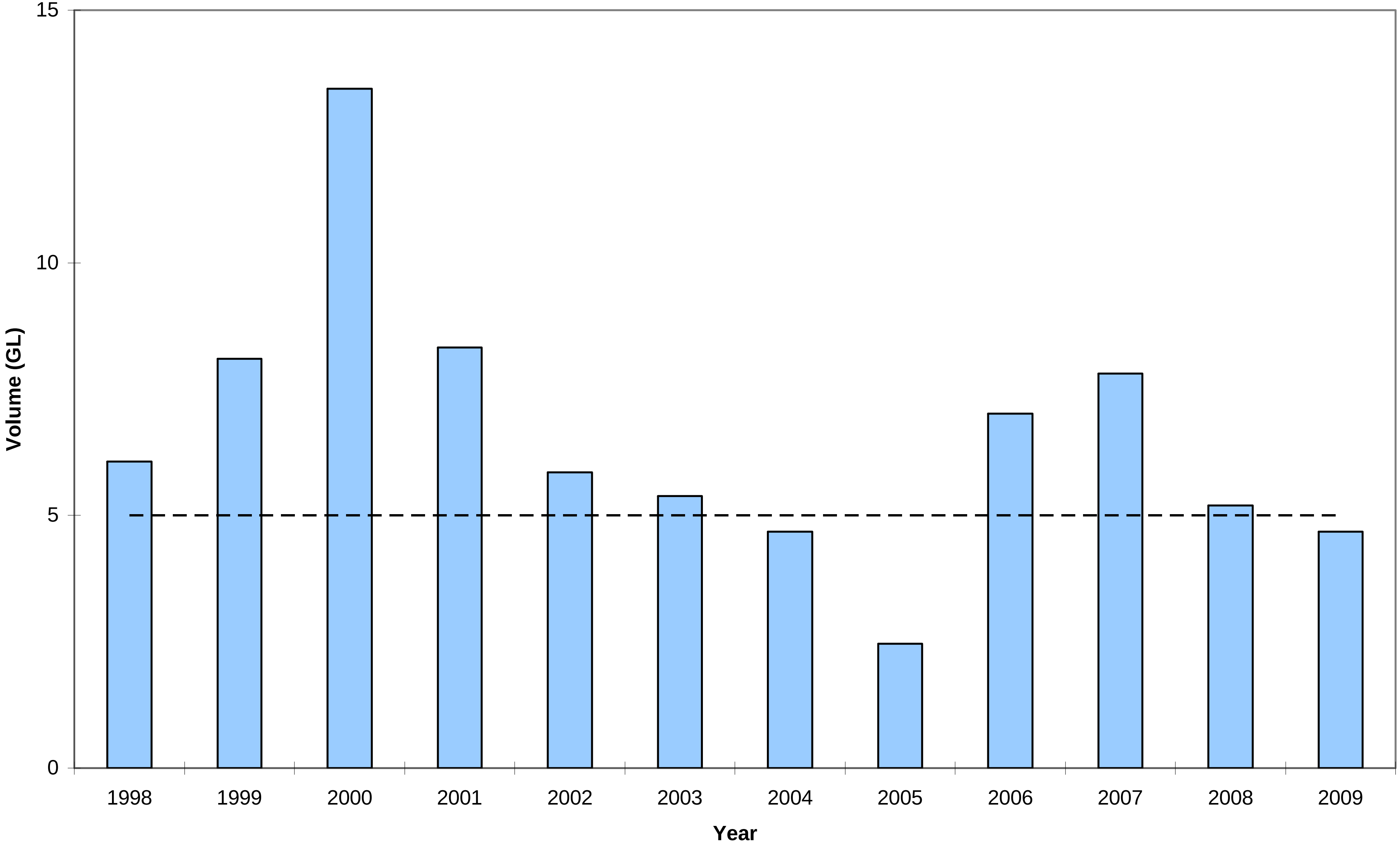


Figure 33 – Predicted Total Annual Dewatering Volumes from JSW-A, JSW-C and Oxbow for Four Discharge Scenarios

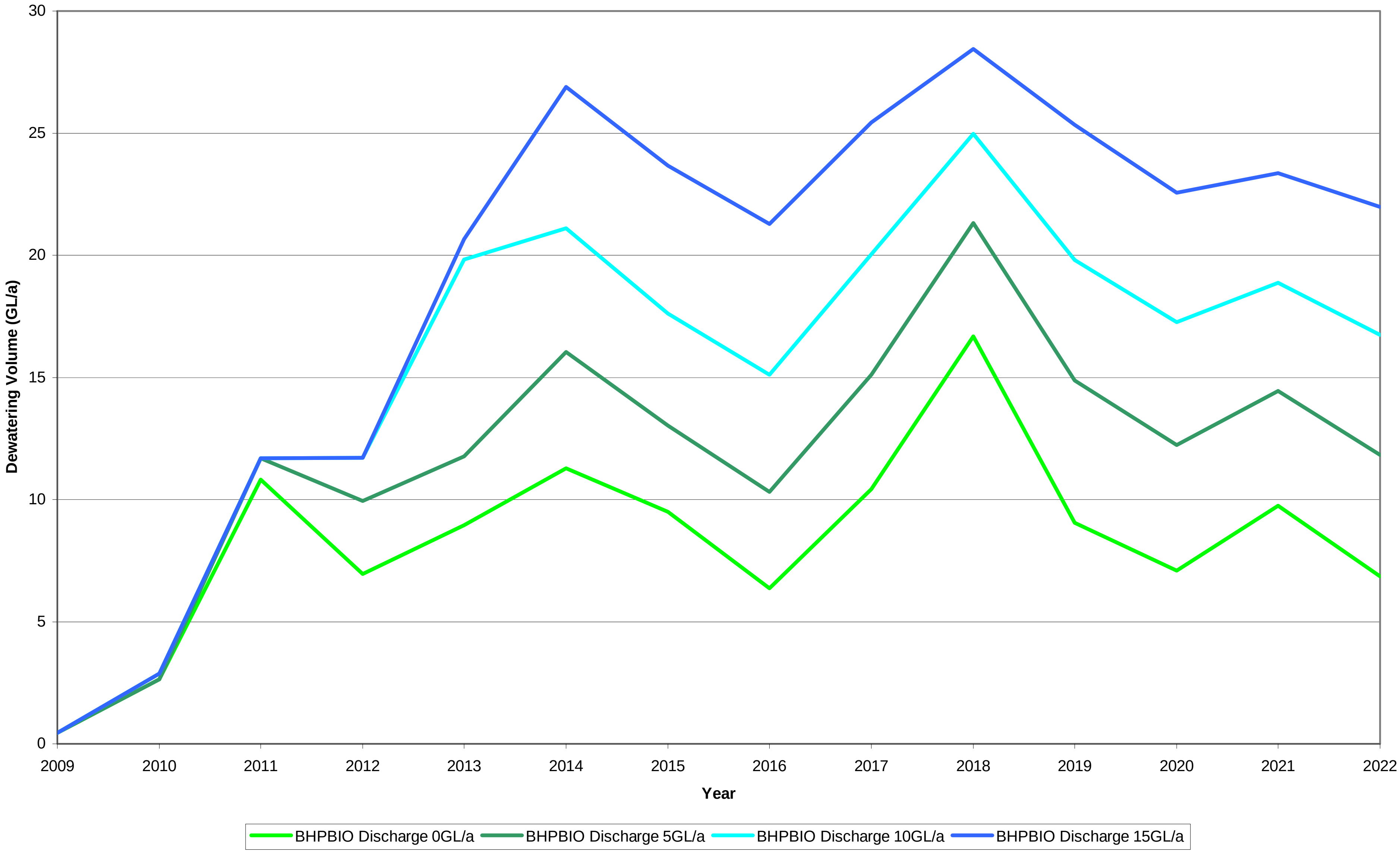
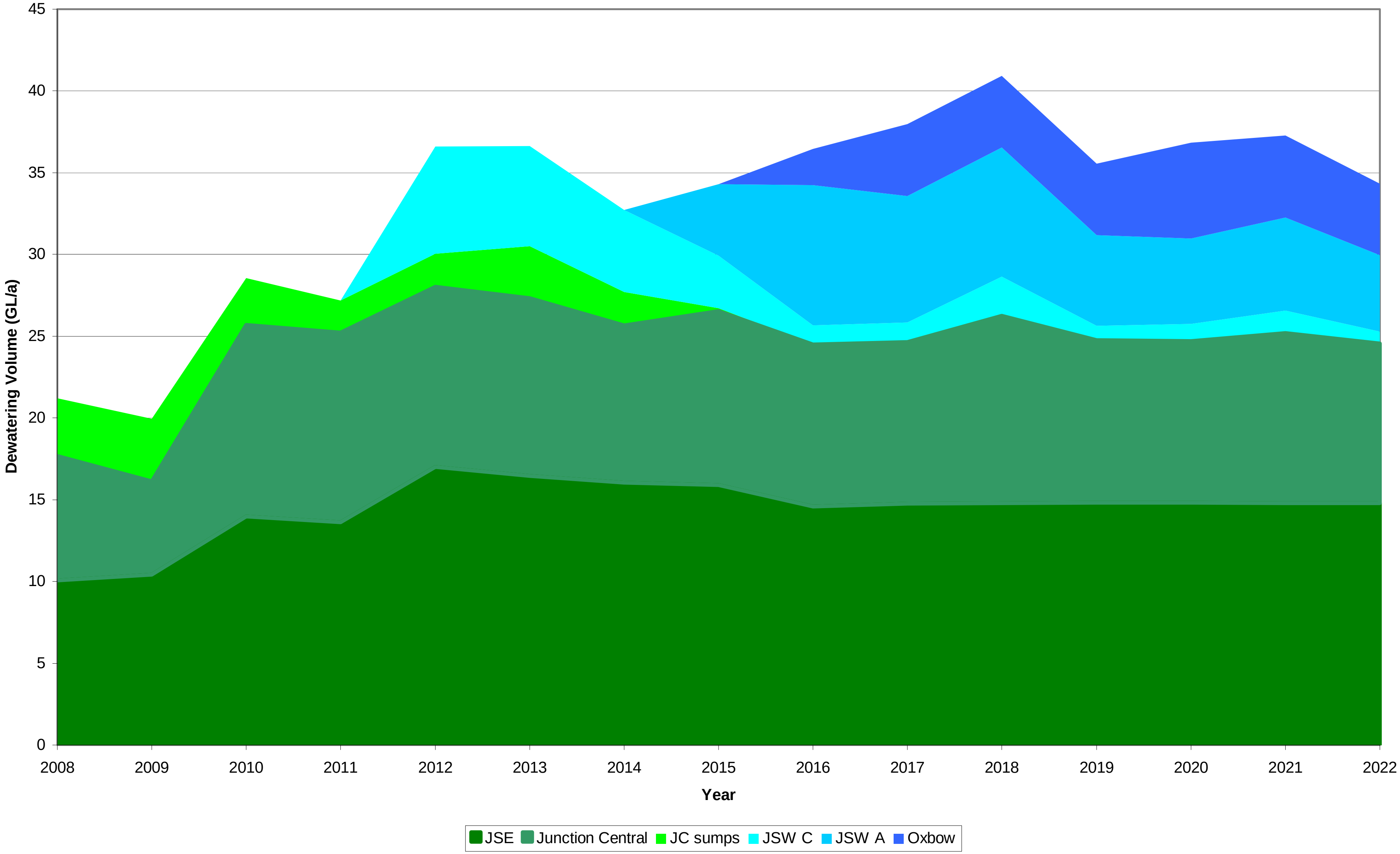


Figure 34 – Predicted Annual Dewatering Volumes for the Yandicoogina Mine



Appendix A

Results of Aquifer Test Pumping Analyses at RTIO Yandicoogina

Results of aquifer pumping tests undertaken in the vicinity of the IMA

Pumped Bore	Start Date	Duration (mins)	Discharge Rate (L/sec)	Aquifer Thickness (m)	Monitored Bore ID	Distance from Pumping Well (m)	Drawdown (m)	Analysis Method	K (m/d)	T (m^2/d)	S	Sy
YJ - W1	20/08/1979	5760	32	52	YJ - W2		9.68	early		6205		
								mid		2570		
								late		916		
					DD8			early		5530	0.0004	
								late		2600		
					P12			early		7900	0.0016	
								late		3160		
					P13			early		2212		
GS11	26/08/1979	3720	38	24.2	GS1	0	0.675	Theis		17400	0.001	
					P12	68	0.035	Distance-Drawdown		20000	0.001	
					DD8	160	0.02	Distance-Drawdown		20000	0.001	
					DD35	330	0	Distance-Drawdown		20000	0.001	
GS46	19/10/1980	3000	30	62.5	GS47 (shallow)		4.8				0.001	
					GS47 (deep)		4.9				0.001	
GS48	19/10/1980	3000	30	61.5			Pumped concurrently with GS48					
PP01	11/12/1997	1440	51	50	PP01	0.15	8.62	Cooper-Jacob Unconfined	17.72	885.6		
					OBS10	49.4	0.84	Cooper-Jacob Unconfined		2376	0.0191	
					PP02	63.6	0.74	Cooper-Jacob Unconfined		2376	0.0191	
					OBS3	67.9	0.66	Cooper-Jacob Unconfined		2376	0.0191	
PP02	13/12/1997	1560	52	50	PP02	0.15	9.508	Hurr-Worthington	13.8	889		
								Cooper-Jacob		757		
					OBS10	21	2.693	Neuman (late)		713	0.014	
					PP03	34.6	2.333	Neuman (late)		713	0.01	
					OBS03	32.5	1.613	Neuman (late)		1130	0.015	
PP03	15/12/1998	1440	62	50	OBS03	50	1.671	Cooper-Jacob Unconfined	17.71	887		
					OBS07	72	1.565	Cooper-Jacob Unconfined	17.71	887		
					PP02	35	2.919	Cooper-Jacob Unconfined	17.71	887		

PP04	17/12/1998	1440	54	50	PP04	0.15	6.793	Cooper-Jacob Unconfined	30.6	1526.4
					OBS03	29.6	1.739	Cooper-Jacob Unconfined	32.1	1598
					PP03	76.5	0.547	Cooper-Jacob Unconfined	32.1	1598
PP05	4/02/1998	1440	30	50	PP05	0.15	15.843	Cooper-Jacob Unconfined	29.5	1468.8
					PP04	44.5	0.384	Cooper-Jacob Unconfined	78.3	3916.8
					P3	71.8	0.458	Cooper-Jacob Unconfined	78.3	3916.8
					PP01	107.2	0.428	Cooper-Jacob Unconfined	78.3	3916.8
SP01	17/01/1998	1440	52	50	SP01	0.15	1.632	Theis & Jacob Recovery (unconfined)	152.6	7675
								Cooper-Jacob Unconfined	83.8	4190
					S13	66.4	0.567	Cooper-Jacob Unconfined	137.2	6854.4
					SP03	97.3	0.527	Cooper-Jacob Unconfined	137.2	6854.4
					S9	78	0.557	Cooper-Jacob Unconfined	137.2	6854.4
SP02	19/01/1998	1440	62	50	SP02	0.15	1.268	Cooper-Jacob Unconfined	120.3	6019.2
					SP03	59.7	0.666	Cooper-Jacob Unconfined	84.67	4233.6
					S13	45.3	0.853	Cooper-Jacob Unconfined	84.67	4233.6
					SP01	110.5	0.606	Cooper-Jacob Unconfined	84.67	4233.6
SP03	23/01/1998	1440	62	50	S9	28.4	0.666	Cooper-Jacob Unconfined	94.32	4708.8
					SP04	85.1	0.656	Cooper-Jacob Unconfined	94.32	4708.8
					S13	47.2	0.636	Cooper-Jacob Unconfined	94.32	4708.8
SP04	26/01/1998	1440	62	50	SP04	0.15	1.671	Cooper-Jacob Unconfined	120.2	6004.8
					S4	37.8	0.596	Cooper-Jacob Unconfined	104.7	5227.2
					S9	78.4	0.631	Cooper-Jacob Unconfined	104.7	5227.2
					SP01	147.2	0.577	Cooper-Jacob Unconfined	104.7	5227.2
SP05	28/01/1998	1440	52	50	SP05	0.15	6.634	Cooper-Jacob Unconfined	19.2	964.8
					S2	24.3	1.078	Cooper-Jacob Unconfined	90.4	4521.6
					S4	56.8	0.517	Cooper-Jacob Unconfined	90.4	4521.6
					SP04	92.7	0.259	Cooper-Jacob Unconfined	90.4	4521.6
SP06	2/02/1998	1440	62	50	SP06	0.15	3.831	Cooper-Jacob Unconfined	46.7	2332.8
					S18	55.9	1.376	Cooper-Jacob Unconfined	55.3	2764.8
					S2	44.3	1.186	Cooper-Jacob Unconfined	55.3	2764.8
					SP05	53.7	1.019	Cooper-Jacob Unconfined	55.3	2764.8

