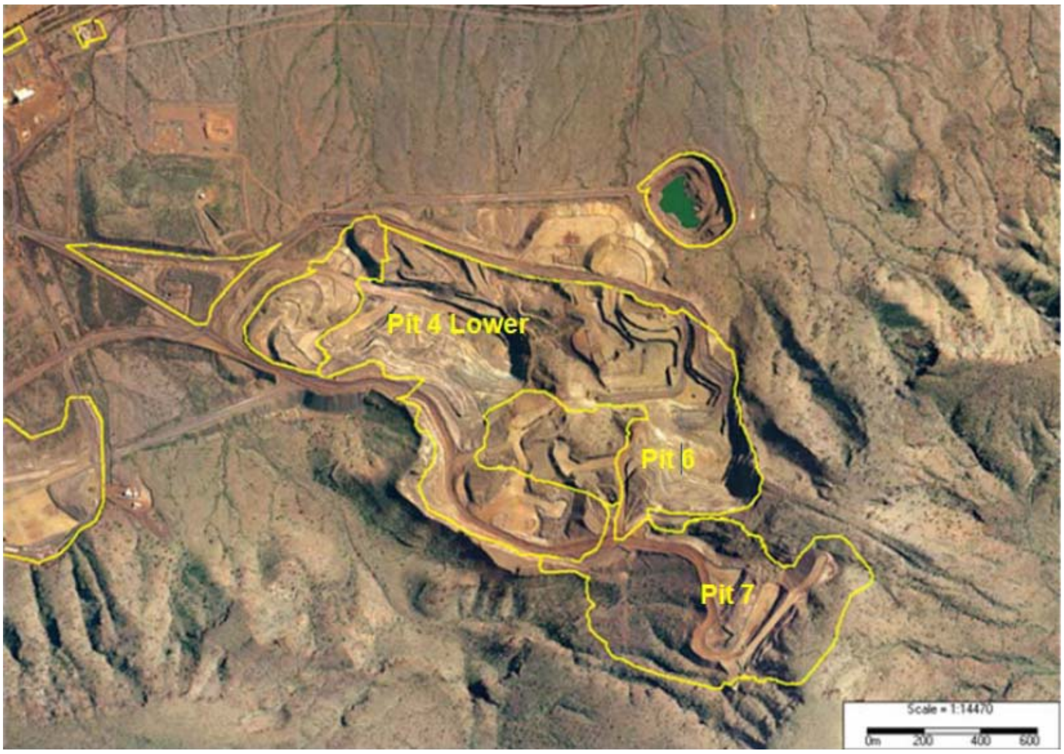
**Technical Projects, Resource Development**

# Brockman 2 groundwater model update

April 2009



*Brockman Syncline 2 below watertable area (pit 5 is the saturated pit to the northeast)*

# Contents page

# Introduction

## Background

Brockman 2 (BS2) mine is located some 45km northwest of Tom Price. It has an annual production rate of 8Mtpa of Brockman Iron Formation ore. Above watertable reserves are due to be mined out late 2009 at current planned production rates. Economic ore reserves are known to occur below the regional water table. This report details the hydrogeological understanding of the immediate area for the purpose of establishing a dewatering strategy for the below watertable Phase 2a & 2b (Pit 4, 4a and 6) expansions. It also documents calibration of the groundwater model to be used to develop the dewatering strategy.

### Dewatering history

The Pit 4 area of BS2 had a pre-mining watertable of approximately 618m RL. RTIO had approval to dewater Pit 4 to 580m RL to allow removal of ore reserves to 590m RL in Pit 4 under the assumption the watertable was not connected with the regional watertable within the Nammuldi valley which occurs at 580m RL.

Dewatering was affected by two production bores completed in the south-eastern high wall of Pit 4. Dewatering commenced in March 2006 and was completed by December 2008 after approximately 2.75GL was abstracted. In addition to dewatering, surplus water to mine requirements was discharged to the disused Pit 5 to the northeast on the southern margin of the Nammuldi valley. Of the 2.75GL abstracted approximately 1.5GL was discharged to Pit 5 (Figure 1).

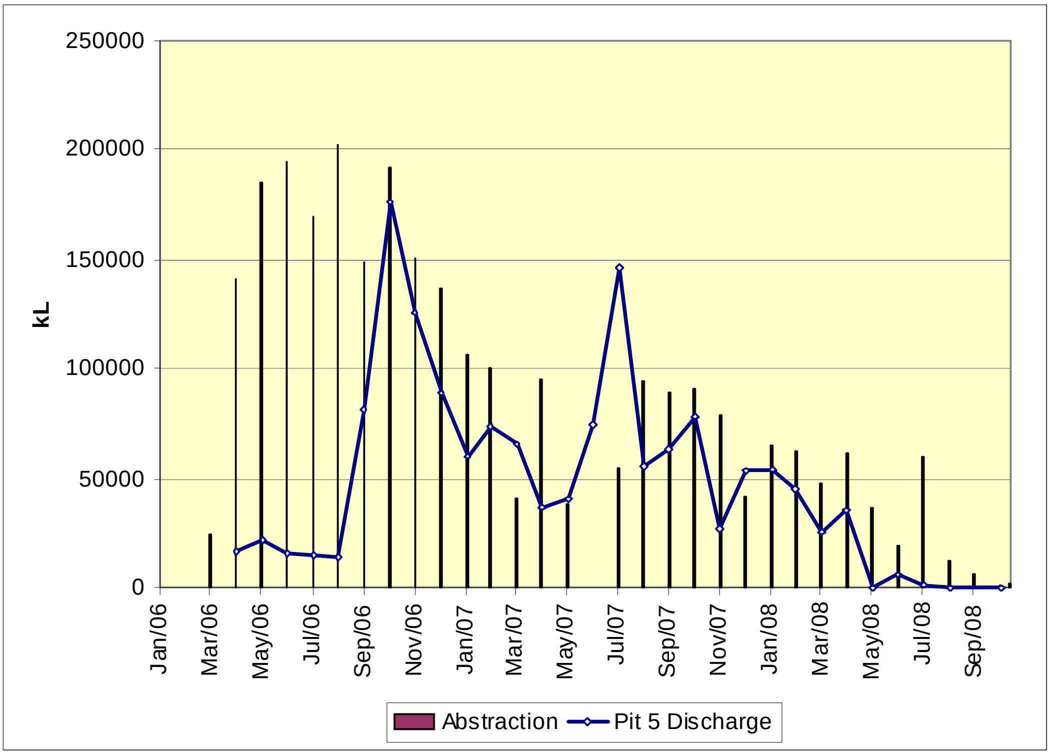


*Figure 1. Pit 4 dewatering (monthly mean) and Pit 5 discharge volumes (from cumulative weekly). The reason for discharge exceeding pumping in Jun/Jul 2007 is unexplained.*

## Previous work

The BS2 mine was predominantly above watertable until 2006 and there is limited previous hydrogeological work on the specific area. Conversely across the valley at Nammuldi deposit there is a considerable body of hydrogeological work to understand both water supply and dewatering for the Greater BS2/Nammuldi site.

A description of the local geology can be sourced from the Developed Resources Handbook End of Year 2008 (Frost-Barnes & Boyle, 2009). This text also provides reference for specific mapping, geological block model and reserves modelling reports for BS2.

The first hydrogeological assessment for BS2 dewatering was completed by SKM in 1997. The next significant report was by Evans & Storey (2005) for Pilbara Iron; however the report appears incomplete. This report dealt with the initial dewatering requirements at Pit 4 to mine to 580m RL. The report provided details of a dewatering plan and discussed mine closure issues for mining to 530RL. The conceptual hydrogeological model from the report is consistent with current understanding in that the ore body is highly permeable, but that it is relatively isolated from the regional watertable by surrounding low permeability BIF.

In the adjacent Nammuldi valley known below watertable resources in the Marra Mamba Iron Formation have resulted in numerous studies. Previous hydrogeological studies were conducted by Layton’s (1978), Hamersley Iron (1991, 2000), PPK (1998, 1999), EPA (2000), Cymod (2004) and Liquid Earth (2004). A short summary of the key findings of each assessment can be found in URS (2008). From these investigations the general conclusion is that the Nammuldi groundwater flow system has limited connectivity with the bedrock aquifers associated with BS2 mine.

# Conceptual Hydrogeological Model

## Setting

BS2 mine is located on the northern limb of the Brockman Syncline and just south of the Nammuldi mine. The ore body comprises mineralised Brockman Iron Formation and associated detrital deposits. The BS2 pits occur along the face of the syncline and comprise a series of above watertable cutbacks into the syncline wall. However economic ore reserves are known to occur below watertable at Pit 4, 4a and 6.

### Physiography

The BS2 mine lies on the northern limb of the Brockman Syncline. The BS2 area is part of the Duck Creek Catchment, a major tributary of the Ashburton River that flows to the west and discharges at the coast. In the immediate area all drainage systems are ephemeral and flow only in response to significant rainfall events.

The upper catchment area rises to over 900m AHD with steep relief driving surface run-off and limiting recharge. The topographic gradient, from the BS2 catchment divide to the Nammuldi valley, is in the order of 0.2, falling some 300m metres in less than 2km. In addition the natural pre-mining local catchment for Pit 4, 6 and 7 is small (~1km$^2$).

### Climate

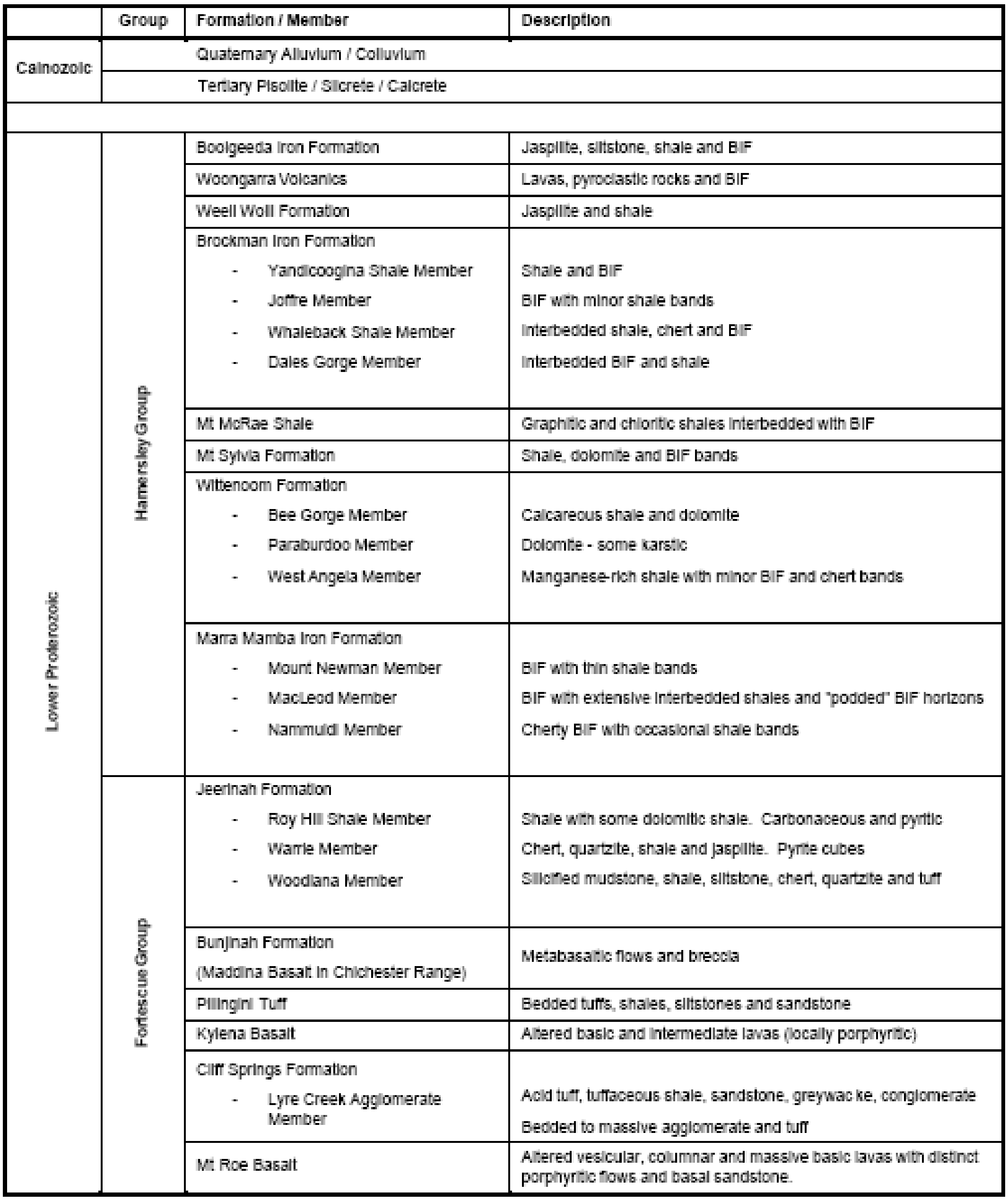
The climate of the Pilbara is arid. Rainfall has been recorded at the BS2 mine since February 1998 and at nearby Tom Price (55km southeast) since October 1972. Average annual rainfall from the two stations is 452mm and 410mm, respectively. Rainfall occurs predominantly in the months of December to March associated with tropical lows and or cyclonic activity. Rainfall events can be particularly intense and generally of short duration.

Evaporation is recorded at BS2 site since May 2004 and is generally lower than anticipated for the Pilbara region at 1835mm/a. There may be spurious data, particular for 2005, which has a recorded annual cumulative evaporation of just 1490mm in not a particularly wet year. Based on at least 10 years of records from sites across the Pilbara the Bureau of Meteorology indicates pan evaporation should be in the order of 3200mm/a.

### Geology

The geology of the region comprises Proterozoic meta-sediments of the Hamersley Group and overlying Tertiary age regolith and valley fill sediments. The sequence of the Hamersley Group is presented in Table 1. The mineralised ore at BS2 occurs within the Dales Gorge Members of the Brockman Iron Formation. Iron enriched detrital sediments have also been exploited within the adjacent Nammuldi valley. The Nammuldi valley is filled with Tertiary sediments overlying the Wittenoom Formation which abuts the Marra Mamba Iron Formation and ridge to the north.

The deposit is divided into two pits separated by a steep valley. The deposit sits in a series of complex doubly plunging east – southeast trending synclinal structures. The valley and the original Pit 4 mark the centres of plunge for both synclines. Mineralisation occurs from the “Colonial Chert” of the Mt McRae Shale (known locally as the Foot Wall Zone) through the Dales Gorge Member into the Whaleback Shale. The contact with unmineralised BIF is generally sharp with a few BIF pods inside the Ore/BIF boundary. A cross section through the BS2 Deposit is shown in Figure 2.



| | Group | Formation / Member | Description |
|---|---|---|---|
| Cainozoic | | Quaternary Alluvium / Colluvium | |
| | | Tertiary Pisolite / Silcrete / Calcrete | |
| | | | |
| Lower Proterozoic | Hamersley Group | Boolgeeda Iron Formation | Jaspilite, siltstone, shale and BIF |
| | | Woongarra Volcanics | Lavas, pyroclastic rocks and BIF |
| | | Weeli Wolli Formation | Jaspilite and shale |
| | | Brockman Iron Formation | |
| | | - Yandicoogina Shale Member | Shale and BIF |
| | | - Joffre Member | BIF with minor shale bands |
| | | - Whaleback Shale Member | Interbedded shale, chert and BIF |
| | | - Dales Gorge Member | Interbedded BIF and shale |
| | | Mt McRae Shale | Graphitic and chloritic shales interbedded with BIF |
| | | Mt Sylvia Formation | Shale, dolomite and BIF bands |
| | | Wittenoom Formation | |
| | | - Bee Gorge Member | Calcareous shale and dolomite |
| | | - Paraburdoo Member | Dolomite - some karstic |
| | | - West Angela Member | Manganese-rich shale with minor BIF and chert bands |
| | | Marra Mamba Iron Formation | |
| | | - Mount Newman Member | BIF with thin shale bands |
| | | - MacLeod Member | BIF with extensive interbedded shales and "podded" BIF horizons |
| | | - Nammuldi Member | Cherty BIF with occasional shale bands |
| | Fortescue Group | Jeerinah Formation | |
| | | - Roy Hill Shale Member | Shale with some dolomitic shale. Carbonaceous and pyritic |
| | | - Warrie Member | Chert, quartzite, shale and jaspilite. Pyrite cubes |
| | | - Woodiana Member | Silicified mudstone, shale, siltstone, chert, quartzite and tuff |
| | | Bunjinah Formation<br>(Maddina Basalt in Chichester Range) | Metabasaltic flows and breccia |
| | | Pilingini Tuff | Bedded tuffs, shales, siltstones and sandstone |
| | | Kylena Basalt | Altered basic and intermediate lavas (locally porphyritic) |
| | | Cliff Springs Formation | Acid tuff, tuffaceous shale, sandstone, greywac ke, conglomerate |
| | | - Lyre Creek Agglomerate Member | Bedded to massive agglomerate and tuff |
| | | Mt Roe Basalt | Altered vesicular, columnar and massive basic lavas with distinct porphyritic flows and basal sandstone. |

*Table 1. Regional stratigraphy of the Brockman Syncline area.*

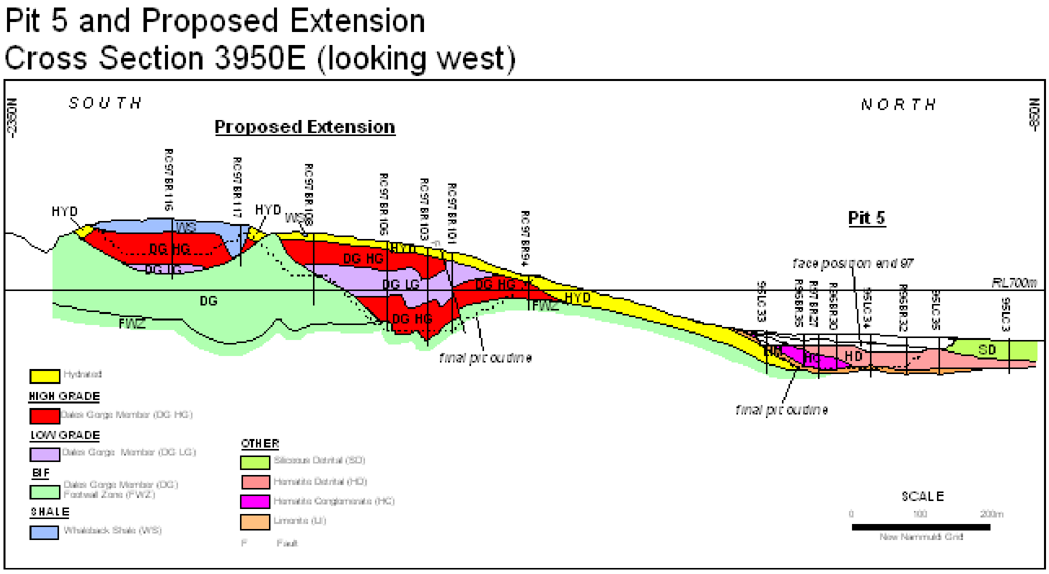


*Figure 2. Brockman Syncline 2 geology section*

# Hydrogeology

## Groundwater occurrence

Pre-mining groundwater occurred across the BS2 ore body at approximately 618m RL. Bores screened in adjacent low permeability BIF had similar head; however further to the north bores within the McRae Shale and Nammuldi valley have groundwater levels at 576 to 580m RL. This near 40m head change occurs over a distance of roughly 175m.

To the south of the ore body (higher up the BS2 valley) the only bore is PZ07BRK04. This bore is screened within mineralised Dales Gorge Member but was constructed post dewatering. Initial heads were similar to the dewatered head in Pit 4; however following cessation of pumping from WB05BRK001 the head had recovered to 611m RL by May 2008. There are no bores further south and thus the head towards the topographic divide of the Brockman Syncline is poorly understood. There are also minimal (only two) dipped levels from Resource Evaluation drilling. These are consistent with the water bore monitoring at around 615m RL. Hence construction of pre-mining watertable levels within the limb of Brockman Syncline is problematic and is some what limiting with respect to a steady state calibration approach.

Within the Nammuldi valley there is more consistency in groundwater elevations and a conceptual model of the watertable is presented in URS (2008, Figure 15). There appears to be a groundwater divide (or col) that separates westerly following groundwater from Lens A, B, C and D from that which flows to the east and north through a “break” in the Nammuldi ridge from Lens E-F.

## Aquifer properties

Evans & Storey (2005) report a hydraulic conductivity of 6m/day and specific yield of 0.15 for mineralised ore from an SKM report. However the quoted reference is from work completed at Homestead Lease and hence the source of this value is now uncertain. On the lower limb of the Brockman Syncline aquifer testing of the mineralised Brockman Iron Formation in nine production bores at Brockman Syncline 4 indicated a range in hydraulic conductance of between 1 and 40m/day, with the majority of early time (ore body) recovery tests indicating 1 to 13m/day (Aquaterra, 2007).

Hydraulic testing occurred on the two dewatering bores within Pit 4 in 2005; however the results were poorly documented (absent) in Evans & Storey (2005). One bore was tested at 50L/s for 10 days with uniform drawdown observed in all bores screened within the ore body.

Hydraulic testing of the unmineralised BIF has not occurred around BS2. However at other RTIO sites slug testing has indicated hydraulic conductance of BIF material to be very low, in the order of $10^{-3}$ to $10^{-4}$m/day. Dewatering of Pit 4 appears to have affected a very local area associated with Pit 4 ore body alone and has had negligible impact on groundwater levels within the Mt McRae Shale or valley detritus. This supports the concept of a very low conductance for the unmineralised BIF material that isolates the Pit 4 ore body from the regional groundwater flow system.

Evans & Storey concluded that a combined bore yield of approximately 3500kL/day would be sufficient to lower the groundwater level to 530 RL. However dewatering has shown that approximately double that rate was applied over the first 9 months before rates diminished to zero and groundwater levels have been left to recover. The minimum pumping level recorded was 547m RL.

Given the estimated material volume removed through mining and the volume of water removed via pumping, and assuming minimal recharge or through flow from surrounding rock, as evidenced by the lack of impact on groundwater levels outside of the ore body; the specific yield of the BS2 ore is in the order of 0.3.