Results of aquifer pumping tests undertaken in the vicinity of Phil's Creek

Pumped Bore	Start Date	Duration (mins)	Discharge Rate (L/sec)	Aquifer Thickness (m)	Monitored Bore ID	Distance from Pumping Well (m)	Drawdown (m)	Analysis Method	K m/d	T m2/d	S	Sy
PC001	13/04/2002	2880	36	67.3	W01YJ015D	4.5	14.25	Hantush - Leaky Aquifer	3.5	233		
								Theis - Jacob	2.2	145		
								Cooper - Jacob	3.3	225	7.27E-5	
					W02YJ016	97	5.04	Hantush - Leaky Aquifer	6.2	418	5.55E-05	
					W02YJ001	284	2.28	Cooper - Jacob (late)	7.8	523	2.45E-04	
								Neuman (late)	7.4	501	2.85E-04	0.0003
					W02YJ015	264	2.27	Cooper - Jacob	7.5	504	3.71E-04	
								Neuman (late)	7.1	481	4.39E-04	0.0004
					W02YJ009D	70	1.61	Cooper - Jacob (late)	9.2	621	3.65E-04	
								Neuman (late)	8.1	543	4.97E-04	0.0005
PC002	17/04/2002	2880	36	61	W02YJ016	65	31.89	Hantush - Leaky Aquifer	5.9	360	3.02E-04	
					W01YJ015D	149	3.02	Hantush - Leaky Aquifer	7.5	455.04	7.76E-04	
								Theis - Jacob	3.8	233.28		
								Cooper - Jacob	7.6	466.56	7.76E-04	
					W02YJ001	193	1.94	Cooper - Jacob	8.7	532.8	9.97E-04	
								Neuman (late)	8.5	521.28	1.10E-03	
					W02YJ015	111	3.14	Cooper - Jacob	6.7	407.52	8.72E-04	
								Neuman (late)	6.7	408.96	8.78E-04	
					W02YJ009D	251	1.86	Cooper - Jacob (late)	8.3	504	8.00E-04	
								Neuman (late)	7.9	483.84	8.92E-04	
PC003	10/12/2001	2880	40	55	PC003	0	20.65	Hantush - Leaky Aquifer	2.2	123		
					D01YJ953	2	9.82	Hantush - Leaky Aquifer	2.5	140	3.03E-02	
					W01YJ015D	70	3.45	Cooper - Jacob (late)	16.1	888	3.74E-05	
								Neuman (late)	8.9	489		0.0003
					W01YJ015S	70	3.29	Cooper - Jacob (late)	16.1	888	3.74E-05	
								Neuman (late)	8.9	489		0.0003
					W01YJ012	163	1.81	Cooper - Jacob (late)	9.3	512	3.80E-03	
					W01YJ011	380	0.84	Cooper - Jacob (late)	25.9	1424	1.18E-03	
					D01YJ952	64	2.5	Cooper - Jacob (early)	6.1	335	1.16E-02	
								Cooper - Jacob (late)	15.1	830	9.09E-04	

PC004	1/05/2002	2880	30	48.46	PC004	0.222	17.29	Cooper - Jacob (early)	1.8	86		
								Cooper - Jacob (late)	2.9	140		
								Theis - Jacob	3.2	156		
					W01YJ012	54	2.85	Cooper - Jacob (mid-late)	7.6	367	3.83E-03	
					W02YJ012	50	3.093	Cooper - Jacob	7.2	350	3.37E-03	
					W02YJ009D	65	3.11	Cooper - Jacob (early)	10.2	493	1.68E-03	
							2.13	Cooper - Jacob (mid-late)	6.6	320	4.46E-03	
					W02YJ009S	65	1.91	Cooper - Jacob	7.3	354	2.19E-03	
					W02YJ008	105	2.34	Cooper - Jacob	8.7	421	2.19E-03	
					W02YJ015	175	1.16	Cooper - Jacob	7.4	358	9.11E-04	
PC005	9/05/2002	2880	20	41	PC005	0		Theis - Jacob (recovery)	1.3	52.3		
					W02YJ004S	109	2.92	Hantush - Leaky Aquifer	8.9	365.76	3.82E-04	
							2.15	Cooper - Jacob	8.4	344.16	7.20E-05	
					W02YJ004D	109		Hantush - Leaky Aquifer	7.1	289.44	1.39E-04	
					W02YJ001	182	0.59	Cooper - Jacob	12.6	516.96	2.22E-05	
								Neuman (late)	12.9	527.04	2.01E-05	
					W01YJ014	294	0.73	Cooper - Jacob (late)	22.4	920.16	9.52E-04	
							0.46	Neuman (late)	22.7	928.8	9.68E-04	
					W02YJ009D	143	1.81	Cooper - Jacob (late)	10.4	427.68	2.51E-05	
							4.44	Neuman (late)	10.6	433.44	2.31E-05	
					W02YJ002	78	20.03	Cooper - Jacob	3.6	148.32	3.76E-04	
							4.27	Neuman	3.9	159.84	2.88E-04	
PC006	6/05/2002	2880	25	49	PC006	0		Theis - Jacob (recovery)	2.7	132		
					W02YJ009S	65	5.73	Hantush - Leaky Aquifer	4.9	239	7.05E-04	
							2.78	Cooper - Jacob	5.2	253	5.54E-04	
					W02YJ009D	65		Hantush - Leaky Aquifer	4.9	242	9.04E-05	
					W02YJ012	119	1.46	Cooper - Jacob	6.5	317	6.59E-04	
							3.34	Neuman (late)	6.5	318	6.59E-04	
					W02YJ001	169	2.16	Cooper - Jacob (late)	6.3	311	5.16E-05	
							4.34	Neuman (late)	6.3	311	5.16E-05	
					W02YJ004D	113	3.52	Cooper - Jacob (late)	5.7	281	1.04E-04	
							1.39	Neuman (late)	5.7	281	1.04E-04	
					W02YJ016		9.51	Cooper - Jacob	10.8	530	2.37E-04	

								Neuman	9.8	478	3.23E-04	
PC007	20/04/2002	2880	36	60.5	PC007	0	0.75	Theis - Jacob	4.8	288		
							0.97	Theis - Jacob (recovery)	3.8	227		
					W02YJ004D	250	1.5	Cooper - Jacob	16.4	993	4.02E-03	
					W02YJ009S	120	2.22	Cooper - Jacob	14.3	864	2.77E-03	
					W02YJ009D	120	0.54	Cooper - Jacob	12.1	730	3.19E-03	
					W02YJ013	80	0.47	Cooper - Jacob	10.7	648	1.48E-03	
PC008	10/12/2001	2880	32		PC008	0	22.03	Hantush - Leaky Aquifer		172		
								Theis - Jacob (early)		235		
								Theis - Jacob (mid)		56		
								Theis - Jacob (late)		223		
								Theis - Jacob (recovery) (early)		1026		
								Theis - Jacob (recovery) (late)		172		
					D01YJ971	20	4.31	Theis - Jacob (early)		208	1.48E-02	
								Theis - Jacob (late)		760	1.91E-04	
								Neuman		218		0.015
					D01YJ970	42	2.35	Theis - Jacob		1075	1.94E-03	
								Neuman		864		0.003
					D01YJ944	200	1.44	Cooper - Jacob (late)		1008	1.32E-03	
					W01YJ012	208	1.17	Cooper - Jacob (late)		753	4.08E-03	

Results of aquifer pumping tests undertaken in the vicinity of Hairpin

Pumped Bore	Start Date	Duration (mins)	Discharge Rate (L/sec)	Aquifer Thickness (m)	Monitored Bore ID	Distance from Pumping Well (m)	Drawdown (m)	Analysis Method	K m/d	T m2/d	S	Sy
HP001	14/05/2002	1440	32		W02YJ029	69	2.91	Cooper - Jacob		496.8	4.20E-04	
								Neuman		398.88	8.53E-04	0.085
					W02YJ024	215	0.74	Cooper - Jacob		1051.2	1.69E-03	
								Neuman		941.76	2.12E-03	0.21
					D01YJ937	56	1.7	Cooper - Jacob		745.92	1.98E-03	
								Neuman		685.44	2.73E-03	0.27
HP003	17/05/2002	2880	20		HP003	0	5.69	Theis - Jacob Recovery		285.12		
					W02YJ017	189	0.86	Cooper - Jacob		714.24	1.60E-03	
								Neuman		662.4	1.45E-03	0.145
					W02YJ024	128.46	1.4	Cooper - Jacob		564.48	4.67E-04	
								Neuman		554.4	5.03E-04	0.05
					W01YJ004	118	1.54	Cooper - Jacob		534.24	4.16E-04	
								Neuman		504	5.36E-04	0.054
					W02YJ026	144	0.95	Cooper - Jacob		858.24	6.60E-04	
								Neuman		642.24	1.53E-03	0.153
HP004	17/11/2001	2880	30		HP004	0	20.38	Hantush - Leaky aquifer		71.5		
					D01YJ1010	5.9	13.91	Hantush - Leaky aquifer		71.5	1.88E-03	
					W01YJ005	96	3.08	Neuman (early)		375	1.35E-04	
								Neuman (late)		358		0.0007
								Cooper - Jacob (late)		564	5.75E-05	
					D01YJ015	100	2.4	Cooper - Jacob (late)		564	3.29E-04	
								Neuman (late)		594		0.0003
					D01YJ848	220	1.73	Neuman (late)		683		0.00017
								Cooper - Jacob (late)		773	9.97E-05	
					D01YJ1040	227	1.07	Cooper - Jacob (late)		871	7.65E-04	
					D01YJ1041	224	1.16	Cooper - Jacob (late)		871	5.24E-04	
					W01YJ018	510	0.25	Neuman (late)		900		0.0066
					D01YJ0861	323	0.12	Theis		821	3.28E-02	
					W01YJ003	205	1.52	Neuman (late)		683		0.000316
								Cooper - Jacob (late)		740	3.16E-04	

					D01YJ937	315	0.89	Neuman (early)		1360	1.58E-04	
								Neuman (late)		748		0.00131
								Cooper - Jacob (late)		799	1.12E-03	
					W01YJ002	320	0.72	Neuman (early)		1420	6.40E-04	
								Neuman (late)		715		0.00232
								Cooper - Jacob (early)		2020	5.19E-04	
								Cooper - Jacob (late)		800	1.84E-03	
					HP005	0	7.09	Theis - Jacob Recovery		424.8		
					W01YJ001	75	2.08	Cooper - Jacob		504	2.97E-04	
								Neuman		457.92	2.97E-04	0.0297
HP005	20/05/2002	1680	22		W02YJ021	82	2.06	Cooper - Jacob		491.04	1.88E-04	
								Neuman		472.32	2.22E-03	0.022
					W01YJ004	108	1.37	Cooper - Jacob		594.72	5.46E-04	
								Neuman		574.56	6.13E-04	0.016
					W02YJ025	128	1.19	Cooper - Jacob		663.84	5.32E-04	
								Neuman		643.68	5.85E-04	0.0585
HP006	20/11/2001	2880	30		HP006	0	17.91	Cooper - Jacob (early)		155		
								Cooper - Jacob (late)		169		
								Neuman (early)		35		
								Neuman (late)		87		
								Theis - Jacob Recovery (early)		659		
								Theis - Jacob Recovery (late)		100		
					D01YJ015	90	3.45	Cooper - Jacob (early)		293	2.06E-04	
								Cooper - Jacob (late)		655	5.92E-06	
								Neuman (early)		142	1.55E-04	
								Neuman (late)		259		0.0022
					D01YJ1040	96	2.74	Cooper - Jacob		731	2.20E-05	
					W01YJ002	200	1.05	Cooper - Jacob (early)		914	6.38E-04	
								Cooper - Jacob (late)		914	1.03E-03	
								Neuman (early)		326	6.52E-04	
								Neuman (late)		821		0.0014
					W01YJ005	220	1.39	Cooper - Jacob		883	0.0001.71	
					D01YJ1041	218	1.53	Cooper - Jacob		768	1.58E-04	

					D01YJ0854	300	0.77	Cooper - Jacob		1360	3.60E-04	
					D01YJ861	284	0.17	Neuman (late)		652	2.81E-06	
					W01YJ018	432	0.31	Theis		748	6.25E-03	
					W01YJ003	136	2.78	Cooper - Jacob		753	7.04E-06	
					W01YJ004	146	1.68	Cooper - Jacob (early)		523	5.29E-04	
								Cooper - Jacob (late)		713	4.35E-04	
								Neuman		430	5.59E-04	
					D01YJ937	284	0.63	Cooper - Jacob (late)		974	2.39E-03	
								Neuman (early)		987	8.90E-04	
								Neuman (late)		987	2.95E-03	
					HP007	0	14.07	Theis - Jacob Recovery		211.68		
					D01YJ1015	39	3.31	Cooper - Jacob		275.04	5.81E-05	
								Neuman		276.48	5.62E-05	0.00562
					W01YJ001	90	1.63	Cooper - Jacob		283.68	8.92E-04	
HP007	23/05/2002	2880	15					Neuman		492.48	2.26E-04	0.026
					W02YJ024	82	1.59	Cooper - Jacob		447.84	2.79E-04	
								Neuman		437.76	3.06E-04	0.0306
					W02YJ018D	123	1.36	Cooper - Jacob		600.48	6.03E-05	
								Neuman		610.56	5.69E-05	0.006
					W01YJ004	73	1.34	Cooper - Jacob		502.56	5.61E-04	
								Neuman		493.92	5.99E-04	0.06

Results of aquifer pumping tests undertaken in the vicinity of Waterstand

Pumped Bore	Start Date	Duration (mins)	Discharge Rate (L/sec)	Aquifer Thickness (m)	Monitored Bore ID	Distance from Pumping Well (m)	Drawdown (m)	Analysis Method	K m/d	T m2/d	S	Sy
WS001	21/08/2004	4320	25	55	WS001		14.58	Cooper-Jacob (early)	2.9	159	1.27E-08	
								Cooper-Jacob (late)	3.6	200	6.90E-10	
								Neuman (early)	1.1	60	9.62E-07	
								Neuman (late)	2.2	120	4.20E-07	
								Theis (early)	1.4	76.9	1.90E-02	
								Theis (late)	2.9	157	1.00E-03	
					WS005OBS		3.78	Cooper-Jacob (early)	3.8	207	7.53E-05	
								Cooper-Jacob (late)	7.0	383	2.73E-06	
					WS001BB		2.5	Cooper-Jacob (early)	4.6	251	7.55E-04	
								Cooper-Jacob (late)	9.0	497	8.08E-06	
WS002	17/08/2004	2880	40	50	WS002		33.95	Cooper-Jacob (early)	2.1	103		
								Cooper-Jacob (late)	1.1	57		
								Neuman (early)	2.1	103	1.00E-04	
								Neuman (late)	2.0	98	1.00E-04	
								Theis (early)	2.1	103		
								Theis (late)	1.6	81		
					WS002OBS		21.02	Cooper-Jacob (early)	1.3	65		
								Cooper-Jacob (late)	20.8	1040		
								Neuman (early)	2.1	103	1.00E-04	
								Neuman (late)	2.0	98	1.00E-04	
					WS001OBS		3.32	Cooper-Jacob	5.9	297		
								Neuman	5.0	252	1.00E-04	
								Theis	5.8	290		
WS003	17/08/2004	2880	45	48	WS003		18.43	Cooper-Jacob (early)	3.5	167	2.05E-02	
								Cooper-Jacob (late)	5.6	270	1.22E-04	
								Neuman (early)	2.7	129		
								Neuman (late)	3.9	186		

								Theis	3.3	157	2.17E-03	
					WS001OBS		3.32	Cooper-Jacob (early)	3.6	172		
								Cooper-Jacob (late)	5.7	274		
								Neuman (early)	4.0	190		
								Neuman (late)	2.5	120		
								Theis	3.4	163		
MC001	26/08/2004	4320	34	60	MC001		3.58	Cooper-Jacob (early)	18.8	1130		
								Cooper-Jacob (late)	12.8	766		
								Neuman (early)	14.5	872		
								Neuman (late)	17.0	1020		
								Theis (early)	13.3	796	8.80E-03	
								Theis (late)	15.2	914	1.10E-03	
					MC6		1.59	Cooper-Jacob (early)	17.2	1030		
								Cooper-Jacob (late)	11.6	697		
								Theis (early)	19.7	1180	2.40E-04	
								Theis (late)	13.6	814	2.90E-04	
					MC4		1.51	Cooper-Jacob (early)	17.8	1070		
								Cooper-Jacob (late)	12.2	733		
								Neuman	21.0	1260		
					MC002		1.64	Neuman	17.0	1020		
MC002	16/08/2004	4320	35	60	MC002		6.53	Cooper-Jacob (early)	15.4	926		
								Cooper-Jacob (late)	6.3	378		
								Neuman (early)	31.2	1870		
								Neuman (late)	8.4	504		
								Theis (early)	4.0	242	1.47E-02	
								Theis (late)	7.0	421	1.06E-02	
					MC6		1.79	Cooper-Jacob (early)	20.0	1200		
								Cooper-Jacob (late)	13.6	813		
								Neuman	23.2	1390		
								Theis	16.4	986	4.64E-05	

					MC1		1.56	Cooper-Jacob (early)	18.5	1110		
								Cooper-Jacob (late)	12.4	745		
MC003	21/10/2004	2880	50	65	MC003		25.58	Cooper-Jacob (early)	2.5	160		
								Cooper-Jacob (late)	6.1	397		
								Neuman (early)	1.5	96	1.00E-04	
								Neuman (late)	2.4	157	1.00E-04	
								Theis	1.7	108		
					MC1		12.3	Cooper-Jacob (early)	3.1	199		
								Cooper-Jacob (late)	9.5	619		
								Neuman (early)	1.8	119	1.00E-04	
								Neuman (late)	2.2	143	1.00E-04	
					MC6		2.6	Cooper-Jacob (late)	10.4	678		
					MC3		1.98	Neuman (late)	6.2	403		

Results of aquifer pumping tests undertaken in the vicinity of Junction South East and Billiard South