### Groundwater chemistry

Groundwater from the ore body is fresh, generally less than 400mg/L TDS. There is no specific dominant cation and dominant anions are $Cl^-$ and $SO_4^{2-}$. For the Pilbara, the groundwater is notably absent in bicarbonate and not very hard; indicating its source is from rainfall with minimal evaporative impact.

### Groundwater balance

The groundwater balance for BS2 is difficult to surmise as critically there is no obvious groundwater flow path for discharge. Given the very tight hydraulic gradient (i.e. 40/175 = 0.2!) between the ore body and the Nammuldi valley the only assumption is that recharge is very minor and if water levels are in equilibrium the recharge must equate to downward flow (assumed) and minor discharge to the Nammuldi valley.

Understanding the age of the groundwater and adding to the groundwater monitoring network, particularly to the south of the ore body, may aid in the understanding of the BS2 ore body flow system. If the groundwater is particularly old (>20,000a) with minimal modern carbon or CFC's then it is likely that modern recharge is near negligible.

# Groundwater modelling

The BS2 groundwater model was constructed using the PMwin Groundwater User Interface (GUI) and the USGS generic finite difference MODFLOW96 code (McDonald and Harbaugh, 1986). The model was originally constructed by Aquaterra Consulting. However, a model completion report was not available; hence this report is the first reference to capture the model construction. Nevertheless comparisons of the previous model and new model are made to provide documentation of the groundwater models evolution.

The modelling approach was to calibrate a steady state model (independent of time) for history matching recharge and hydraulic conductance with the conceptual pre-mining groundwater levels. Subsequent to acceptable steady state calibration a transient model was calibrated to the Pit 4 dewatering operations. During transient calibration only minor changes were made to the steady state conductance terms and calibration was achieved by perturbing storage parameters until an acceptable history match was achieved. The collective groundwater model suite for BS2 (i.e. the steady state and transient models) are archived to \\Pe-Hidata\Resource Planning\ Technical Projects \Hydrogeology \Model Archive\BS2.

## Model construction

### Grid & layer configuration

The model construction uses a finite difference grid comprising 135 rows by 195 columns. Grid cells range from 100 x 100m down to 10 x 10m in the critical Pit 4 dewatering area. The model grid is referenced to the Brockman 2 local mine grid.

The model comprises seven layers of equal thickness (20m). This allows for stable resolution of the numeric finite difference flow calculations but results in a simplified approximation of the regional geological and hydrogeological interpretation. The top of Layer 1 of the model is set at RL 620m and thus bisects the natural topography. The base of the model is at RL 480m.

### Boundary conditions

The model area includes the catchment topographic divide directly south of BS2 Pit 7 and extends northwards to include part of Nammuldi Lens A, all of Lens B, C and D and half of Nammuldi Lens E-F. Hence the model is specific to the BS2 deposit only and not suitable for use for dewatering predictions for Nammuldi BWT proposal without substantial modifications.

The southern model boundary condition comprises a no flow boundary defined by the contours of the Brockman Syncline topographic divide. In the original Aquaterra constructed model there was a small area along the ridge with constant head boundary conditions. However a sensitivity of model output in steady state indicated the constant head had no bearing on the model water budget and was thus removed.

On the western edge of the model is a constant head boundary in Layers 3-7 of 576m RL representing the groundwater outflow to the west along the Nammuldi Valley south of Lens A. On the eastern boundary in Layers 3-7 is a constant head boundary RL of 579m, representing groundwater inflow from the east just south of Lens E-F and flowing westerly in the Nammuldi valley. To the north dissecting the Marra Mamba Iron Formation ridge is a constant head boundary of 576m RL representing groundwater outflow. The boundary conditions result in the majority of Layer 1 and 2 across the valley to remain unsaturated (no flow) owing to the vertical discretisation of layers. They also replicate a groundwater divide (or col) that occurs roughly east of Lens C & D pit as presented by URS (2008, Fig 15). These boundary conditions are significant modifications to the original Aquaterra model; but better represent the flow system and no flow boundary conditions anticipated from the geology and recent interpretation by URS (2008). The model grid and boundary conditions for Layers 3 to 7 are presented for the original Aquaterra and new RTIO model in Figure 3.

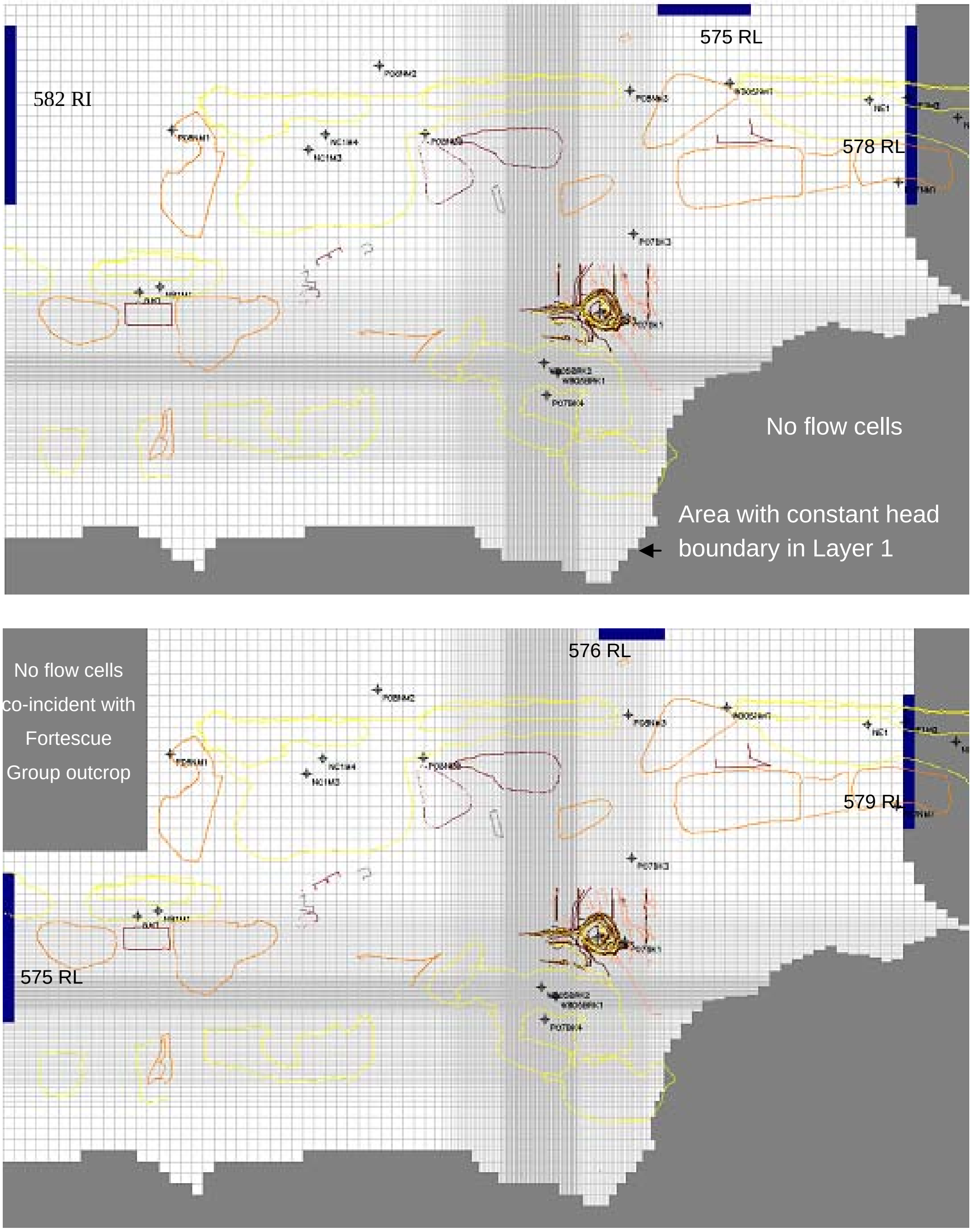


*Figure 3. Layer 3 model grid and boundary conditions for Aquaterra (top) and new RTIO model.*

### Recharge

From the conceptual model the only source of recharge is via rainfall and groundwater through flow from adjacent valley areas at the model boundaries (detailed above). Rainfall was applied using the MODFLOW Recharge package and was assigned to the highest active cell in the model. There were two principal zones, the valley area and ore body and the unmineralised BIF of the Brockman Syncline and Nammuldi Ridge. The spatial distribution of each recharge zone is provided in Appendix A. Assuming an annual average rainfall of 452mm, steady state calibrated recharge was in the order of 1% for the valley and the ore; and 0.1% for the unmineralised BIF and MMIF.

Given the absence of a shallow watertable or phreatophytic vegetation no evaporative or transpiration losses are applied to the groundwater model.

## Model calibration

### Steady state

The steady state calibration assumes that over the long term the groundwater system is in a state of equilibrium, where groundwater levels do not change and in flow equals outflow. Hence steady state calibrations are independent of time and storage. This reduces the number of variables for calibration to the system boundary conditions (inflows and outflows) and hydraulic conductance to arrive at an equivalent watertable or head level to that of the conceptual model of the system. Steady state calibration represents the first step in testing conceptual models and water balances for groundwater systems analysis. This is the process used to arrive at the distribution of hydraulic conductance terms within the BS2 model.

Table 1 provides a summary of the aquifer types and parameters. The conductance terms are represented as isotropic in the xy and vertical directions. The spatial distribution of each hydraulic zone given in Table 1 is provided in Appendix A.

*Table 1. Hydraulic conductance of delineated zones*

| Zones | Layer 1 | Layer 2 | Layer 3 | Layer 4 | Layer 5 | Layer 6 | Layer 7 |
|---|---|---|---|---|---|---|---|
| Mineralised BIF | 50 | 50 | 50 | 50 | 50 | 1 | na |
| Unmineralised BIF | 0.0003 | 0.0003 | 0.0003 | 0.0003 | 0.0003 | 0.0003 | 0.0003 |
| McRae Shale / Nammuldi Member | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Fault | 20 | 20 | 20 | 20 | 20 | 20 | 20 |
| Dyke | 0.0002 | 0.0002 | 0.0002 | 0.0002 | 0.0002 | 0.0002 | 0.0002 |
| Mineralised Halo | 10 | 2 | 2 | 2 | na | na | na |
| Hydrated BIF / AWT Ore | 2 | na | na | na | na | na | na |
| Tertiary Valley | 5 | 5 | 5 | 5 | na | na | na |
| Wittenoom Formation / Marra Mamba Iron F. | na | na | na | 2 | 2 | 1 | 1 |

**BIF=Brockman Iron Formation*

Model derived steady state groundwater elevations are presented in Figure 4. A graph of conceptual heads (given by first dipped water level) versus modelled heads is presented in Figure 5.