Pumped Bore	Start Date	Duration (mins)	Discharge Rate (L/sec)	Aquifer Thickness (m)	Monitored Bore ID	Distance from Pumping Well (m)	Drawdown (m)	Analysis Method	K m/d	T m2/d	S	Sy
CB001	22/07/2006		100	55	CB001			Neuman	15.1	828		
					CB001			Cooper-Jacob Time Drawdown	30.7	1688		
					JSE42			Cooper-Jacob Distance Drawdown	75.2	4134	2.00E-07	
					CB001			Cooper-Jacob Time Distance Drawdown	30.7	1688	8.00E-04	
					CB001			Theis	31.0	1704	9.04E-04	
					JSE43			Theis	32.6	1794	1.73E-04	
CB002	19/07/2006	2880	100	55	CB002			Neuman	6.5	358		
					CB002			Theis	18.3	1006		
					CB002			Cooper-Jacob Time Drawdown	17.0	934		
					CB002			Cooper-Jacob Distance Drawdown	39.7	2181		
					CB002			Theis (early)	20.7	1137		
					CB002			Theis (late)	7.5	414		
					JSE8		8					
					JSE42		3.65					
					JSE43		2.6					
					JSE44		2.15					
CB004	26/07/2006	2880	90	55	CB004			Neuman	2.7	147		
					CB004			Theis	9.7	534	1.00E-07	
					CB004			Cooper-Jacob Time Drawdown	12.9	712		
					CB004			Cooper-Jacob Distance Drawdown	470.5	25880		
					CB004			Cooper-Jacob Time Distance Drawdown	12.9	712		
					JSE44		3.74	Theis	29.0	1596	3.73E-05	
					JSE28		1.145					
					JSE29		3.56					
CB005	14/07/2006	4320	80	55	CB005			Neuman	2.4	129		
					CB005			Theis	8.2	454	5.00E-07	
					CB005			Cooper-Jacob Time Drawdown	11.2	617		

					CB005			Cooper-Jacob Distance Drawdown	7.7	424	3.40E-05	
					CB005			Cooper-Jacob Time Distance Drawdown	11.2	617		
					JSE44		2.49	Theis	29.3	1612	1.44E-05	
					JSE28		1.565					
					JSE29		2.8					
					JSE42		2.11					
					SB001		4.24	Neuman	20.8	1146		
					SB001			Theis	68.8	3785		
					SB001			Cooper-Jacob Time Drawdown	64.3	3536		
SB001	21/04/2006	4080	102	55	SB001			Cooper-Jacob Distance Drawdown	68.1	3745	9.71E-05	
					SB001			Cooper-Jacob Time Distance Drawdown	64.3	3536	4.00E-07	
					JSE22		1.895	Theis	86.4	4755	1.60E-05	
					JSE25		0.84					
					JSE20		0.62					
					JSE21		0.72					
					JSE31		0.53					
					SB002		6.48	Neuman	13.8	759		
					SB002			Theis	43.8	2410	4.20E-06	
					SB002			Cooper-Jacob Time Drawdown	39.4	2164		
					SB002			Cooper-Jacob Distance Drawdown	46.0	2527	1.11E-04	
SB002	20/05/2006	4320	120	55	SB002			Cooper-Jacob Time Distance Drawdown	39.4	2164	1.86E-05	
					SB002			Theis (early)	52.9	2908	8.00E-07	
					SB002			Theis (late)	23.5	1292	5.00E-03	
					JSE31		1.345	Theis	95.7	5261	1.30E-05	
					JSE33		0.44					
					JSE20		0.64					
					JSE21		0.49					
					JSE22		0.805					
SB003	16/04/2006	4320	112	55	SB003		4.43	Neuman	18.6	1021		
					SB003			Theis	47.1	2590	2.18E-04	

					SB003			Cooper-Jacob Time Drawdown	47.4	2608		
					SB003			Cooper-Jacob Distance Drawdown	54.6	3000	4.94E-05	
					SB003			Cooper-Jacob Time Distance Drawdown	47.4	2608	1.92E-04	
					JSE21		1.36	Theis	70.3	3865	4.13E-05	
					JSE20		1.56					
					JSE22		1.01					
					JSE31		0.78					
					JSE33		0.61					
SB004	15/05/2006	4320	120	55	SB004		2.875	Neuman	29.1	1602		
					SB004			Theis	111.2	6115	8.00E-07	
					SB004			Cooper-Jacob Time Drawdown	91.5	5031		
					SB004			Cooper-Jacob Distance Drawdown	99.2	5457	6.02E-05	
					SB004			Cooper-Jacob Time Distance Drawdown	91.5	5031	1.64E-05	
					JSE21		1.48	Theis	114.1	6275	1.44E-05	
					JSE22		0.99					
					JSE31		0.73					
					JSE20		1.095					
					JSE33		0.485					
SB005	25/05/2006	2880	120	55	SB005		5.54	Neuman	15.1	828		
					SB005			Theis	51.0	2806	1.90E-06	
					SB005			Cooper-Jacob Time Drawdown	55.6	3056		
					SB005			Cooper-Jacob Distance Drawdown	658.1	36193		
					SB005			Cooper-Jacob Time Distance Drawdown	55.6	3056	4.00E-07	
					JSE31		1.84					
					JSE20		1.72					
					JSE22		1.36					
					JSE33		1.84	Theis	79.1	4350	7.79E-05	
TB001	8/08/2005	4320	60	55	TB001		1.02	No Data				
					YJP109		0.9	No Data				
					JSE9		0.87	No Data				

					JSE11		0.895	No Data				
					JSE23		0.95	No Data				
					JSE24		0.94	No Data				
					JSEB4		0.15	No Data				
					D04YJ2026		0.95	No Data				
TB002	3/08/2006	1720	60	55	TB002			Theis	57.0	3130	3.34E-02	
								Double Porosity	57.0	3130	3.34E-02	
					JSE28		1.12	Theis	34.9	1920	7.89E-04	
					JSE8		0.92	Theis	34.4	1890	2.34E-04	
								Double Porosity	30.4	1670	1.65E-04	
					DO4YJ1989		0.76	Theis	34.2	1880	7.48E-04	
								Double Porosity	28.3	1560	5.52E-04	
					JSE29			Theis	37.2	2040	8.73E-04	
								Double Porosity	24.3	1350	7.13E-04	
					YJP109			Theis	83.0	4570	1.07E-03	
								Double Porosity	71.8	3950	8.31E-04	
					JSE26			Theis	54.5	3000	5.33E-05	
								Double Porosity	46.5	2560	7.17E-05	
					JSE9			Theis	94.4	5190	3.38E-02	
					JSE27			Theis	59.8	3290	2.98E-03	
								Double Porosity	56.9	3130	1.06E-04	
TB003	24/09/2004	4320	100		TB003		18.34	Cooper-Jacob (early)		1470		
								Cooper-Jacob (late)		218		
				70	D04YJ2026		1.75	Cooper-Jacob (early)		3390		
								Cooper-Jacob (late)		1790		
					JSE11		1.46	Cooper-Jacob (late)		1780	2.90E-03	
NB001	30/12/2007	2880	40		NB001	0	27.58					
					JSE59	9	18.76					
					D03YJ1620	444	0.93					
					D04YJ1948	401	1.64					
					JSE54	834	0.64					
					JSE69	366	0.35					
NB002	4/01/2008	1440	110		NB002	0	26.07					
					JSE60		15.21					

					D03YJ1620	723	0.58					
					JSE54	568	1.73					
					JSE56	406	2.58					
					JSEB5	405	2.57					
NB003	19/09/2004	4320	100		NB003	0	16.1					
					D04YJ1948	70	4.73					
					JSE3	100	7.17					
					D04YJ1930	177	4.66					
NB004	7/01/2008	2280	45		NB004	0	29.62					
					JSE57		14.64					
					D03YJ1620	1004	0.01					
					JSE54	318	1.44					
					JSE56	135	3.81					
					JSEB5	134	3.81					
					NB001	583	0.63					
RB001	29/05/2006	4320	110	55	RB001			Neuman	0.0	3		
					RB001			Theis	0.2	9	7.92E-04	
					RB001			Cooper-Jacob Time Drawdown	0.2	14		
					RB001			Cooper-Jacob Distance Drawdown	0.1	5	3.61E-04	
					RB001			Cooper-Jacob Time Distance Drawdown	0.2	14	2.00E-07	
					JSE31			Theis	0.3	14	9.00E-07	
					RB001		6.36					
					JSE34		0.01					
					JSE39		0.96					
					JSE41		0.19					
RB002	3/06/2006	4320	110	55	RB002		7.99	Neuman	1.5	84		
					RB002			Theis	4.9	271	1.30E-06	
					RB002			Cooper-Jacob Time Drawdown	7.1	390		
					RB002			Cooper-Jacob Time Distance Drawdown	7.1	390		
					RB002			Theis	5.1	282	3.30E-07	

					JSE41			Theis	8.2	451	9.90E-06	
					JSE41			Theis	15.8	871		
					JSE30		1.05					
					JSE39		0.05					
					JSE40		0.05					
RB004	1/05/2006	4320	40	55	RB004		39.935	Neuman	0.6	32		
					RB004			Theis	1.5	85	5.90E-06	
					RB004			Cooper-Jacob Time Drawdown	2.4	130		
					RB004			Cooper-Jacob Distance Drawdown	20.4	1120	1.40E-06	
					RB004			Cooper-Jacob Time Distance Drawdown	2.4	130		
					RB004			Cooper-Jacob Time Drawdown (late)	16.0	879		
					RB004			Cooper-Jacob Time Drawdown (early)	1.1	61		
					JSE38		2.59	Theis	18.1	996	6.80E-06	
					JSE35		0.69					
					JSE17		0.92					
					JSE16		0.01					
					JSE30		0.72					
RB005	26/04/2006	4320	80	55	RB005		22.12	Neuman	2.4	130		
					RB005			Theis	10.4	574		
					RB005			Cooper-Jacob Time Drawdown	10.6	583		
					RB005			Cooper-Jacob Distance Drawdown	0.1	6		
					RB005			Cooper-Jacob Time Distance Drawdown	6.2	342	1.07E-05	
					RB005			Theis (early)	10.4	574		
					RB005			Theis (late)	8.2	450	1.00E-07	
					RB005			Theis	32.5	1789		
					JSE35		9.875					
					JSE38		1.61					
					WW04		0.01					
					JSE36		0.345					
					JSE37		0.085					

JSE1	29/09/2004	4320	100	50.75	JSE1		6.72	Cooper-Jacob (early)	57.5	2920		
								Cooper-Jacob (late)		620		
								Neuman		619		
				69.09	D03YJ1647		3.92	Cooper-Jacob (early)		1680	2.80E-03	
								Theis (early)		1970	2.10E-03	
								Theis (late)		900		
				52.8	D03YJ1667		3.67	Neuman (early)		1180	2.00E-03	
								Neuman (late)		960	1.00E-02	
					YJ-DD239			Neuman		860	3.00E-02	
								Theis (early)		1110	3.80E-03	
					JSEB1		0.9					
					SB		4.48					
JSE4	17/09/2004	4320	100	64.54	JSE4		16.095	Cooper-Jacob		580		
								Theis		590		
				73.32	JSE3		6.2	Cooper-Jacob (early)		880	1.50E-04	
								Neuman (early)		550	3.10E-03	
								Theis		780	1.90E-04	
					D04YJ1930		3.66	Cooper-Jacob (early)		1060	3.10E-03	
								Cooper-Jacob (late)		570		
								Neuman (early)		900	3.00E-03	
								Theis (early)		1220	2.70E-03	
								Theis (late)		660		
					D04YJ1948		3.45	Neuman (early)		980	6.50E-03	
								Neuman (late)		650	1.30E-02	
								Theis (early)		1400	6.80E-04	
JSE8	11/09/2004	4320	110	67.5	JSE8		6.99	Cooper-Jacob (early)		2810		
								Cooper-Jacob (late)		730		
					D04YJ1989		3.01	Cooper-Jacob (early)		1900	1.50E-03	
								Neuman (early)		1600	1.63E-03	
				56.6	JSE7		2.98	Cooper-Jacob (early)		1920	8.30E-04	

								Neuman (early)		1460	1.00E-03	
								Neuman (late)		970	2.00E-03	
				63.54	JSE6		No Data	Cooper-Jacob (early)		2090	4.30E-04	
								Cooper-Jacob (late)		1250	4.70E-03	
					JSEB3		0.24					
JSE13	5/11/2004	4320	110	87.62	JSE13		13.99	Cooper-Jacob		721		
								Neuman (early)		749		
				50.86	JSE15		5.26	Cooper-Jacob		803	2.70E-01	
								Neuman (early)		1060	4.37E-02	
								Neuman (late)		785	3.30E-01	
				76	JSE17		3.705	Cooper-Jacob		1160	1.30E-01	
								Neuman (early)		965	1.32E-04	

Results of aquifer pumping tests undertaken in the vicinity of Junction South West and Oxbow

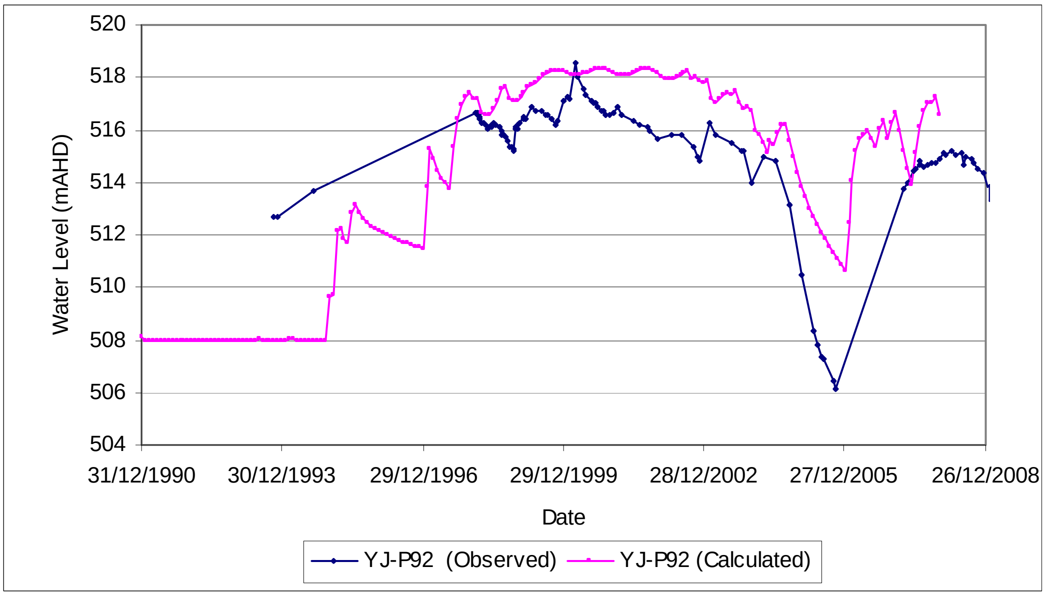
Pumped Bore	Start Date	Duration (mins)	Discharge Rate (L/sec)	Aquifer Thickness (m)	Monitored Bore ID	Distance from Pumping Well (m)	Drawdown (m)	Analysis Method	K m/d	T m2/d	S	Sy
WB09YOXB001	13/08/2009	7200	60	70	WB09YOXB001	0	19.66	Cooper-Jacob	18.5	1300		
								Logan	5.2	364		
								Neuman	6.2	369		
				60	PZ08YOXB001	10	4.6	Neuman	8.65	519	8.22E-04	0.52
								Cooper-Jacob (Middle)	28	1880	1.45E-02	
								Cooper-Jacob (Late)	7.7	516		
								Theis	13.7	923	2.33E-01	
				65	PZ08YOXB002	77	2.7	Neuman (manual)	21	1360	3.43E-04	0.00204
								Cooper-Jacob (Middle)	31.9	2130	3.74E-02	
								Cooper-Jacob (Late)	9.4	630	1.61E-01	
								Theis	38	2600	1.65E-02	
				67	PZ08YOXB004	1205	0.5	Neuman	43.5	2920	6.84E-04	0.231
								Cooper-Jacob (Middle)	108	7250	5.31E-02	
								Cooper-Jacob (Late)	28.8	1910	8.88E-02	
								Theis	69	4620	6.56E-01	
WB08YJSW001	14/06/2009	7200	65	70	WB08YJSW001	0	47.85	Cooper-Jacob	7.9	558		
								Logan	3.57	250		
								Neuman	3.18	223		
				68	PZ08YJSW005	10	10.4	Neuman	4.9	319	9.10E-04	0.0062
								Cooper-Jacob (All)	7.2	482	2.17E-01	
								Theis	5.94	398	3.56E-01	
				67	PZ08YJSW008	108	6.3	Neuman	5.94	398	1.26E-05	0.000525
								Cooper-Jacob (Middle)	8.28	555	7.75E-01	
								Cooper-Jacob (Late)	6.41	429	2.21E-01	
								Theis	13.3	891	7.11E-01	
				70	PZ08YJSW006	175	6.2	Neuman	6.5	455	2.37E-04	0.237
								Cooper-Jacob (Middle)	6.36	445	2.32E-01	
								Cooper-Jacob (Late)	9.36	655	4.80E-02	
								Theis	6.94	486	5.74E-07	
				67	PZ08YJSW007	287	5.5	Neuman	7.48	501	3.85E-05	0.385

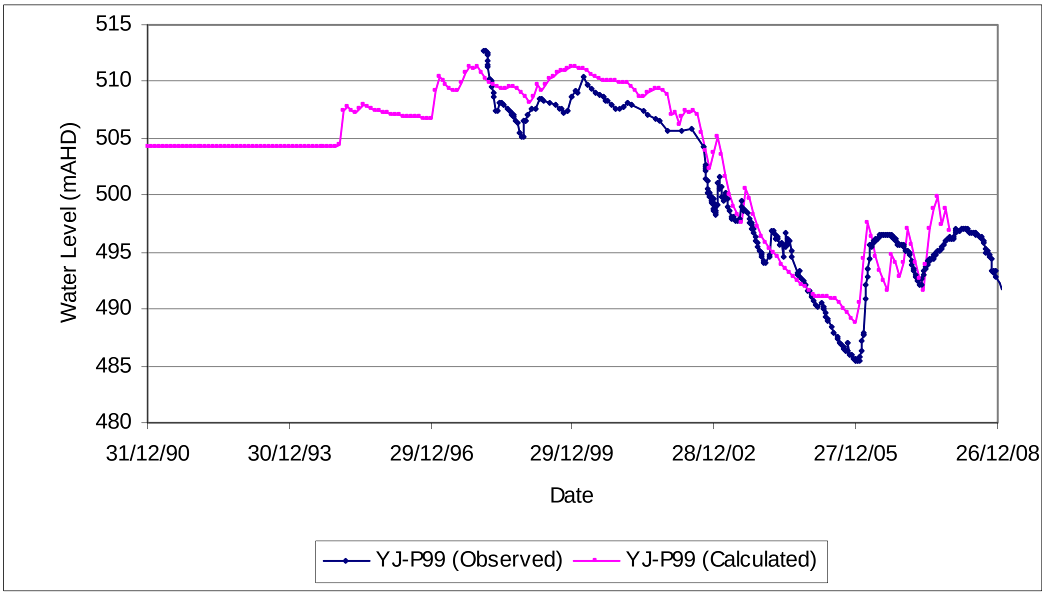
								Cooper-Jacob (Middle)	7.39	495	3.98E-01	
								Cooper-Jacob (Late)	5.99	401	6.39E-01	
								Theis	7.48	501	2.83E-01	
				67	PZ08YJSW010	502	5	Neuman	9.42	631	1.00E-05	0.1
								Cooper-Jacob (Middle)	8.4	562	1.41E-01	
								Cooper-Jacob (Late)	6.44	431	2.63E-01	
								Theis	8.39	562	1.00E-01	
WB08YJSW002	29/09/2009	2880	80	60	WB08YJSW002	0	38.19	Cooper-Jacob (Recovery)	8.3	497		
								Logan	4	241		
								Neuman (ATP)	2.2	130		
				68	PZ08YJSW006	15	8	Neuman	4.3	292	7.33E-04	0.0733
								Cooper-Jacob (All)	7.87	527	9.97E-01	
								Theis	6.15	412	2.33E+00	
				67	PZ08YJSW008	166	4.9	Neuman	3.88	260	2.67E-04	0.000119
								Cooper-Jacob (Middle)	8.61	577	2.41E-01	
								Cooper-Jacob (Late)	6.54	438	5.78E-01	
								Theis	7.75	519	2.33E-01	
				67	PZ08YJSW005	190	4.8	Neuman	9.06	589	1.44E-04	0.162
								Cooper-Jacob (Middle)	9.06	607	1.62E-01	
								Cooper-Jacob (Late)	6.6	442	4.55E-01	
								Theis	9.75	653	1.16E-01	
				67	PZ08YJSW010	541	4	Neuman	6.9	462	3.99E-02	0.1
								Cooper-Jacob (Middle)	9.19	616	4.87E-02	
								Cooper-Jacob (Late)	7.04	471	1.04E-01	
								Theis	7.75	519	5.21E-02	
WB09YJSW004	16/07/2009	21600	95	70	WB09YJSW004	0	16.53	Cooper-Jacob	11.9	834		
								Logan	9.7	684		
								Neuman (ATP)	3.3	231		
				67	PZ08YJSW014	7.5	8.9	Neuman (manual)	8.68	582	1.66E-02	0.0387
								Cooper-Jacob (All)	9.35	627	7.16E-01	
								Theis	9.74	653	9.27E-01	
				67	PZ08YJSW016	92	8.7	Neuman	6.9	462	9.76E-05	0.0976
								Cooper-Jacob (All)	8.97	601	6.99E-01	
								Theis	10.9	732	4.64E-01	

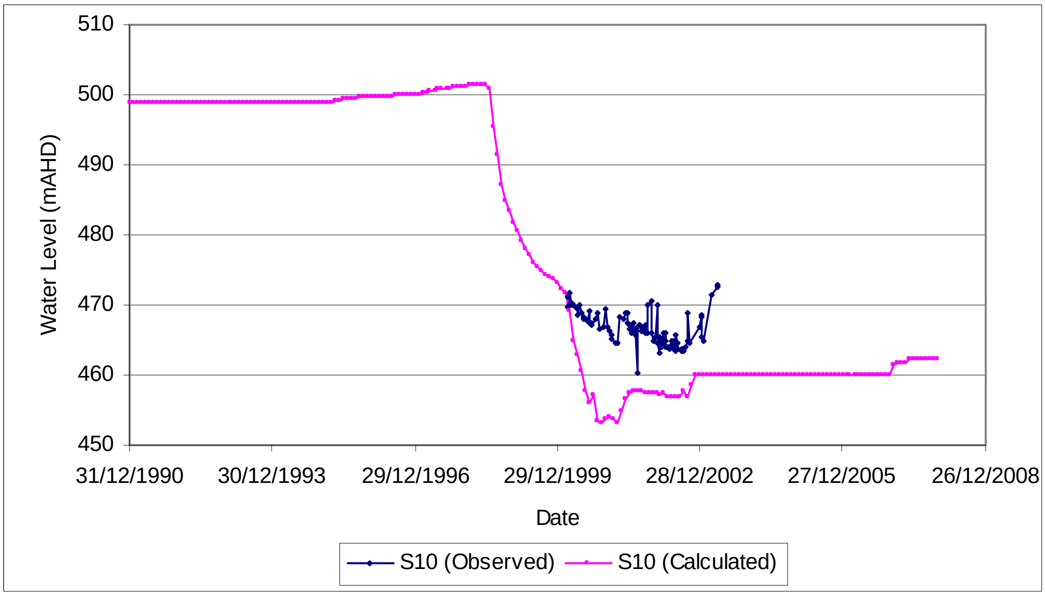
				67	PZ08YJSW015	108	8.4	Neuman	7.74	518	4.98E-05	0.198
								Cooper-Jacob (All)	9.43	631	4.10E-01	
								Theis	8.68	582	4.14E-01	
				67	PZ08YJSW012	166	8.9	Neuman	6.9	462	2.12E-05	0.212
								Cooper-Jacob (Middle)	8.38	562	2.27E-01	
								Cooper-Jacob (Late)	10.2	686	8.59E-02	
								Theis	8.68	582	1.46E-01	
WB09YJSW005	24/09/2009	4320	100	60	WB09YJSW005	0	37.55	Theis Recovery (manual)	9.95	597		
								Logan (manual)	6.76	406		
								Neuman	6.08	365		
				67	PZ08YJSW016	10	10.7	Neuman (manual)	4.58	307	7.00E-03	0.0388
								Cooper-Jacob (All)	9.18	615		
								Theis	6.9	486		
				67	PZ08YJSW014	93	7.9	Neuman	9.14	612	7.11E-01	0.196
								Cooper-Jacob (All)	8.46	567	8.32E-01	
								Theis	83.15	546	9.75E-01	
				67	PZ08YJSW015	125	8	Neuman	8.15	546	5.56E-01	0.2
								Cooper-Jacob (All)	8.93	598	2.89E-01	
								Theis	9.14	612	3.46E-01	
				67	PZ08YJSW012	204	7.8	Neuman	8.15	546	3.31E-01	0.295
								Cooper-Jacob (All)	8.5	569	1.94E-01	
								Theis	8.15	546	2.45E-01	
WB09YJSW006	24/06/2009	7200	80	70	WB09YJSW006	0	14.15	Theis Recovery (manual)	16.3	1145		
								Logan (manual)	3.57	660		
								Neuman	5.56	389		
				67	PZ08YJSW023	21	7.9	Neuman (manual)	4.86	550	6.92E-03	0.00499
								Cooper-Jacob (Middle)	18.1	1210	8.64E-02	
								Cooper-Jacob (Late)	8.83	592		
								Theis	11.5	776		
				67	PZ08YJSW021	119	4.4	Neuman	23.1	1550	5.51E-05	0.551
								Cooper-Jacob (Middle)	277	1860	6.39E-01	
								Cooper-Jacob (Late)	9.4	631		
								Theis	32.6	2180	4.38E-01	
				67	PZ08YJSW024	693	1.9	Neuman	11.5	776	2.89E-04	0.0289

Appendix B

Transient Calibration Hydrographs


520
518
516
514
512
510
508
506
504
Water Level (mAHD)
31/12/1990
30/12/1993
29/12/1996
29/12/1999
28/12/2002
27/12/2005
26/12/2008
Date
YJ-P92 (Observed)
YJ-P92 (Calculated)


515
510
505
500
495
490
485
480
Water Level (mAHD)
31/12/90
30/12/93
29/12/96
29/12/99
28/12/02
27/12/05
26/12/08
Date
YJ-P99 (Observed)
YJ-P99 (Calculated)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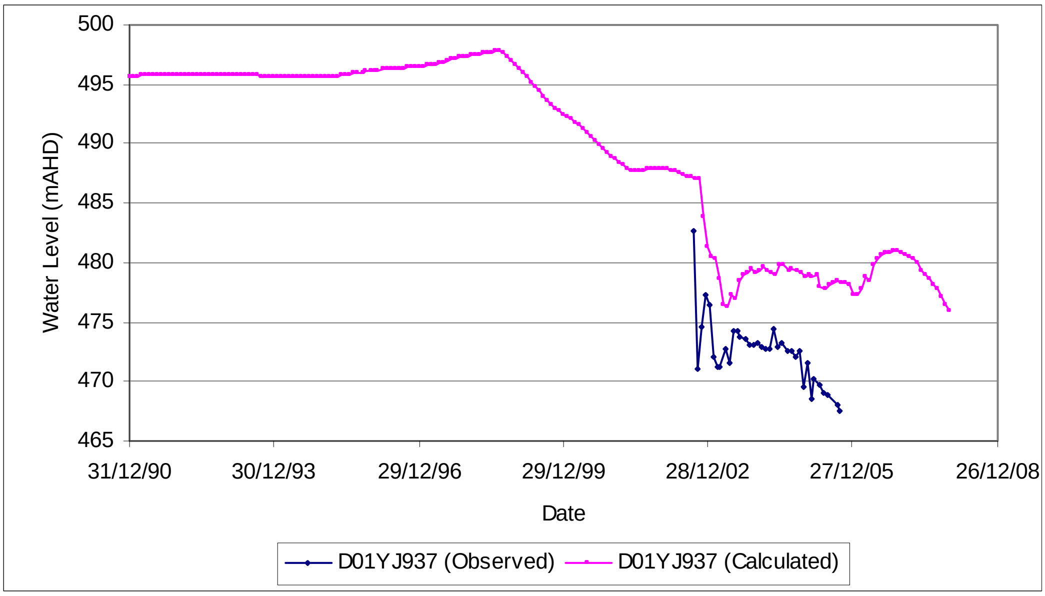
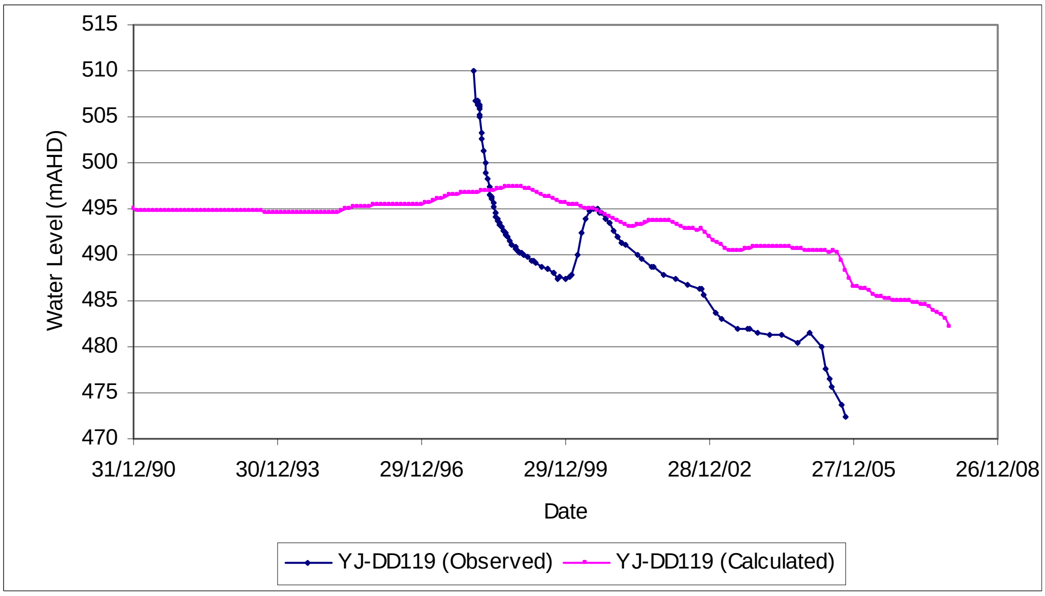
500
490
480
470
460
450
Water Level (mAHD)
31/12/1990
30/12/1993
29/12/1996
29/12/1999
28/12/2002
27/12/2005
26/12/2008
Date
S10 (Observed)
S10 (Calculated)