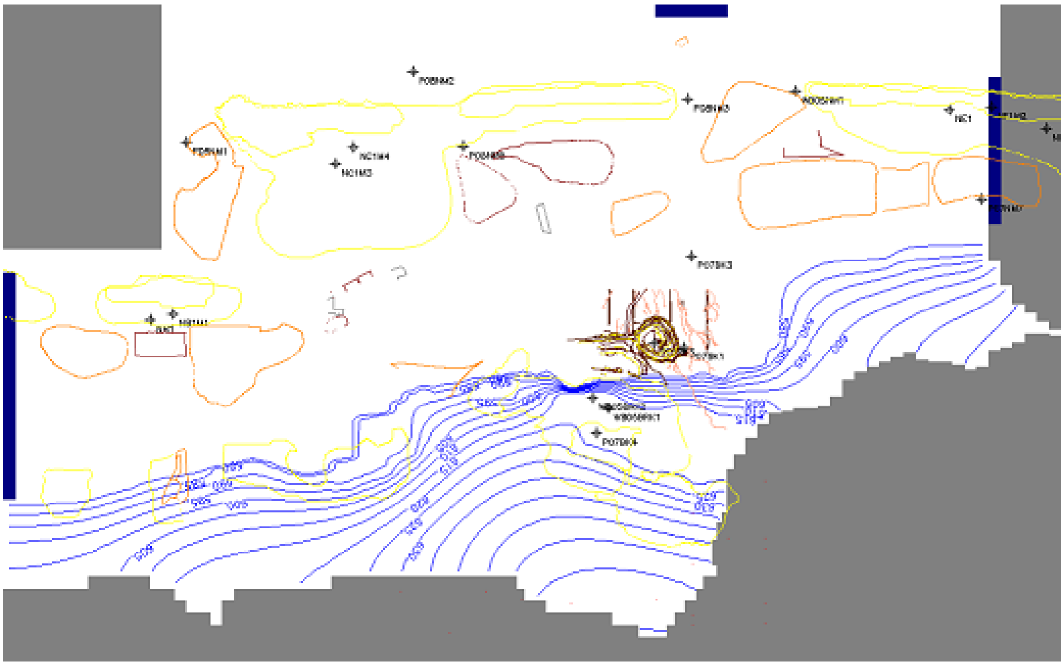


*Figure 4. Steady state groundwater level contours*

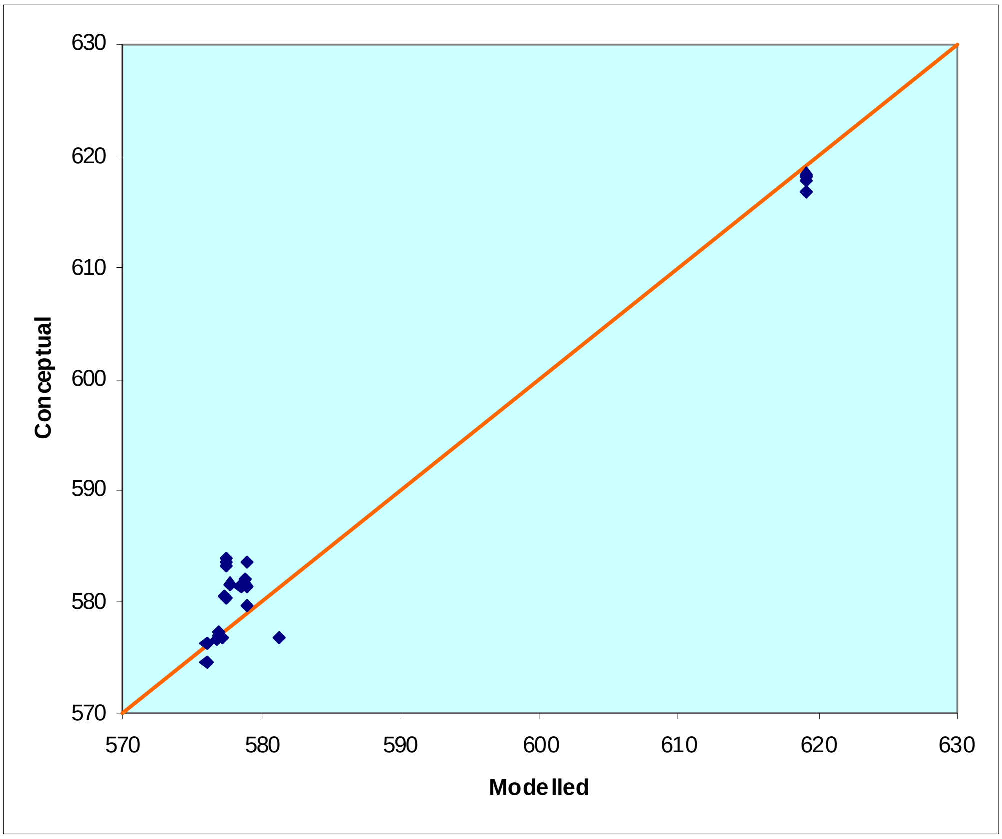


*Figure 5. Steady state calibration*

### Steady state water balance

The steady state water balance comprises two main components; rainfall recharge and outflow or inflow via constant head. Recharge from rainfall is equivalent to ~340m$^3$/a. An additional ~200m$^3$/a is made up of inflow from the constant head at RL 579 to the south of Lens E. Groundwater outflow is approximated by the constant head at RL 576 to the north (250m$^3$/a) and RL 575 to the west (290m$^3$/a) and is equivalent to ~540m$^3$/a.

Additionally a zone budget demonstrated that only ~40m$^3$/a leaked from BIF low permeability zone to the Nammuldi valley along the 7.5km section represented within the model (cumulative horizontal exchange between the valley zone and the BIF zone).

## Transient calibration

The transient calibration is dependent on time and storage. The transient calibration effectively history matches model generated water levels to observed groundwater levels based on the measured temporal stresses applied to the system. In this case the key stresses are the abstraction via the dewatering of Pit 4, surplus water discharge to Pit 5 and rainfall events. The specific time period the transient calibration covers is from the 10th January 2005 to 11th November 2008. The stress periods are broken into monthly time steps and monthly averages are used in the simulation.

The calibration is affected by adjusting storage parameters, in particular the specific yield in the case of dewatering simulations. The calibrated specific yield for the transient simulation is presented in Table2. The spatial distribution of the zones is identical to that of the hydraulic conductance terms.

*Table 2. Specific yield of delineated zones*

| Zones | Layer 1 | Layer 2 | Layer 3 | Layer 4 | Layer 5 | Layer 6 | Layer 7 |
|---|---|---|---|---|---|---|---|
| Mineralised BIF (Ore) | 0.28 | 0.28 | 0.28 | 0.28 | 0.05 | 0.02 | na |
| Unmineralised BIF* | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 |
| McRae Shale / Nammuldi Member | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Fault | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Dyke | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 |
| Mineralised Halo | 0.2 | 0.2 | 0.2 | 0.2 | na | na | na |
| Hydrated BIF/ AWT ore | 0.2 | na | na | na | na | na | na |
| Tertiary Valley | 0.05 | 0.02 | 0.02 | 0.05 | na | na | na |
| Wittenoom Formation | na | na | na | 0.01 | 0.01 | 0.01 | 0.01 |

**BIF=Brockman Iron Formation*

The calibration hydrographs for the key BS2 bores are presented in Appendix B. In general a good history match occurred with the exception of two key bores; PZ05BRK001 and PZ05BRK004. These bores responded with increasing head to the Pit 5 recharge from using surplus dewatering water and indicate that the groundwater model under predicts recharge from this event. Additionally the impact of the monthly discretisation of head levels in the pit lake create a “step like” feature in the model output that does not replicate observed levels.

### Rainfall recharge

For the transient calibration the monthly rainfall recharge total was calculated from cumulative daily totals for each month. The transient calibration retained the same two spatial zones but was applied in monthly time steps and was given as 1% and 0.1% of the cumulative monthly rainfall where observed daily rainfall exceeded observed daily evaporation by at least 20mm.

### Dewatering

Dewatering of Pit 4 is represented by using the MODFLOW Well package. The mean monthly abstraction rate is applied uniformly across the screened layers. As upper layers go dry the abstraction is divided evenly among the remaining saturated layers to ensure the model represents total observed groundwater abstraction.  Daily abstraction rates and cumulative rates for the two bores are presented in Figure 6.

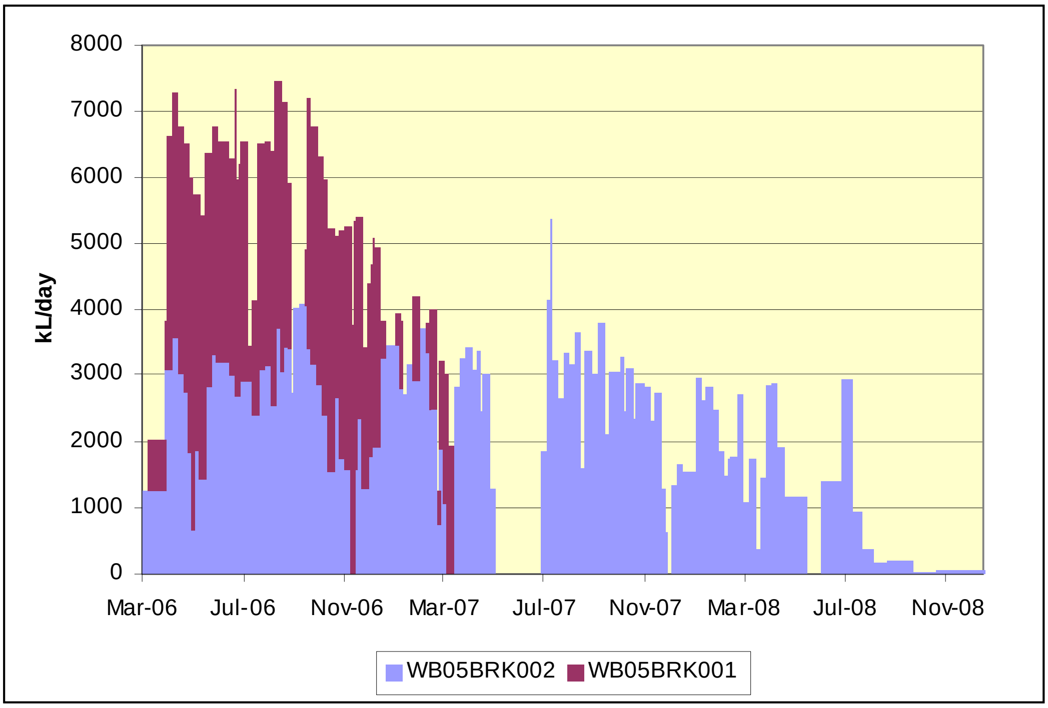


*Figure 6.  Daily abstraction rates for the two dewatering bores near Pit 4*

The total dewatering measured was checked against the model calculated dewatering using the model budget data and was matched 100%.

## Surplus water management

Groundwater abstracted from Pit 4 was used by the operations when ever practical. However there was generally an over supply of water owing to the required dewatering rate and so surplus water was discharged in the nearby abandoned Pit 5 where it recharged the valley groundwater system.

Pit 5 recharge via surplus water discharge was represented in the model using the MODFLOW General Head Boundary package.  Head in Pit 5 was used to allow water into the groundwater model based on an assumed conductance.  The head in the lake was measured on three occasions and thus was extrapolated for the majority of the transient calibration.