500
495
490
485
480
475
470
465
Water Level (mAHD)
31/12/90
30/12/93
29/12/96
29/12/99
28/12/02
27/12/05
26/12/08
Date
D01YJ937 (Observed)
D01YJ937 (Calculated)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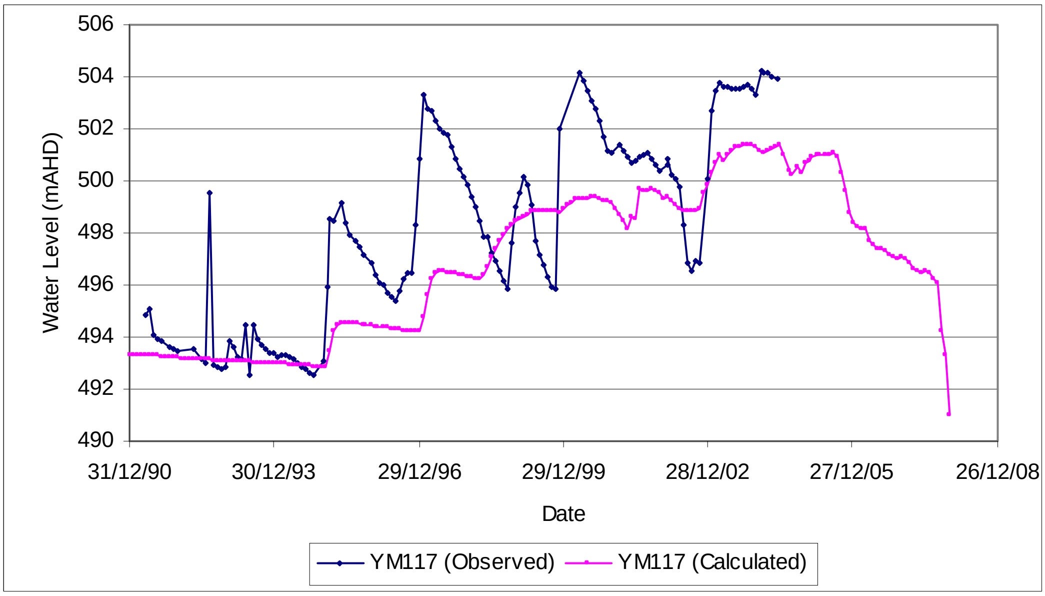
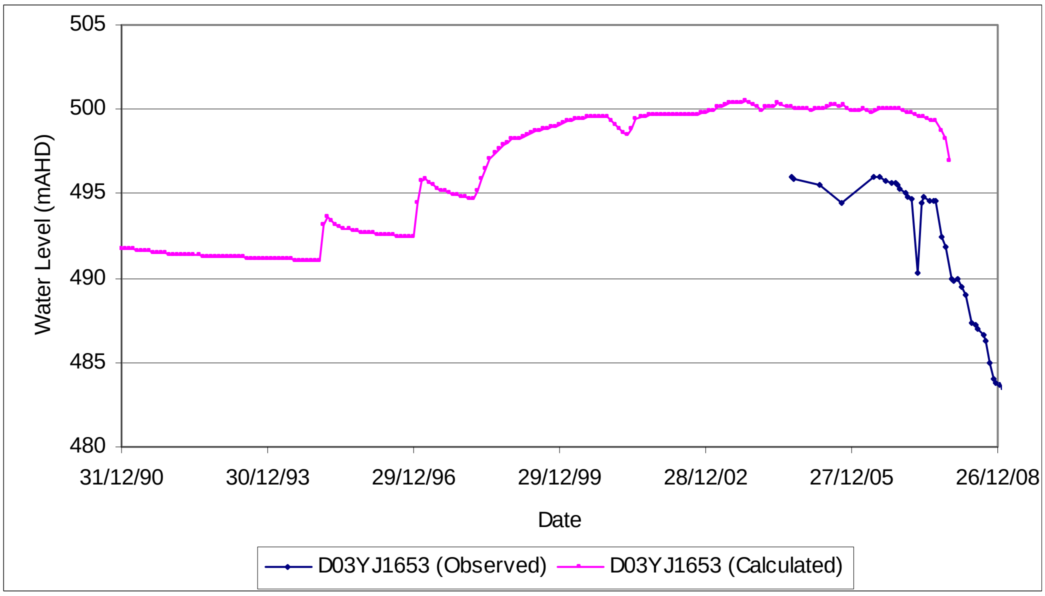
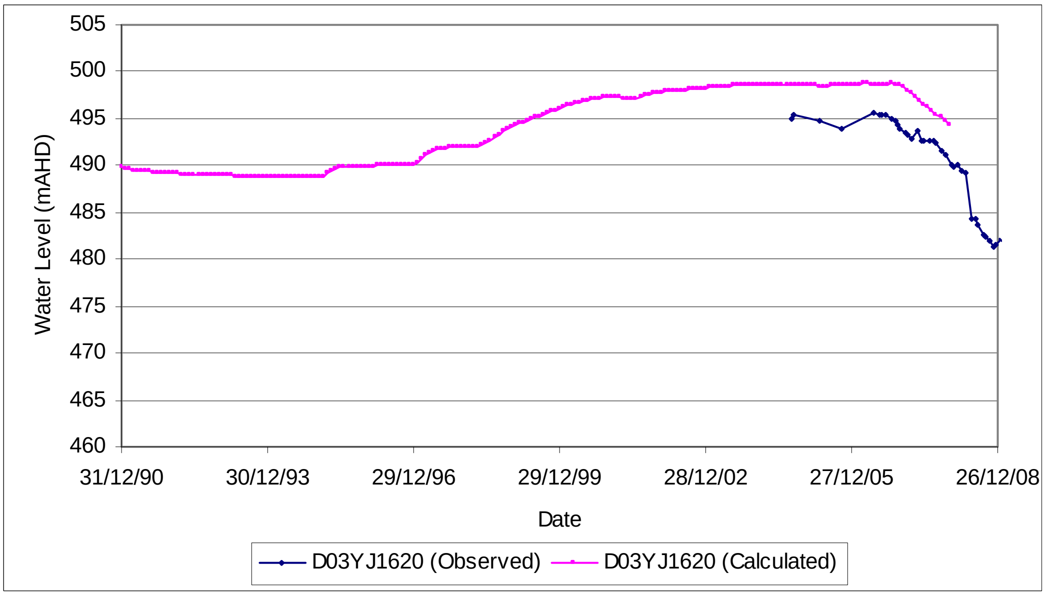
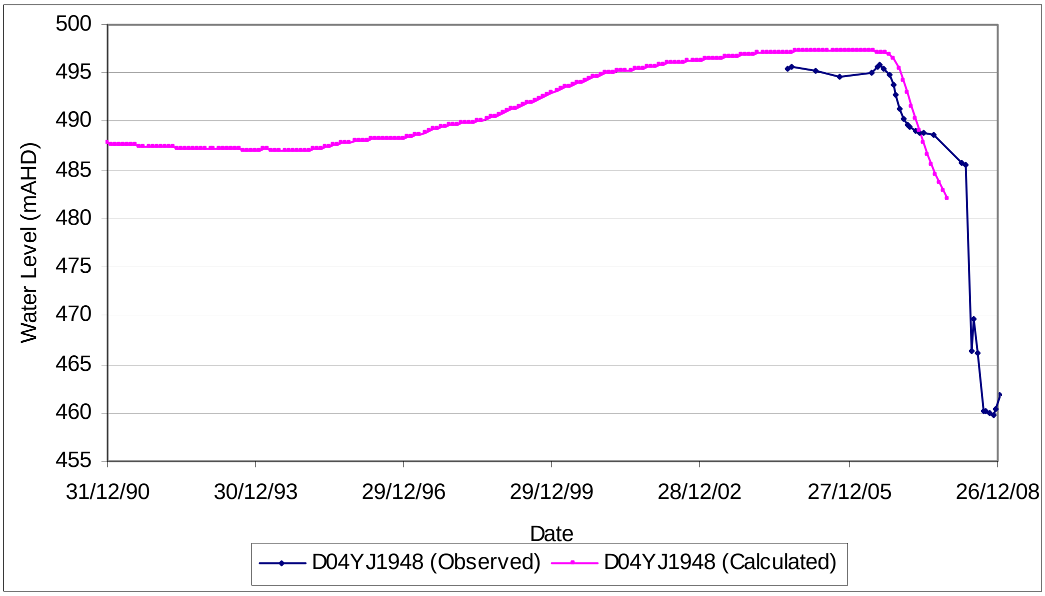
510
505
500
495
490
485
480
475
470
Water Level (mAHD)
31/12/90
30/12/93
29/12/96
29/12/99
28/12/02
27/12/05
26/12/08
Date
YJ-DD119 (Observed)
YJ-DD119 (Calculated)


506
504
502
500
498
496
494
492
490
Water Level (mAHD)
31/12/90
30/12/93
29/12/96
29/12/99
28/12/02
27/12/05
26/12/08
Date
YM117 (Observed)
YM117 (Calculated)


505
500
495
490
485
480
Water Level (mAHD)
31/12/90
30/12/93
29/12/96
29/12/99
28/12/02
27/12/05
26/12/08
Date
D03YJ1653 (Observed)
D03YJ1653 (Calculated)


505
500
495
490
485
480
475
470
465
460
Water Level (mAHD)
31/12/90
30/12/93
29/12/96
29/12/99
28/12/02
27/12/05
26/12/08
Date
D03YJ1620 (Observed)
D03YJ1620 (Calculated)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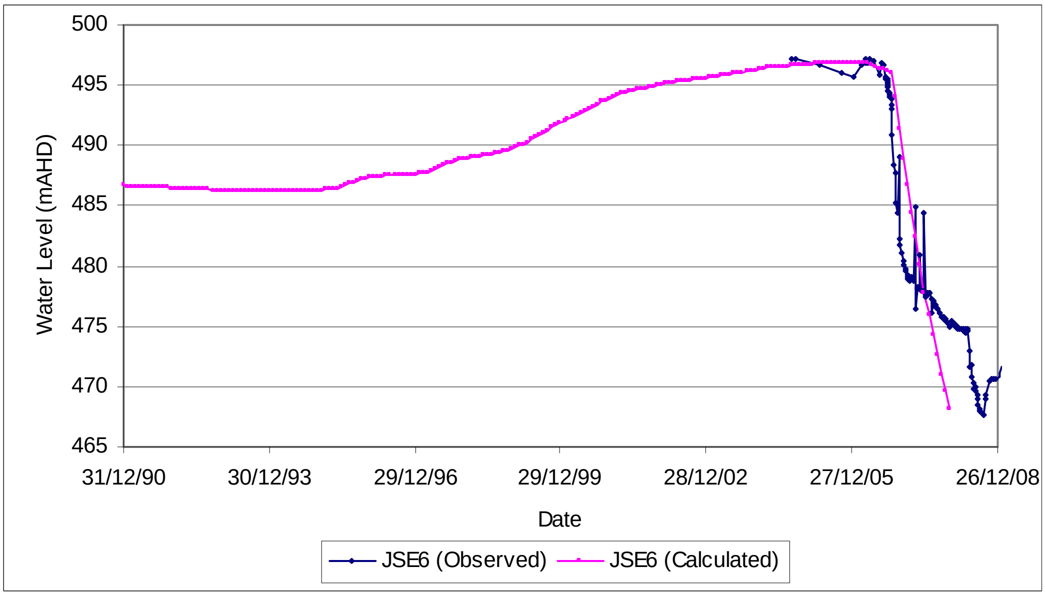
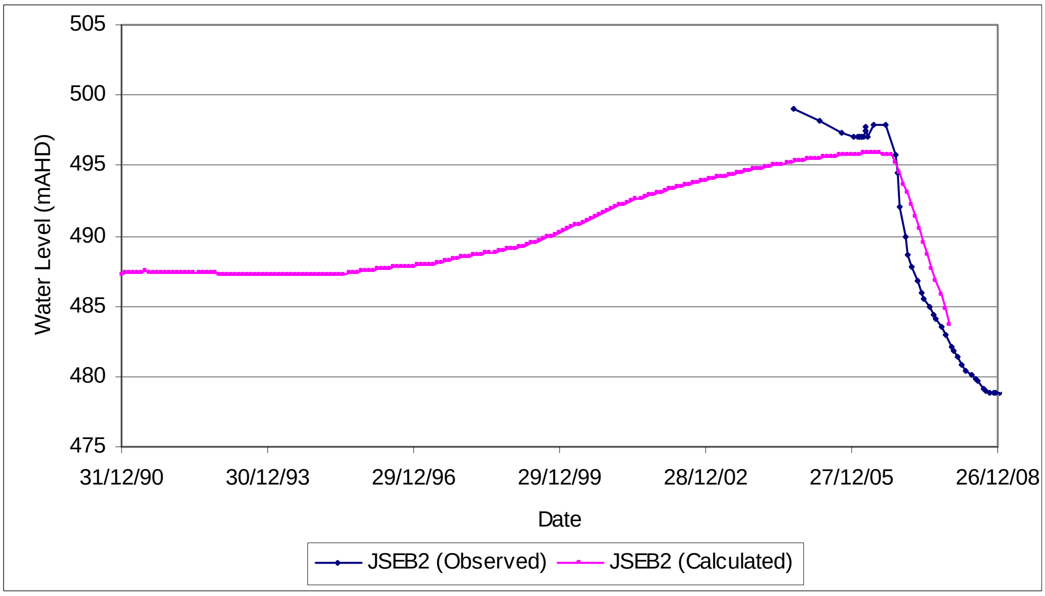
480
475
470
465
460
455
Water Level (mAHD)
31/12/90
30/12/93
29/12/96
29/12/99
28/12/02
27/12/05
26/12/08
Date
D04YJ1948 (Observed)
D04YJ1948 (Calculated)


500
495
490
485
480
475
470
465
Water Level (mAHD)
31/12/90
30/12/93
29/12/96
29/12/99
28/12/02
27/12/05
26/12/08
Date
JSE6 (Observed)
JSE6 (Calculated)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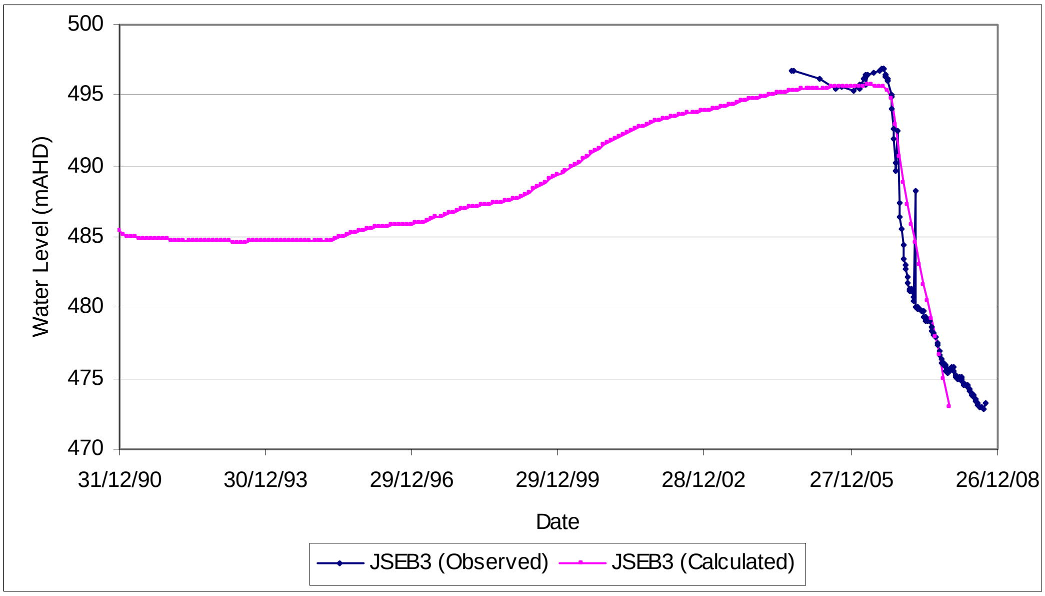
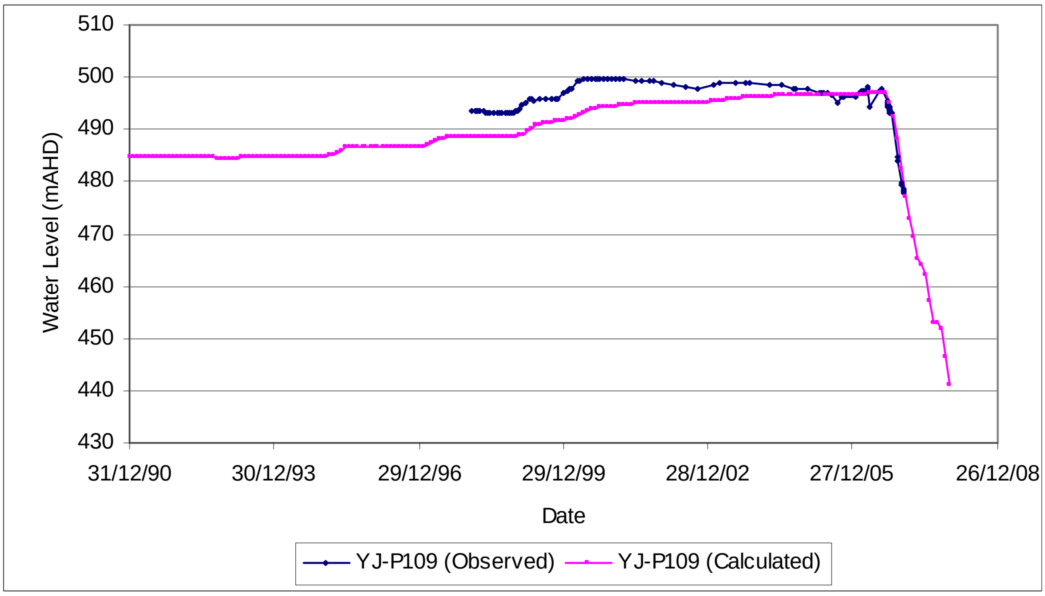
500
495
490
485
480
475
Water Level (mAHD)
31/12/90
30/12/93
29/12/96
29/12/99
28/12/02
27/12/05
26/12/08
Date
JSEB2 (Observed)
JSEB2 (Calculated)


500
495
490
485
480
475
470
Water Level (mAHD)
31/12/90
30/12/93
29/12/96
29/12/99
28/12/02
27/12/05
26/12/08
Date
JSEB3 (Observed)
JSEB3 (Calculated)



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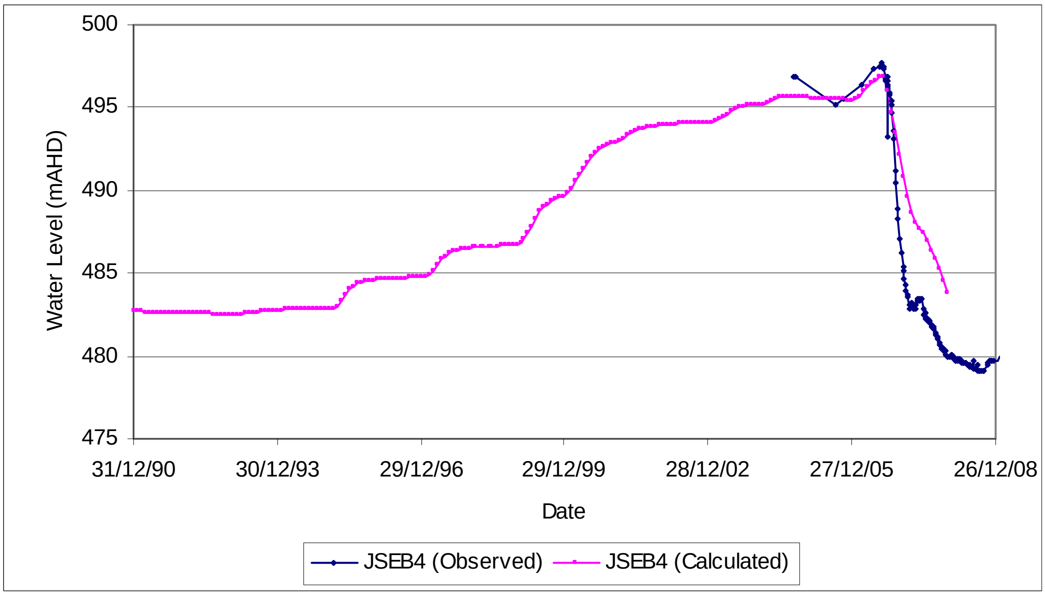
480
470
460
450
440
430
Water Level (mAHD)
31/12/90
30/12/93
29/12/96
29/12/99
28/12/02
27/12/05
26/12/08
Date
YJ-P109 (Observed)
YJ-P109 (Calculated)



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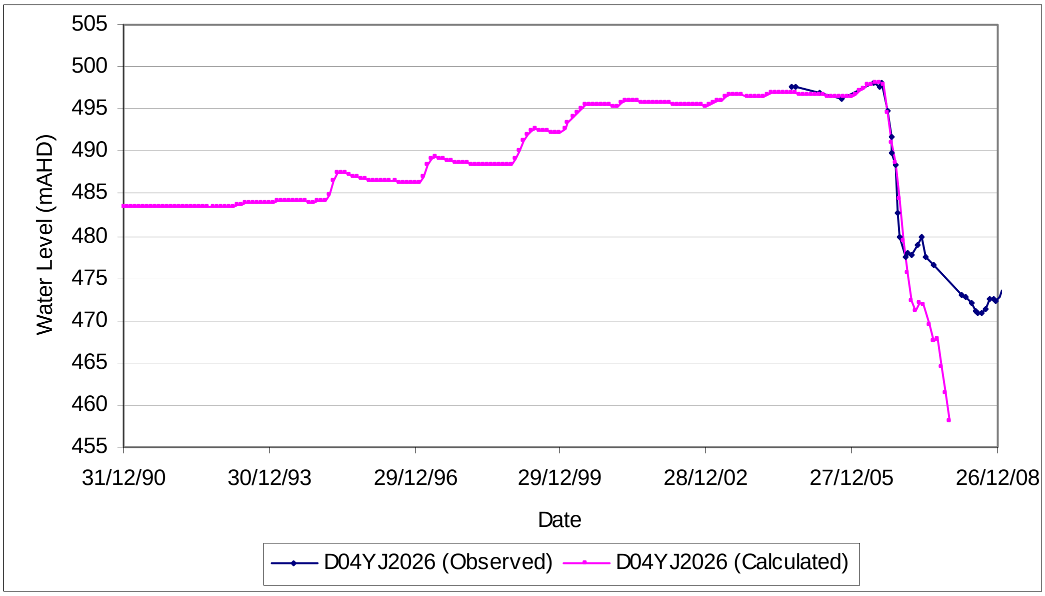
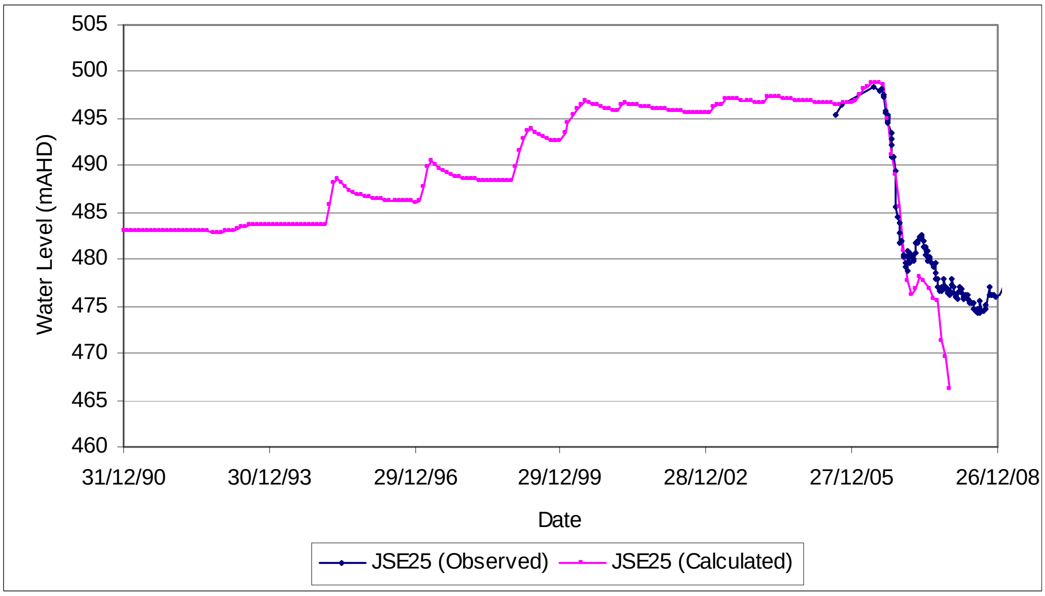
495
490
485
480
475
Water Level (mAHD)
31/12/90
30/12/93
29/12/96
29/12/99
28/12/02
27/12/05
26/12/08
Date
JSEB4 (Observed)
JSEB4 (Calculated)



505
500
495
490
485
480
475
470
465
460
455
Water Level (mAHD)
31/12/90
30/12/93
29/12/96
29/12/99
28/12/02
27/12/05
26/12/08
Date
D04YJ2026 (Observed)
D04YJ2026 (Calculated)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495
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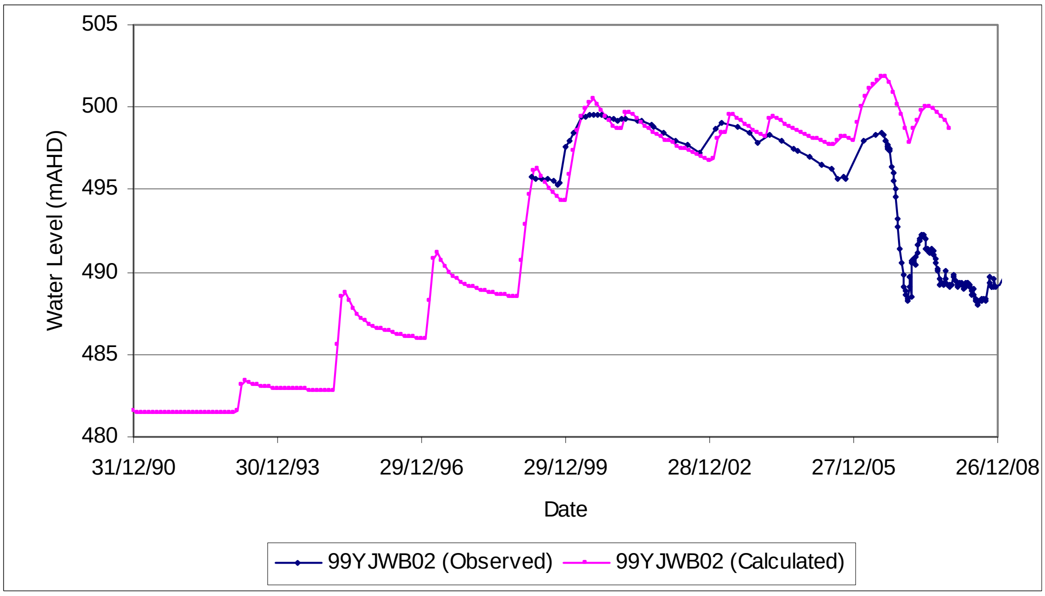
485
480
475
470
465
460
Water Level (mAHD)
31/12/90
30/12/93
29/12/96
29/12/99
28/12/02
27/12/05
26/12/08
Date
JSE25 (Observed)
JSE25 (Calculated)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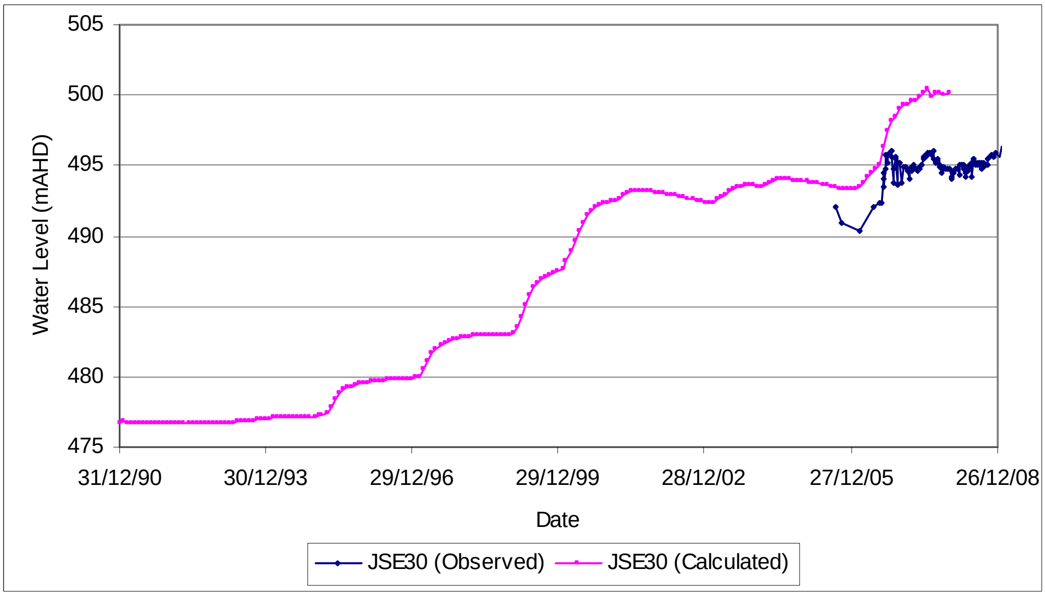
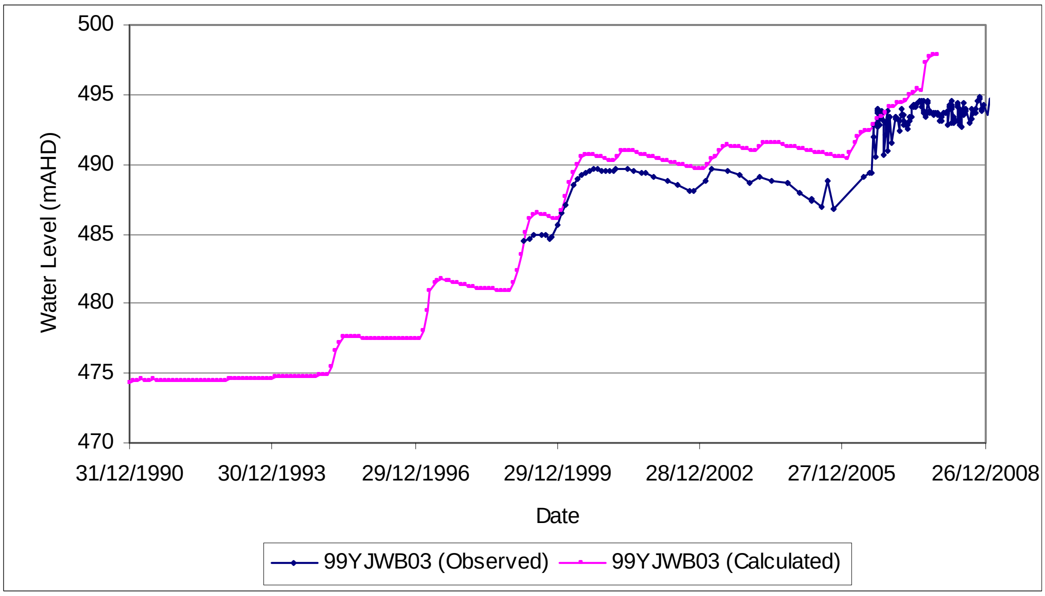
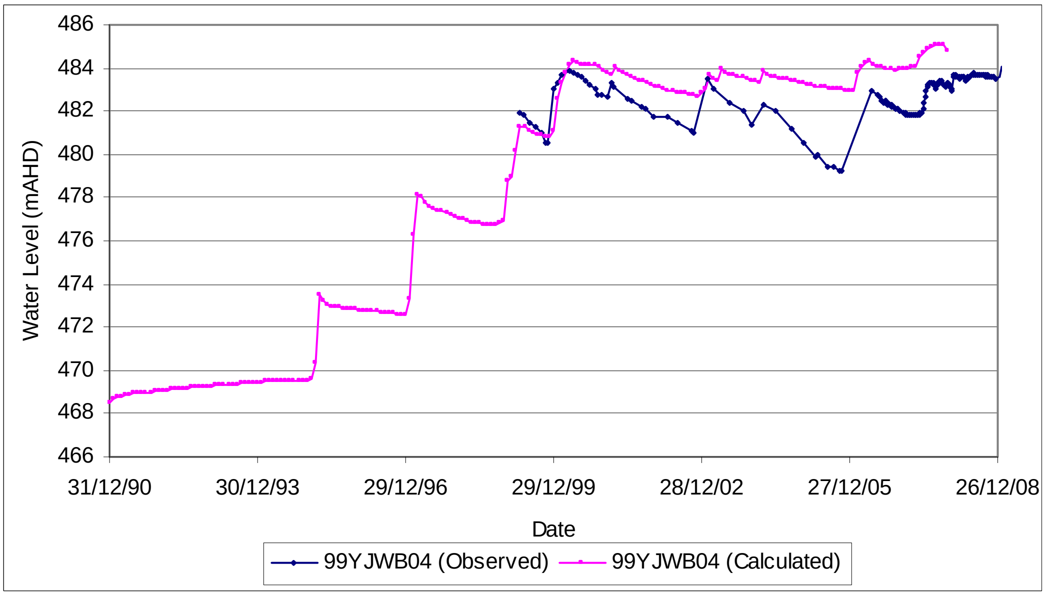
500
495
490
485
480
Water Level (mAHD)
31/12/90
30/12/93
29/12/96
29/12/99
28/12/02
27/12/05
26/12/08
Date
99YJWB02 (Observed)
99YJWB02 (Calculated)

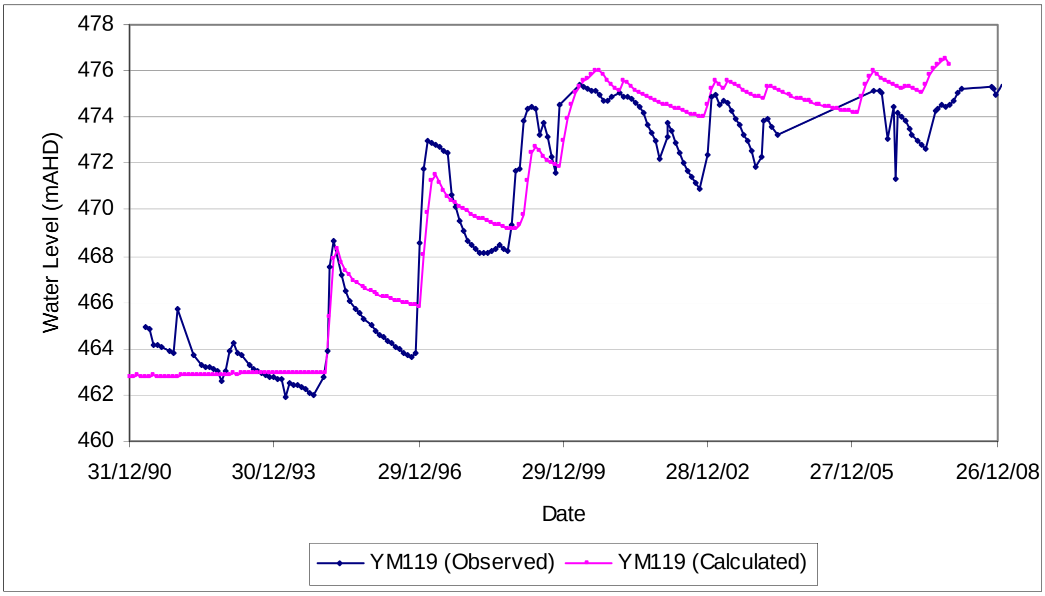

505
500
495
490
485
480
475
Water Level (mAHD)
31/12/90
30/12/93
29/12/96
29/12/99
28/12/02
27/12/05
26/12/08
Date
JSE30 (Observed)
JSE30 (Calculated)



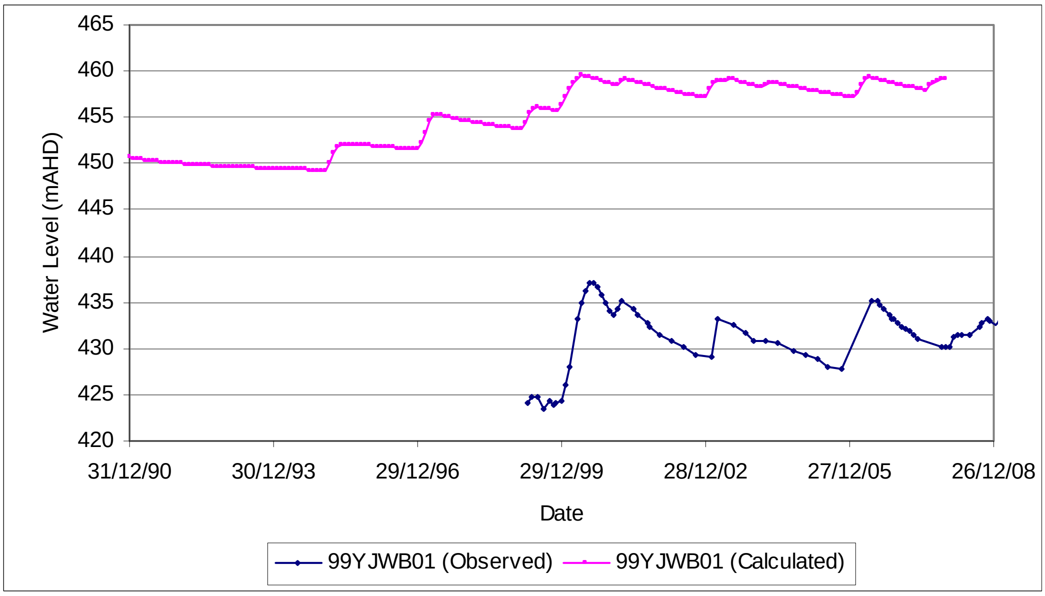
500
495
490
485
480
475
470
Water Level (mAHD)
31/12/1990
30/12/1993
29/12/1996
29/12/1999
28/12/2002
27/12/2005
26/12/2008
Date
99YJWB03 (Observed)
99YJWB03 (Calculated)



486
484
482
480
478
476
474
472
470
468
466
Water Level (mAHD)
31/12/90
30/12/93
29/12/96
29/12/99
28/12/02
27/12/05
26/12/08
Date
99YJWB04 (Observed)
99YJWB04 (Calculated)