The Pit 5 RL was assumed to be 590m.  Pit 5 contained blast holes on a ~10 x 10m spacing.  As such a high conductance (10m/d) was used to allow water to ingress to the groundwater model.  Water was input direct to Layer 3, by passing Layer 2 to circumvent re-wetting and associated numerical stability and mass balance errors.  The rate of water input to the groundwater flow system can be taken from the model balance and is plotted against the rate of discharge in Figure 7.  This demonstrates the rate of infiltration predicted in the model is relatively steady.  Once a head is established in the Pit via discharge, the infiltration is limited by the conductance term as Pit 5 is above the regional watertable and as such the hydraulic gradient is equivalent to unity and would not vary with time or discharge volume.

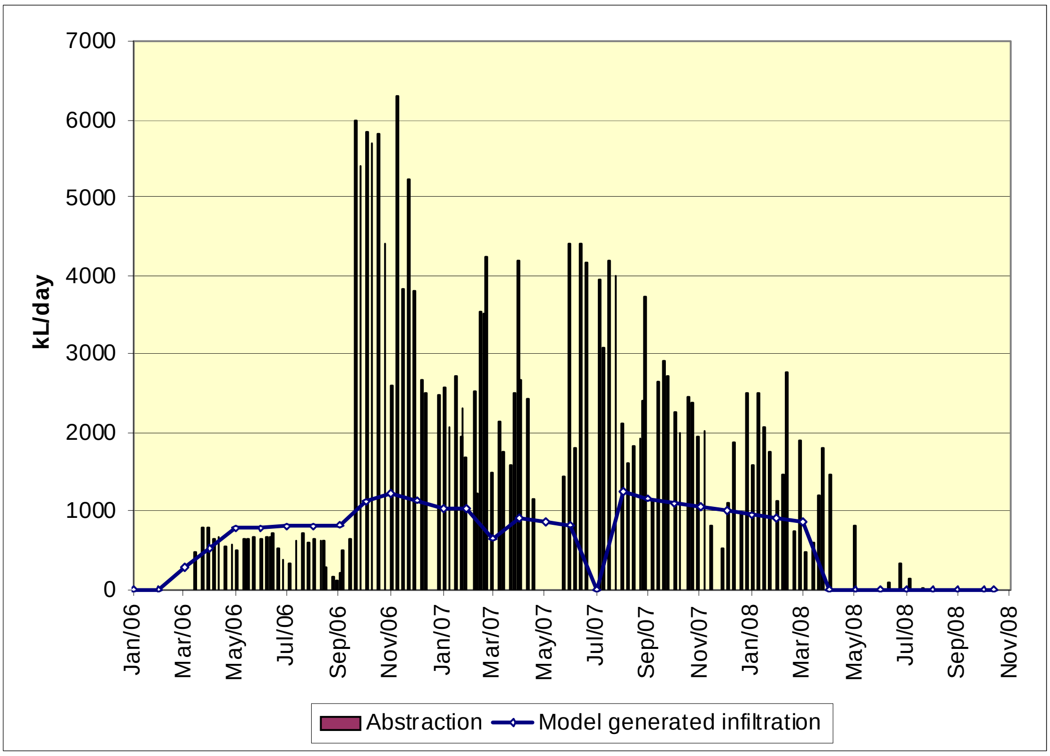


*Figure 7. Model generated infiltration beneath Pit 5 given assumed Pit 5 lake head and conductance terms.*

## Mass balance

The main components of the model balance have been described above and are presented graphically in Figure 8. Additionally the overall mass balance error from the transient model solution was 0.00%.

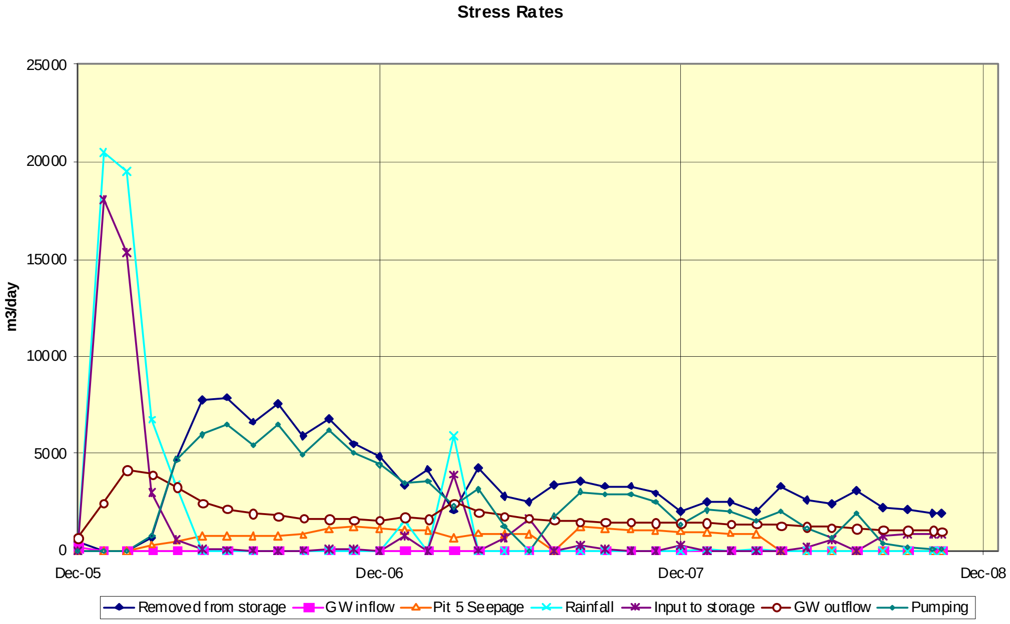


*Figure 8. Transient model monthly water balance. A significant recharge event occurred at the commencement of modelling, after which the principal movement of groundwater is via abstraction and removal of groundwater from storage.*

# Conclusions

The 2005 Aquaterra groundwater model has been updated via construction of a steady state model and transient model calibrated to dewatering of the Pit 4 ore body to 580 RL. In addition, the model included representation of discharge of the surplus dewatering water to Pit 5; but could not replicate the observed head level rise. The model does not include any representation of groundwater abstraction for water supply for the Greater Nammuldi operations across the valley.

The existing conceptual model of separate groundwater flow systems between the BS2 and Nammuldi valley groundwater flow system has been confirmed primarily through observations of the extent of draw down as a result of dewatering and “draw up” as a result of discharge to Pit 5. Based on the steady model it is predicted approximately 6m$^3$/day/km (i.e. a very negligible amount) is transferred across a 7km front between the Brockman Syncline and the Nammuldi valley.

To improve understanding and aid calibration a series of monitoring bores are necessary to the south of Pit 4. In addition, age dating (CFC & C$^{14}$) of Pit 4 groundwater would assist in understanding the percentage of modern recharge contributing to the groundwater flow system of the BS2 pit area. This would in turn aid with understanding potential outcomes of mine closure management measures.

The current model is deemed sufficient to use in a predictive mode to understand further dewatering required for the Phase 2a (lateral extension of Pit 4) and 2b (deepening of Pit 4 to 530 RL) expansions at BS2.

# References

Aquaterra, 2007, Brockman Syncline 4; Dewatering and water supply bore installation: Unpublished Report for RTIO Expansion Projects, September 2007.

Cymod, 2004, Hamersley iron assessment of dewatering requirements, Nammuldi Iron ore mine. Unpublished Report for Hamersley Iron Pty. Ltd: April 2004: RTIO-PDE-0031796.

EPA, 2000, Nammuldi – Silvergrass Iron ore project, 55km northwest of Tom Price. Hamersley Iron Pty. Ltd. Report and recommendations of the Environmental Protection Authority. Assessment No. 1247. Bulletin 997, October 2000. RTIO-PDE-0020530.

Evans & Storey, 2005, Brockman BS2 Lower Hydrogeological Report: Unpublished Report for Pilbara Iron, June 2005. RTIO-PDE-0020528_3

Frost-Barnes & Boyle, 2009, Developed Resources Handbook, End of Year 2008: Confidential Report for RTIO.

Hamersley Iron, 1991, Report on study of water levels, Nammuldi Deposit Lens A to G for Hamersley Iron Pty. Ltd. GDSR 4180.

Hamersley Iron, 2000, Consultative Environmental Review. Published Report; Hamersley Iron Pty. Ltd. February 2000. GDSR 4268.

Layton Groundwater Consultant's, 1978, Nammuldi Project Dewatering. Review and Evaluation for Hamersley Exploration Pty. Ltd. Unpublished Report; 1978. GDSR 0817.

Liquid Earth, 2004, Nammuldi dewatering model update 2004. Unpublished Report for Hamersley Iron Pty. Ltd: 2004: GDSR 4530.

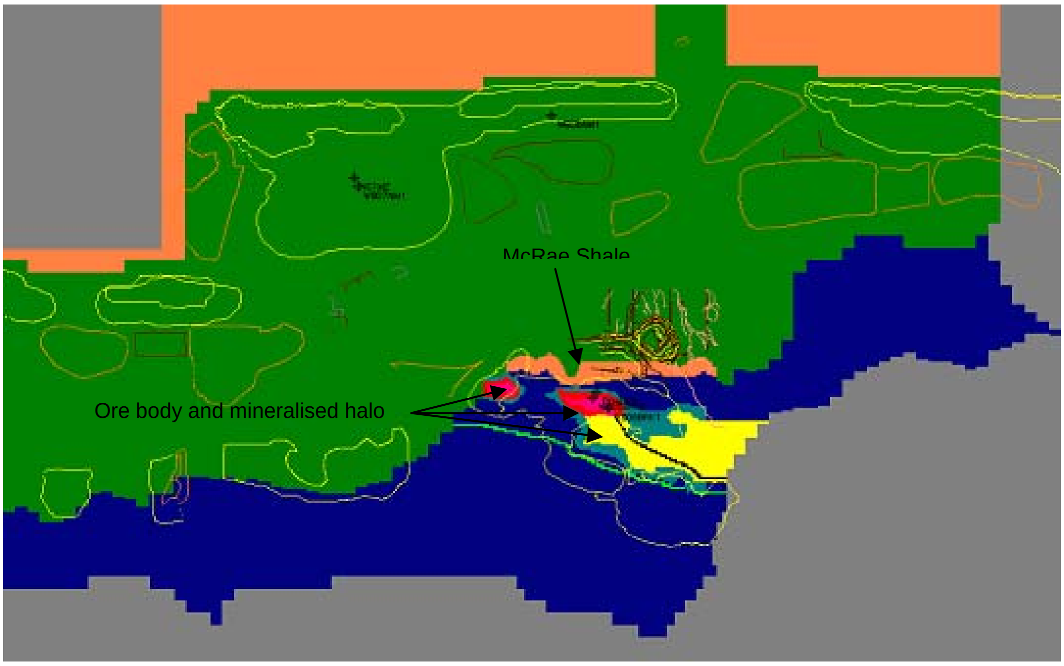
PPK, 1998. Preliminary assessment of groundwater issues at the Nammuldi, Homestead and Silvergrass Deposits. Unpublished Report for Hamersley Iron Pty. Ltd: 1998

PPK, 1999, Nammuldi/Silvergrass East Hydrogeological Investigations. Volume 1 & 2: Unpublished Report for Hamersley Iron Pty. Ltd: 1999; RTIO-PDE-0031800 & RTIO-PDE-0031849

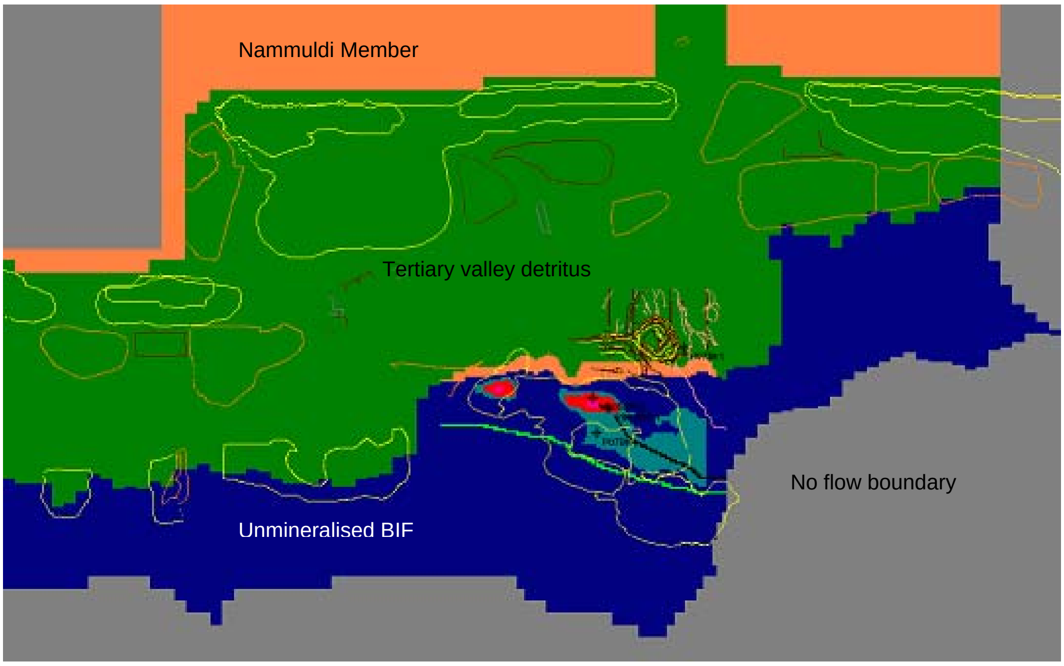
URS, 2008, Nammuldi Hydrogeological Review: Unpublished Report prepared for RTIO Expansion Projects; 2008.

# Appendix A

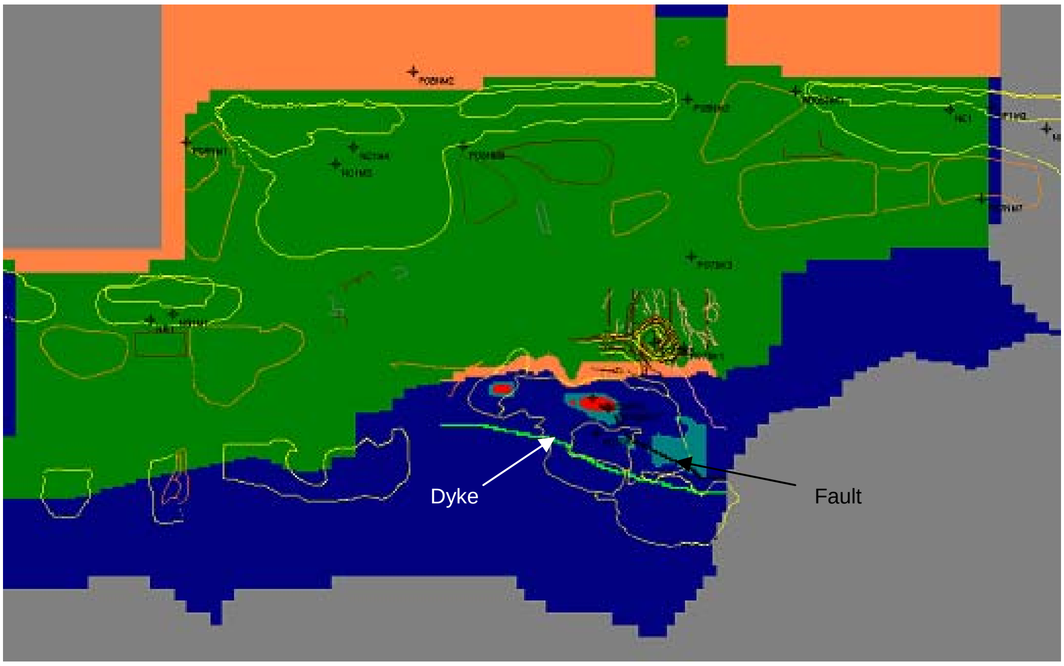
## Spatial distribution of parameters



*Layer 1*



*Layer 2*



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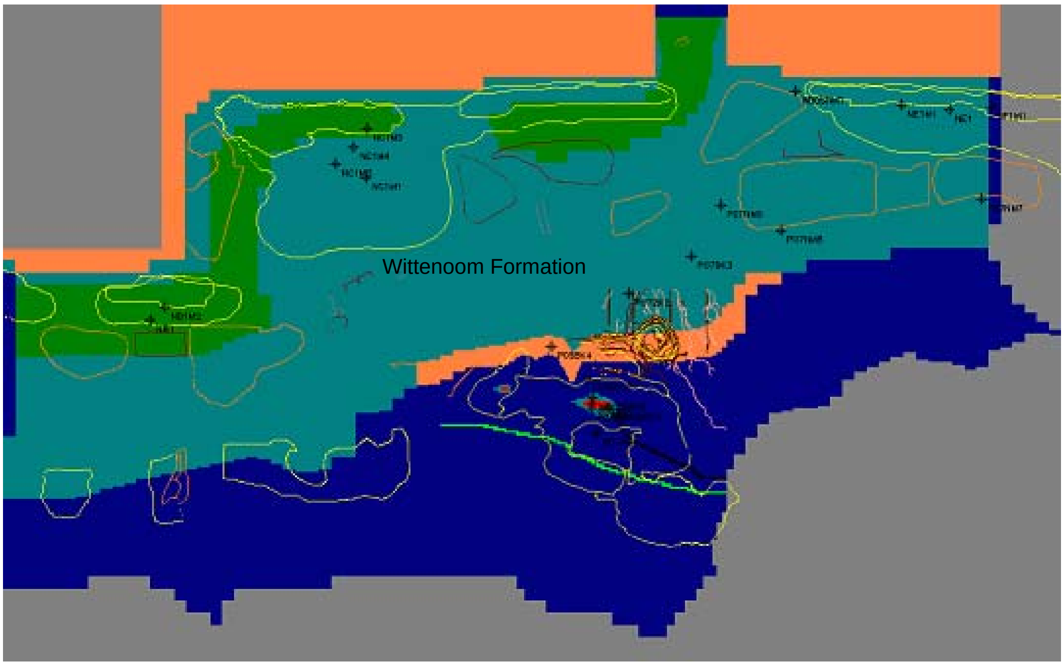

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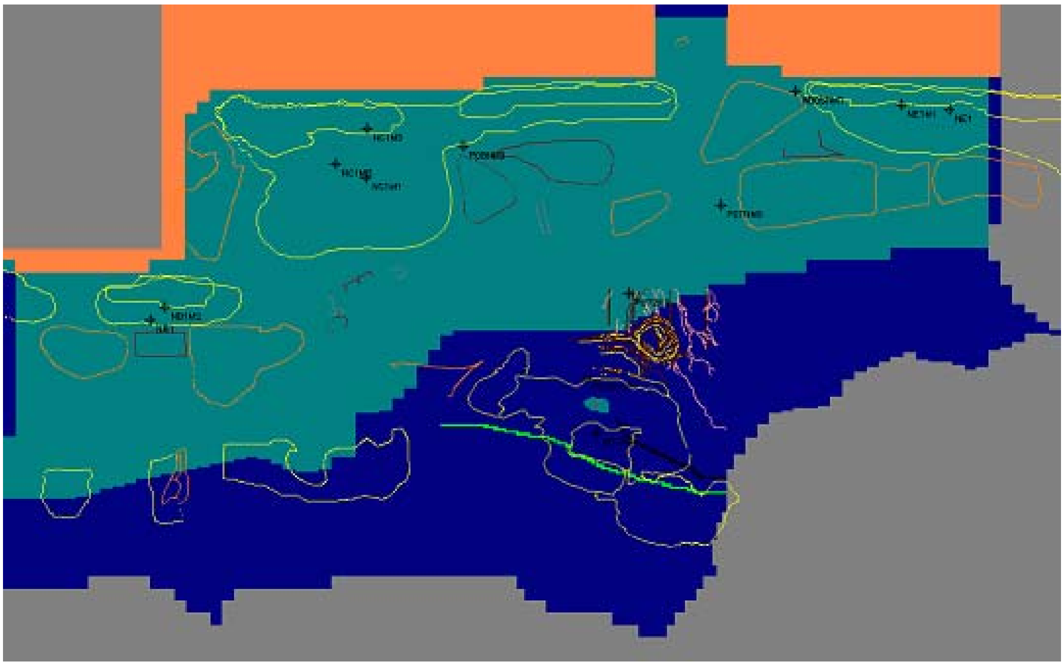
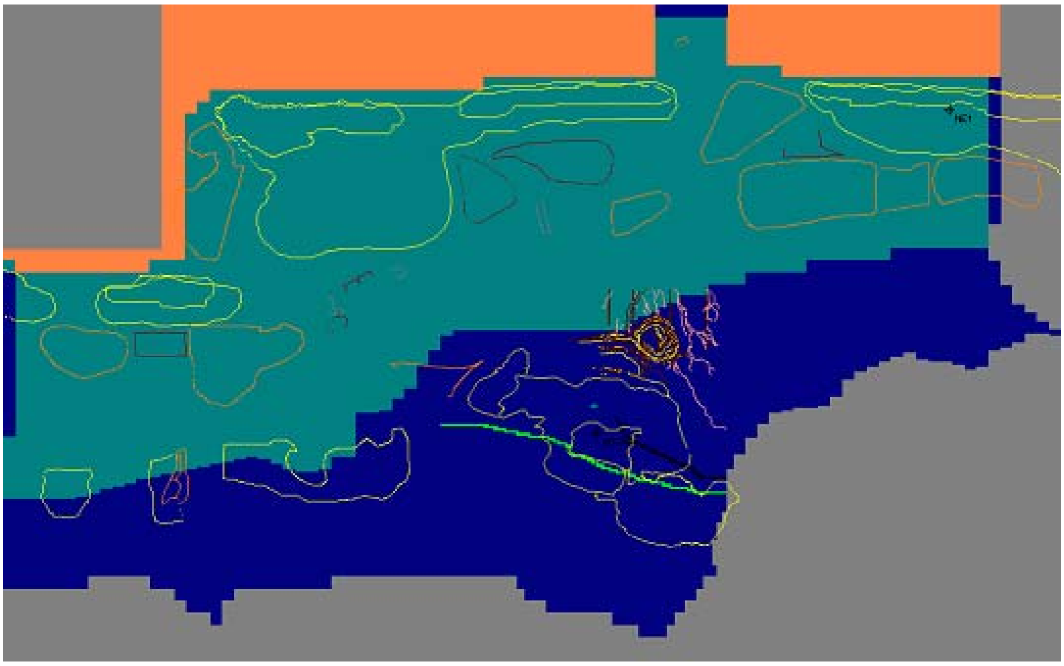
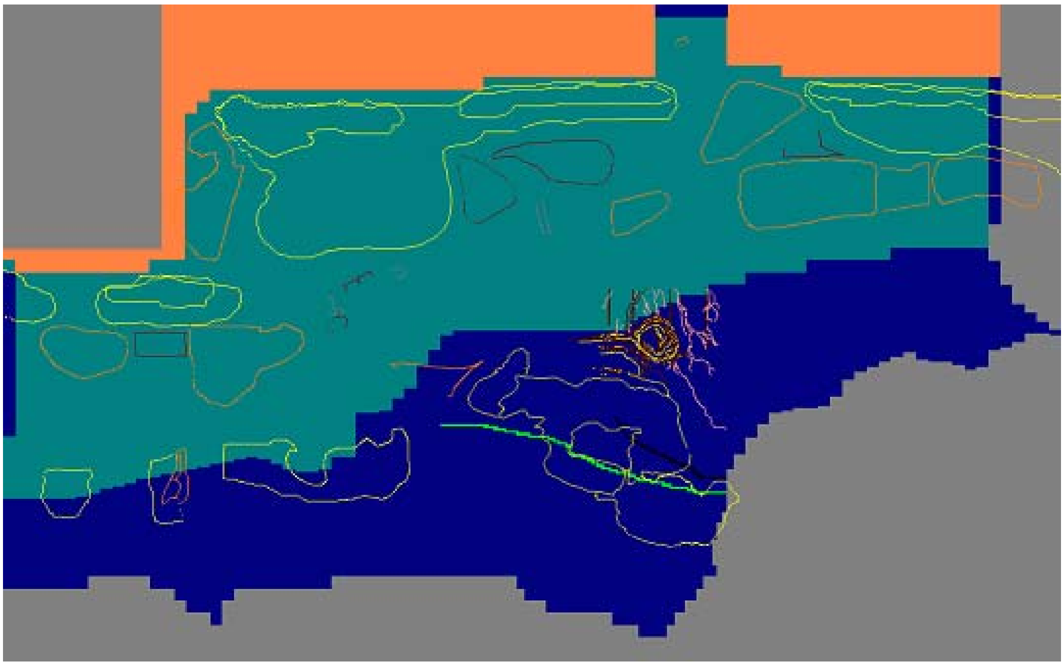