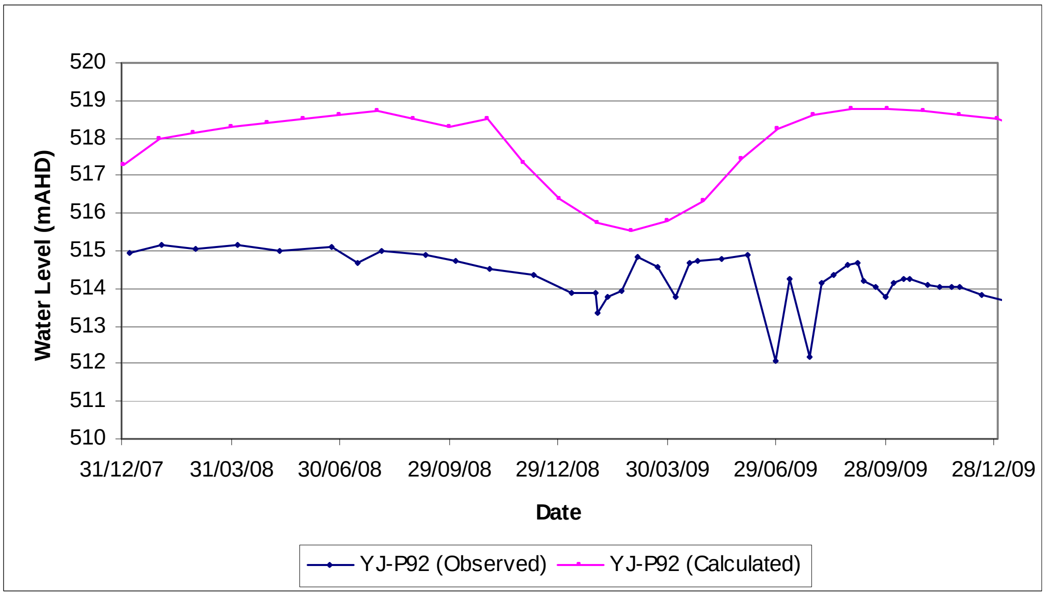


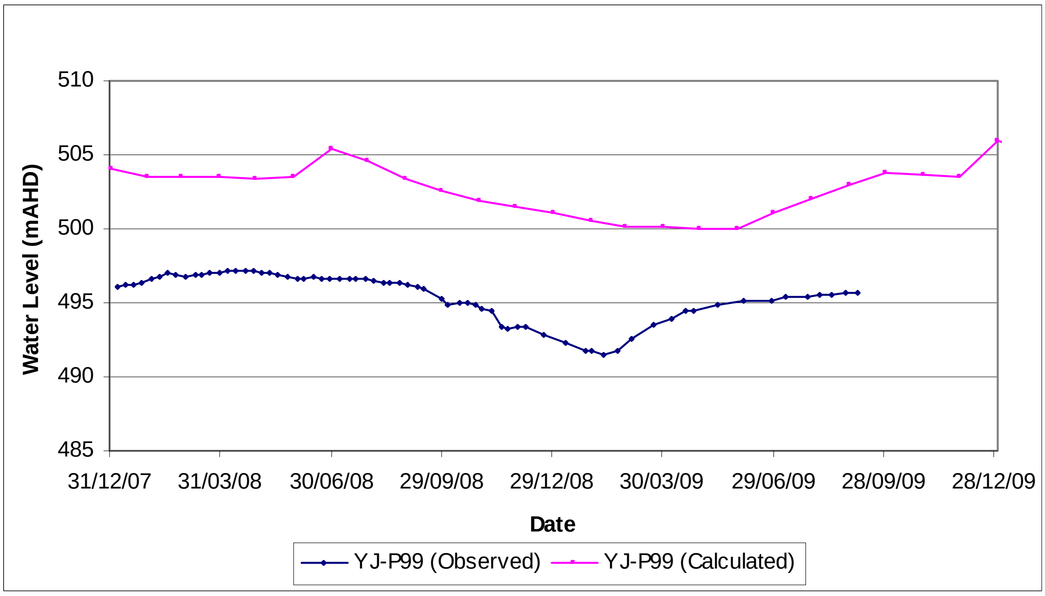
478
476
474
472
470
468
466
464
462
460
Water Level (mAHD)
31/12/90
30/12/93
29/12/96
29/12/99
28/12/02
27/12/05
26/12/08
Date
YM119 (Observed)
YM119 (Calculated)

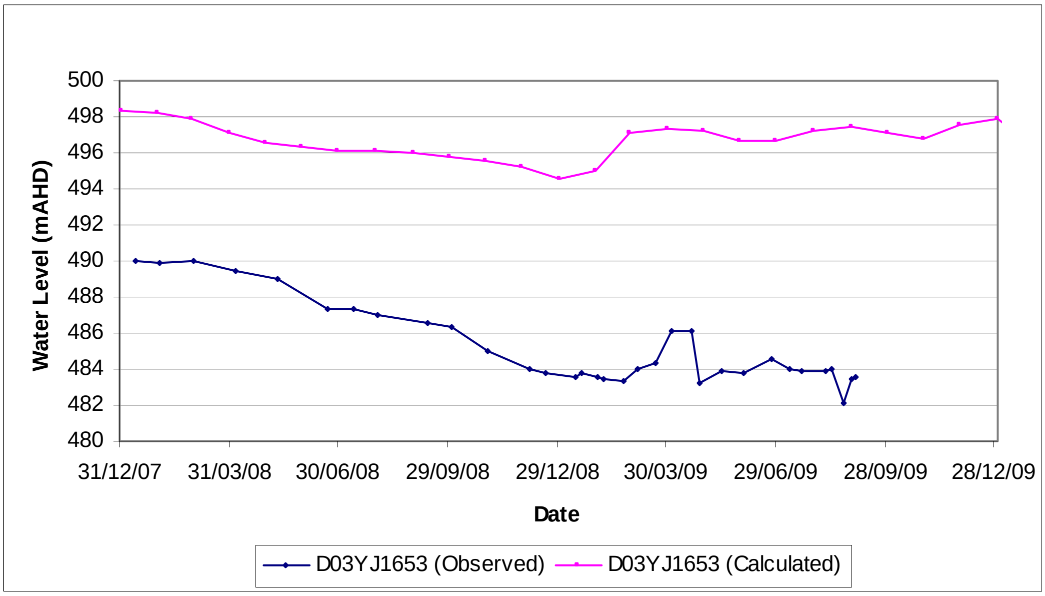

465
460
455
450
445
440
435
430
425
420
Water Level (mAHD)
31/12/90
30/12/93
29/12/96
29/12/99
28/12/02
27/12/05
26/12/08
Date
99YJWB01 (Observed)
99YJWB01 (Calculated)

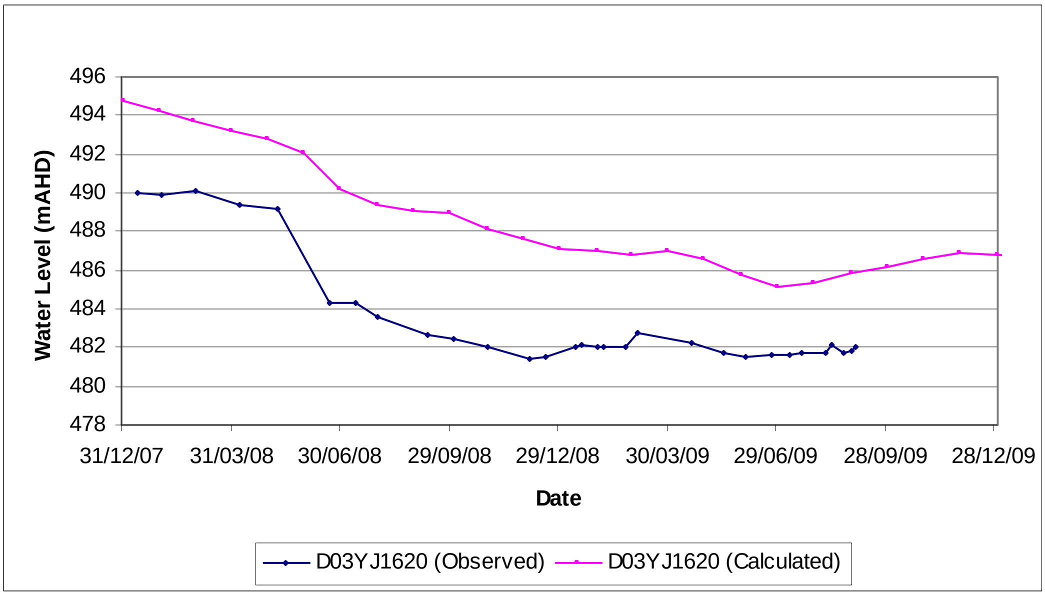
Appendix C

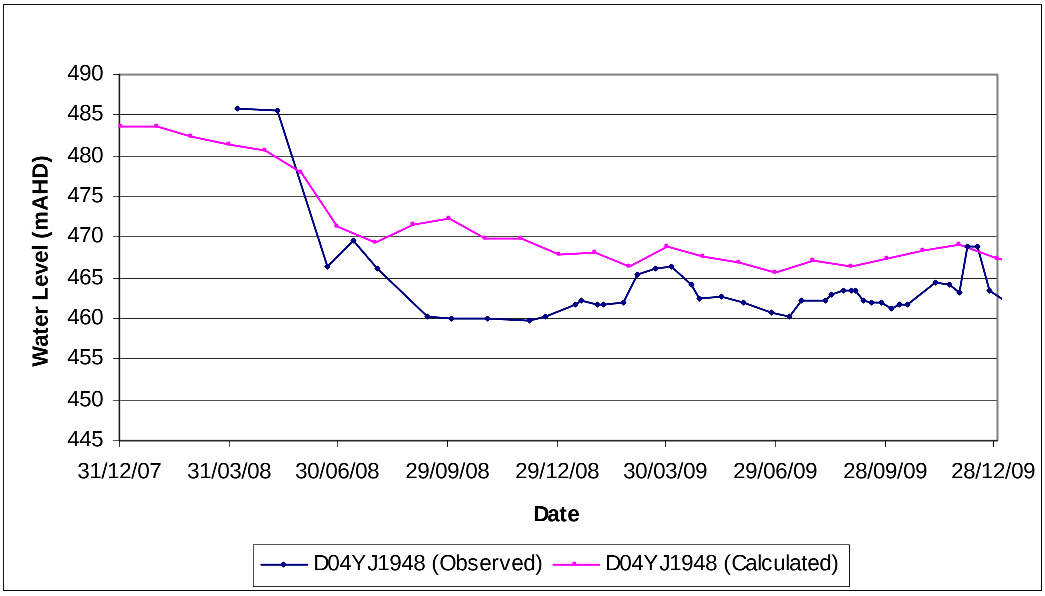
Verification Hydrographs

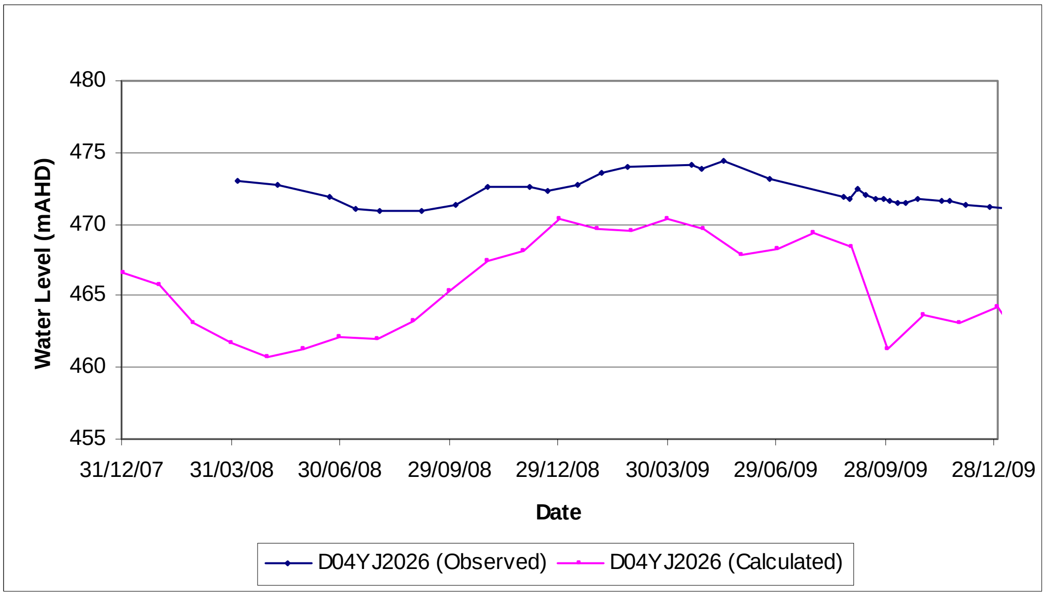

520
519
518
517
516
515
514
513
512
511
510
Water Level (mAHD)
31/12/07
31/03/08
30/06/08
29/09/08
29/12/08
30/03/09
29/06/09
28/09/09
28/12/09
Date
YJ-P92 (Observed)
YJ-P92 (Calculated)

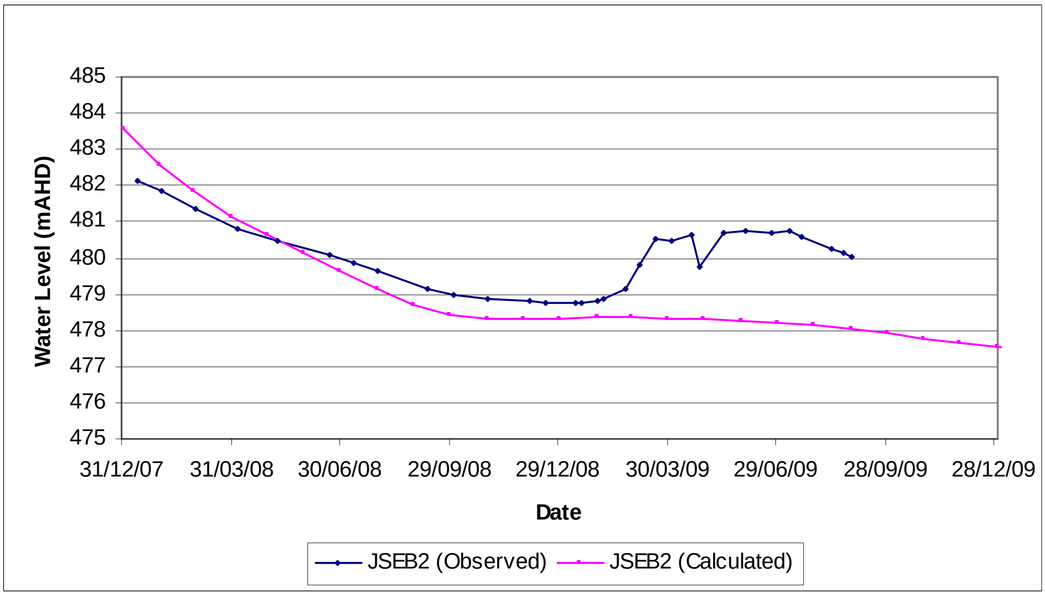

510
505
500
495
490
485
Water Level (mAHD)
31/12/07
31/03/08
30/06/08
29/09/08
29/12/08
30/03/09
29/06/09
28/09/09
28/12/09
Date
YJ-P99 (Observed)
YJ-P99 (Calculated)

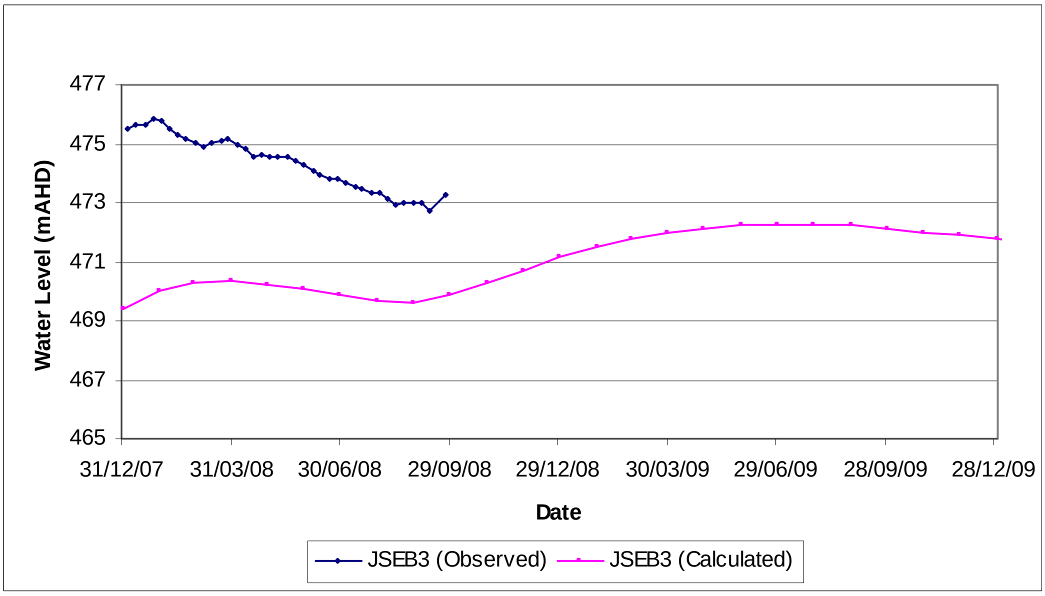

500
498
496
494
492
490
488
486
484
482
480
Water Level (mAHD)
31/12/07
31/03/08
30/06/08
29/09/08
29/12/08
30/03/09
29/06/09
28/09/09
28/12/09
Date
D03YJ1653 (Observed)
D03YJ1653 (Calculated)