*Layer 5*

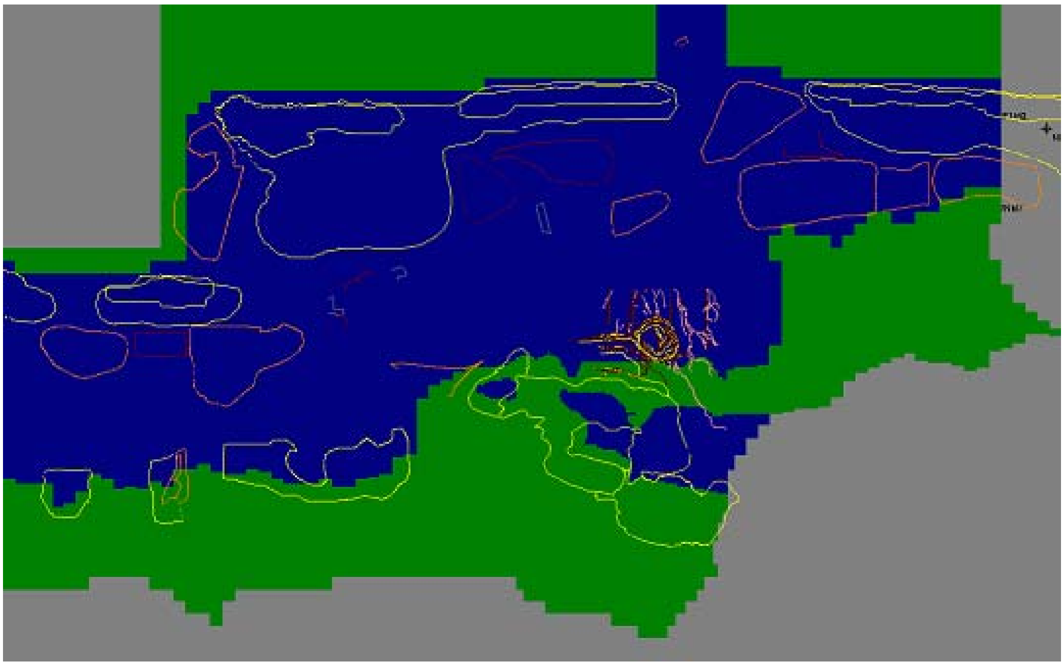


*Layer 6*



*Layer 7*

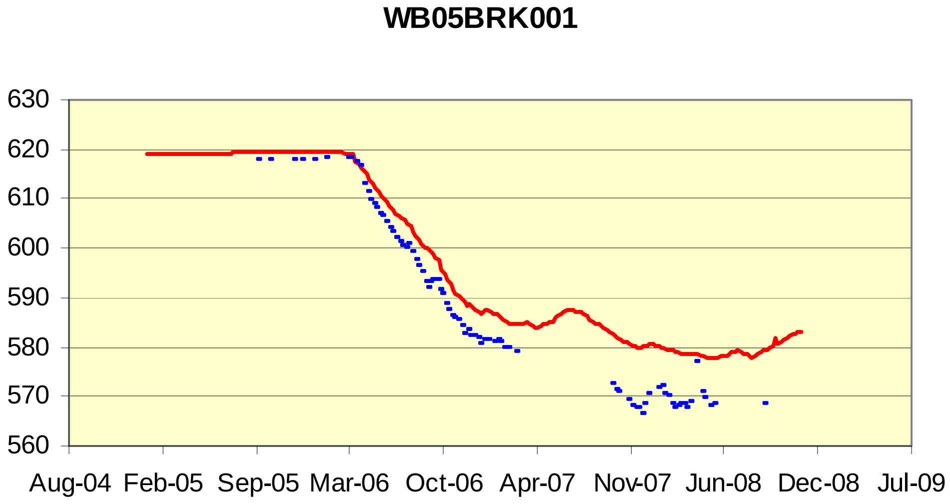
# Recharge zones

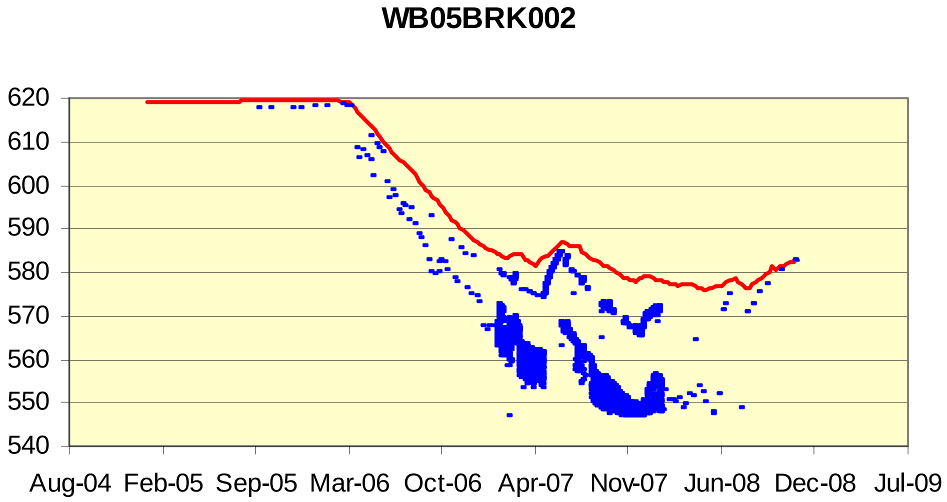


*Recharge zones 1 and 2 (Blue = 1% MAR, Green 0.1% MAR).   MAR = Monthly average rainfall*

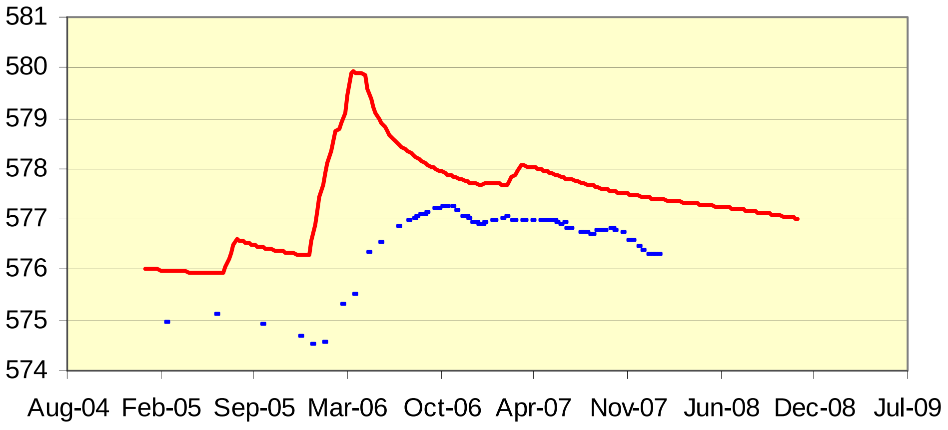
# Appendix B

Hydrographs of model generated levels are represented by red lines, blue dashes are observed groundwater levels over time.