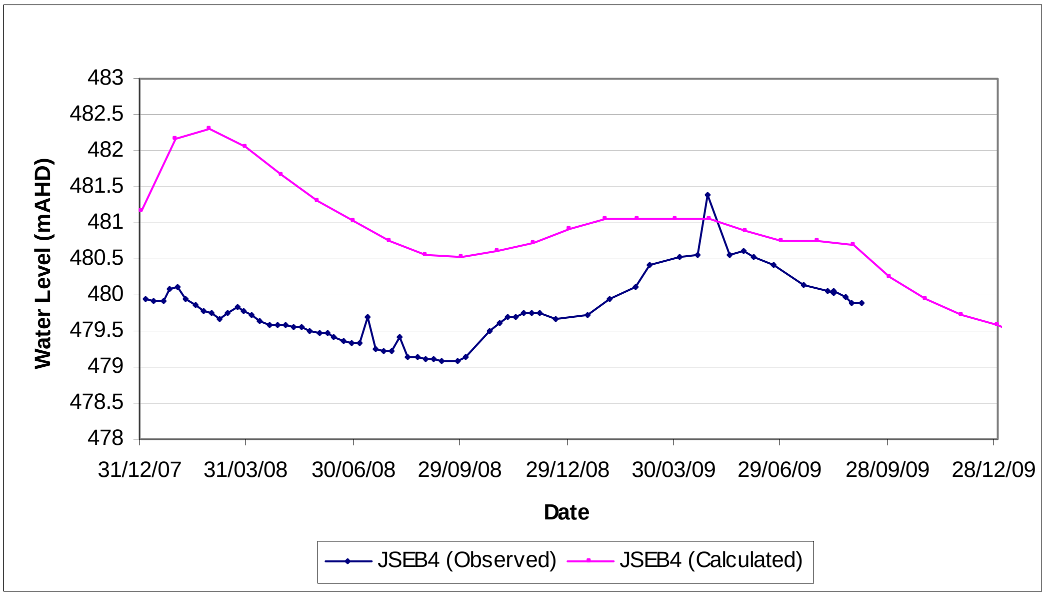

496
494
492
490
488
486
484
482
480
478
Water Level (mAHD)
31/12/07
31/03/08
30/06/08
29/09/08
29/12/08
30/03/09
29/06/09
28/09/09
28/12/09
Date
D03YJ1620 (Observed)
D03YJ1620 (Calculated)


490
485
480
475
470
465
460
455
450
445
Water Level (mAHD)
31/12/07
31/03/08
30/06/08
29/09/08
29/12/08
30/03/09
29/06/09
28/09/09
28/12/09
Date
D04YJ1948 (Observed)
D04YJ1948 (Calculated)

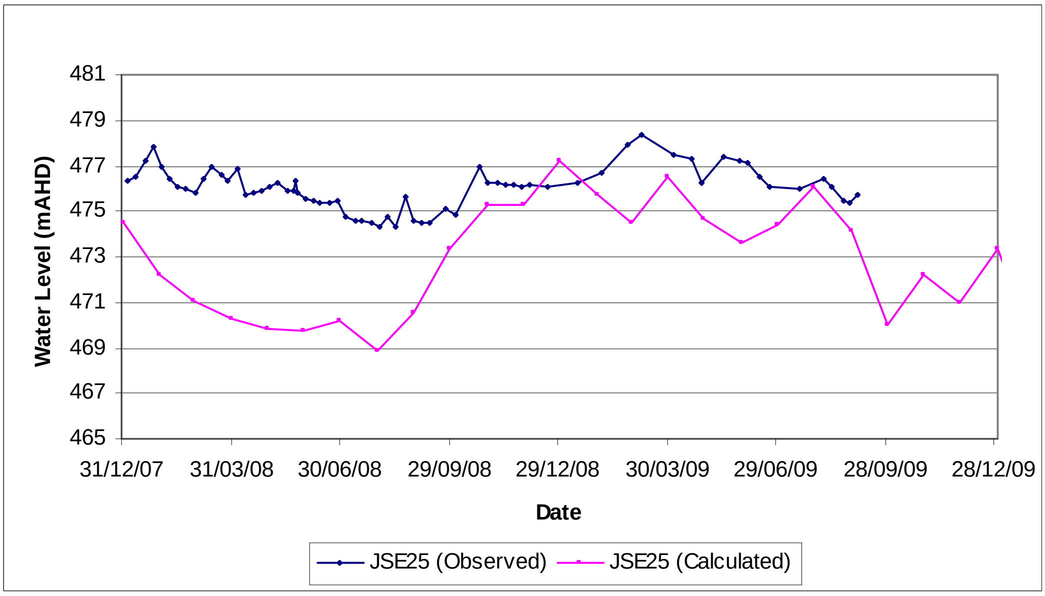

480
475
470
465
460
455
Water Level (mAHD)
31/12/07
31/03/08
30/06/08
29/09/08
29/12/08
30/03/09
29/06/09
28/09/09
28/12/09
Date
D04YJ2026 (Observed)
D04YJ2026 (Calculated)

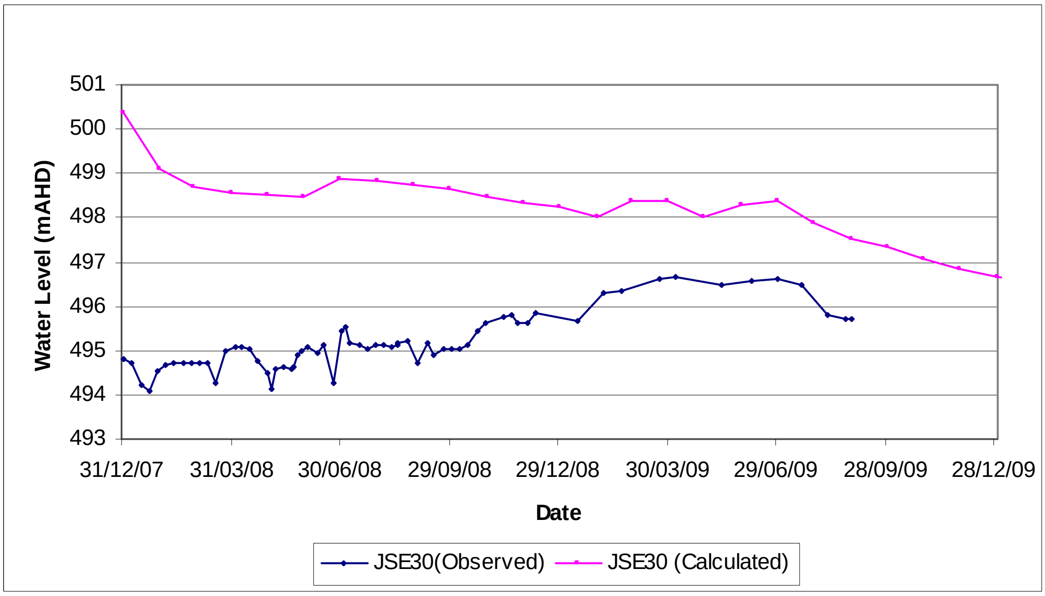

Water Level (mAHD)
485
484
483
482
481
480
479
478
477
476
475
31/12/07
31/03/08
30/06/08
29/09/08
29/12/08
30/03/09
29/06/09
28/09/09
28/12/09
Date
JSEB2 (Observed)
JSEB2 (Calculated)


Water Level (mAHD)
477
475
473
471
469
467
465
31/12/07
31/03/08
30/06/08
29/09/08
29/12/08
30/03/09
29/06/09
28/09/09
28/12/09
Date
JSEB3 (Observed)
JSEB3 (Calculated)


Water Level (mAHD)
483
482.5
482
481.5
481
480.5
480
479.5
479
478.5
478
31/12/07
31/03/08
30/06/08
29/09/08
29/12/08
30/03/09
29/06/09
28/09/09
28/12/09
Date
JSEB4 (Observed)
JSEB4 (Calculated)


480
475
470
465
460
455
Water Level (mAHD)
31/12/07
31/03/08
30/06/08
29/09/08
29/12/08
30/03/09
29/06/09
28/09/09
28/12/09
Date
JSE6 (Observed)
JSE6 (Calculated)


481
479
477
475
473
471
469
467
465
Water Level (mAHD)
31/12/07
31/03/08
30/06/08
29/09/08
29/12/08
30/03/09
29/06/09
28/09/09
28/12/09
Date
JSE25 (Observed)
JSE25 (Calculated)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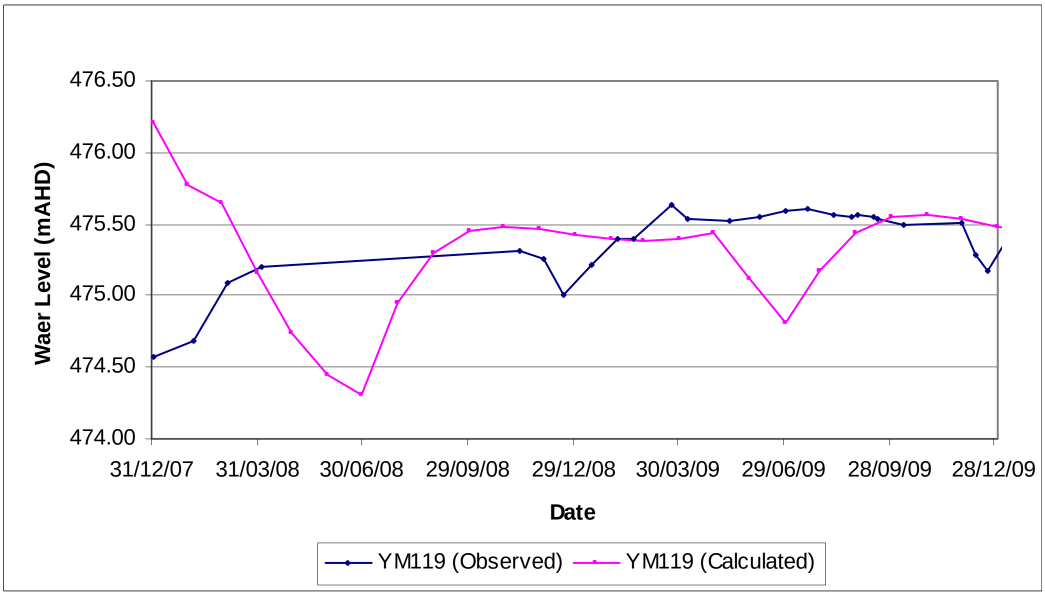
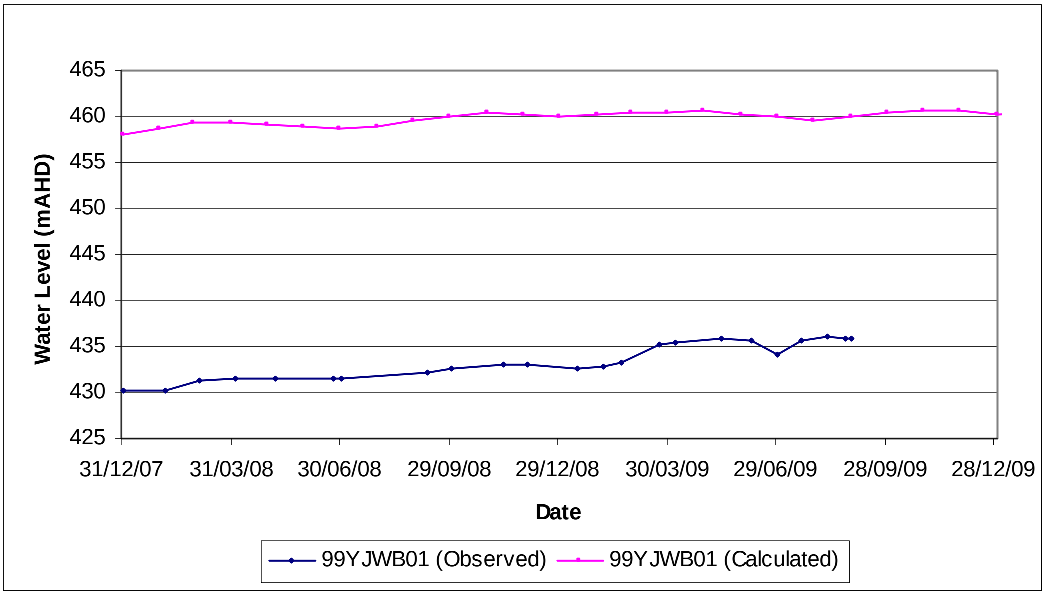
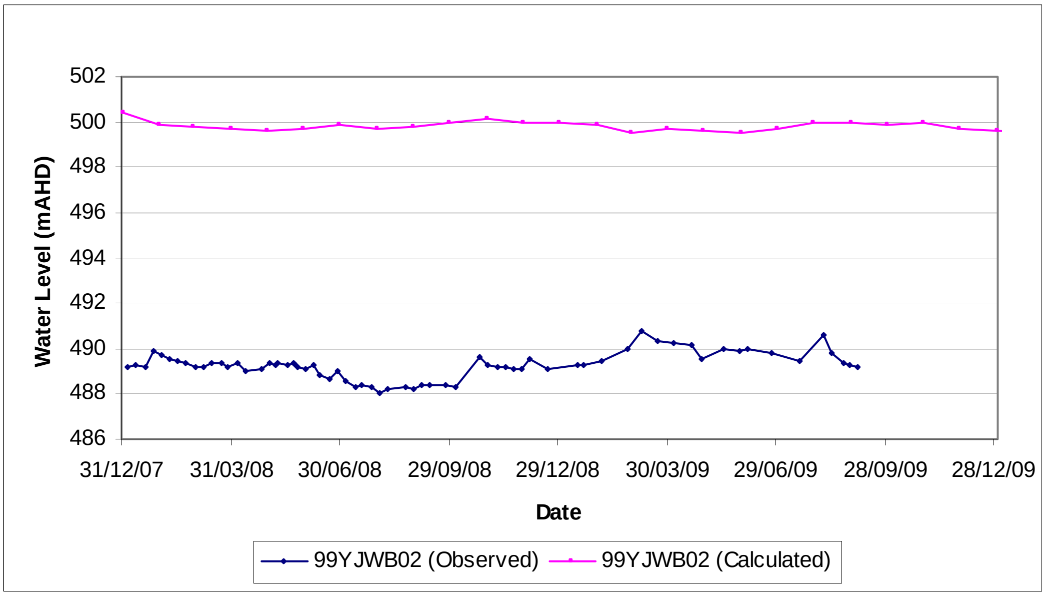
500
499
498
497
496
495
494
493
Water Level (mAHD)
31/12/07
31/03/08
30/06/08
29/09/08
29/12/08
30/03/09
29/06/09
28/09/09
28/12/09
Date
JSE30(Observed)
JSE30 (Calculated)


476.50
476.00
475.50
475.00
474.50
474.00
Waer Level (mAHD)
31/12/07
31/03/08
30/06/08
29/09/08
29/12/08
30/03/09
29/06/09
28/09/09
28/12/09
Date
YM119 (Observed)
YM119 (Calculated)


465
460
455
450
445
440
435
430
425
Water Level (mAHD)
31/12/07
31/03/08
30/06/08
29/09/08
29/12/08
30/03/09
29/06/09
28/09/09
28/12/09
Date
99YJWB01 (Observed)
99YJWB01 (Calculated)


502
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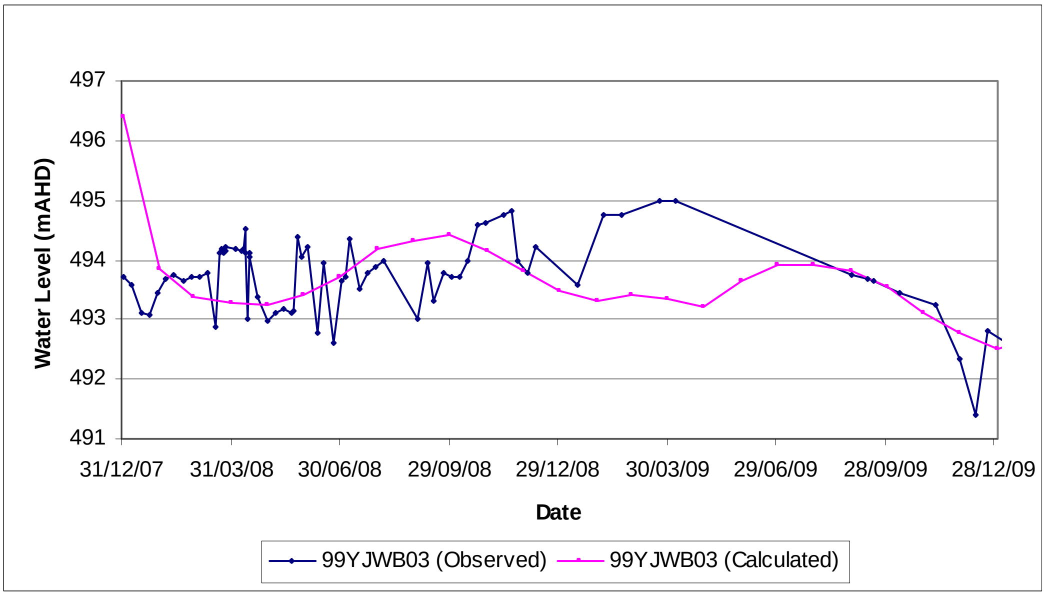
496
494
492
490
488
486
Water Level (mAHD)
31/12/07
31/03/08
30/06/08
29/09/08
29/12/08
30/03/09
29/06/09
28/09/09
28/12/09
Date
99YJWB02 (Observed)
99YJWB02 (Calculated)


497
496
495
494
493
492
491
Water Level (mAHD)
31/12/07
31/03/08
30/06/08
29/09/08
29/12/08
30/03/09
29/06/09
28/09/09
28/12/09
Date
99YJWB03 (Observed)
99YJWB03 (Calculated)


485
484.5
484
483.5
483
482.5
Water Level (mAHD)
31/12/07
31/03/08
30/06/08
29/09/08
29/12/08
30/03/09
29/06/09
28/09/09
28/12/09
Date
99YJWB04 (Observed)
99YJWB04 (Calculated)