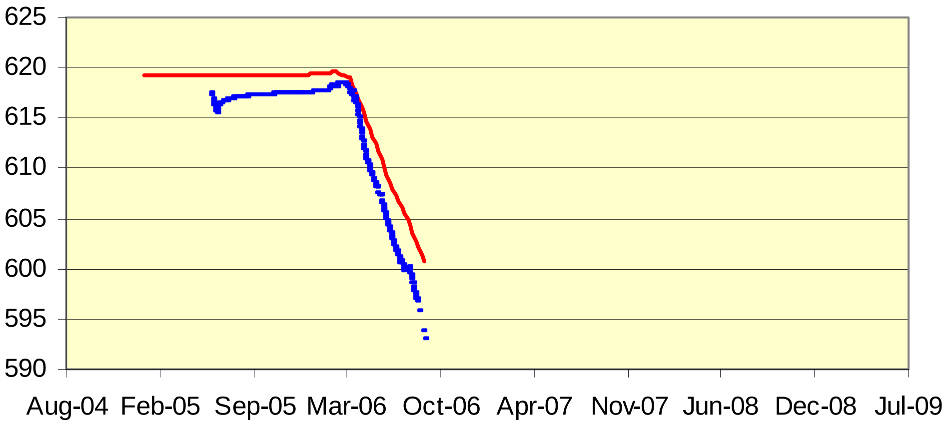




## NM1B1



## PZ04BRK001



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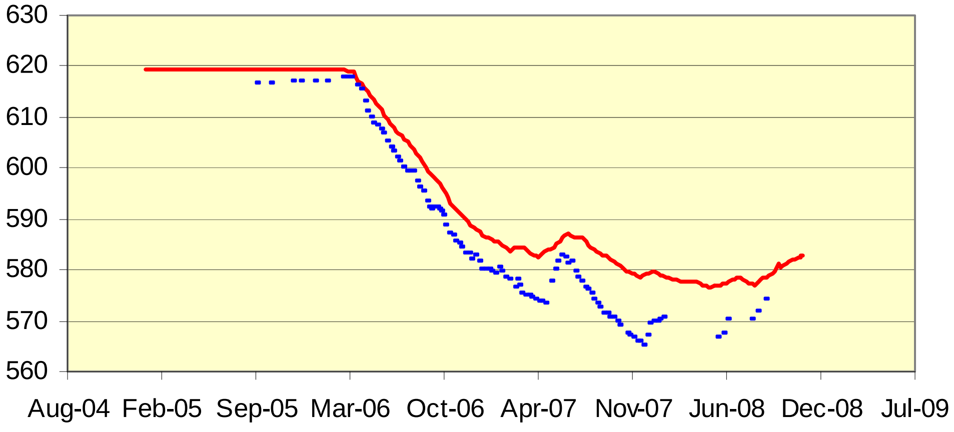
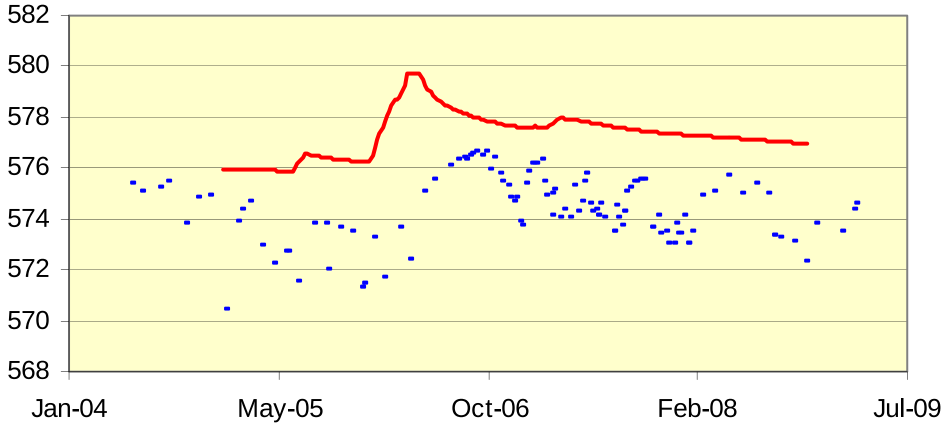


## NM1B2



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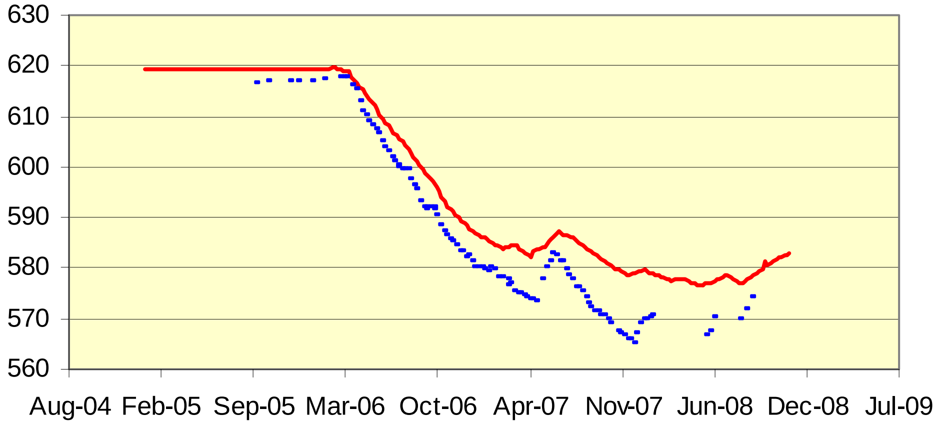

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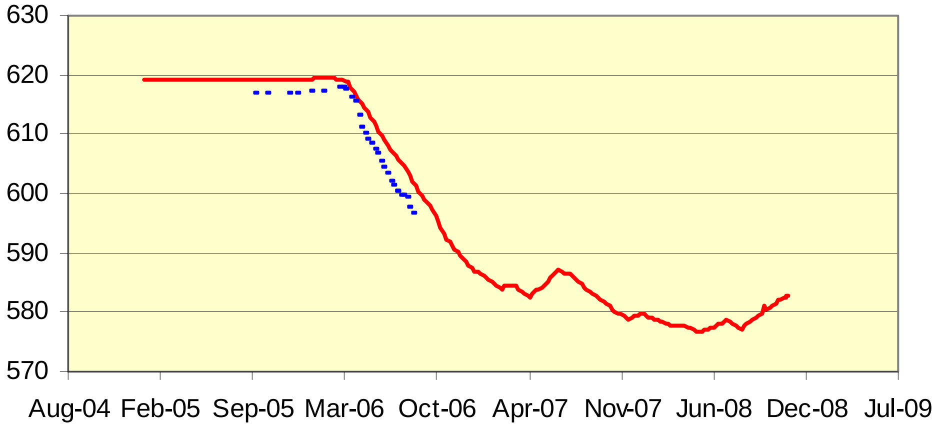
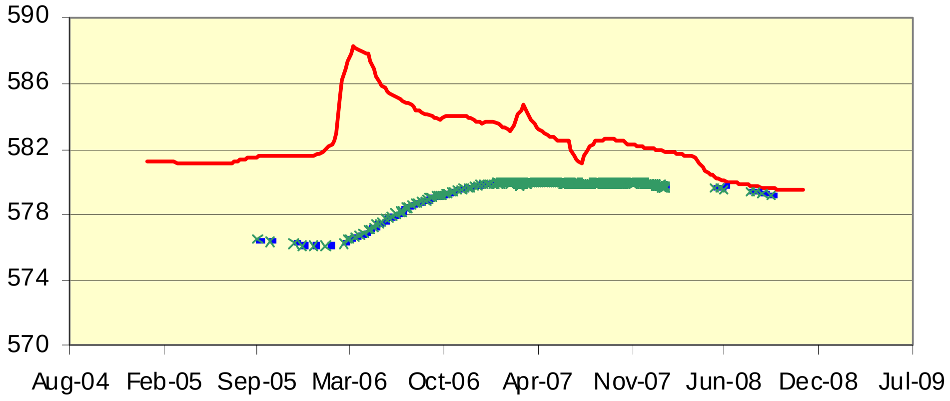


## PZ05BRK001S & D



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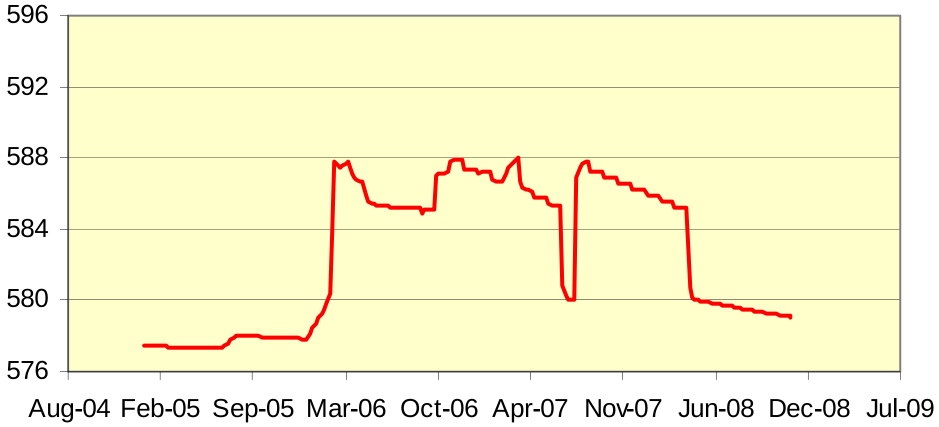
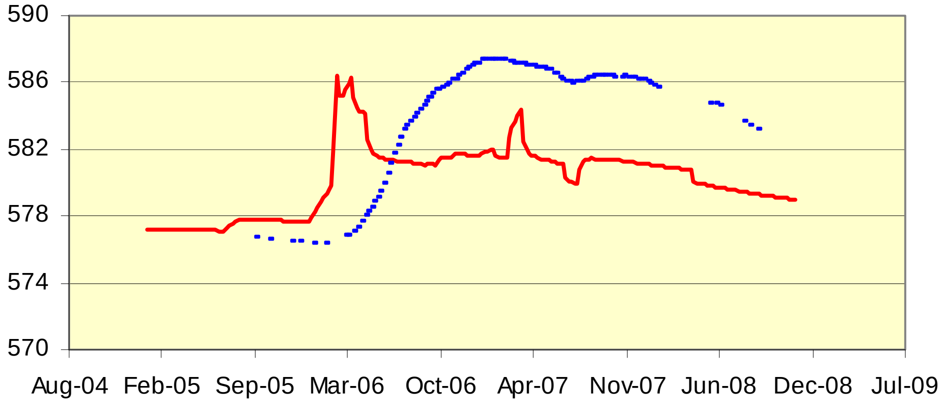
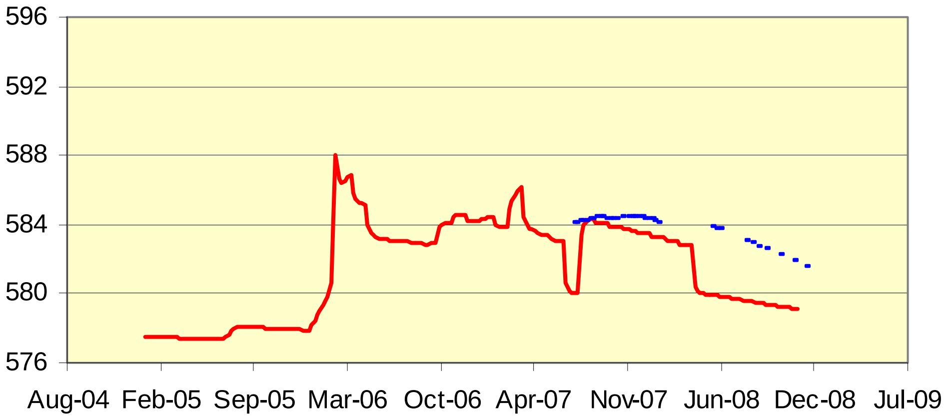


## PZ05BRK004



**P07BK001**



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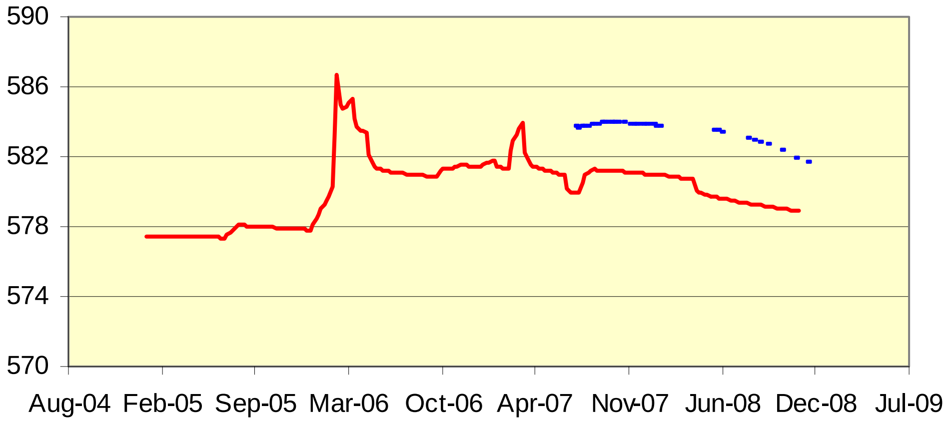

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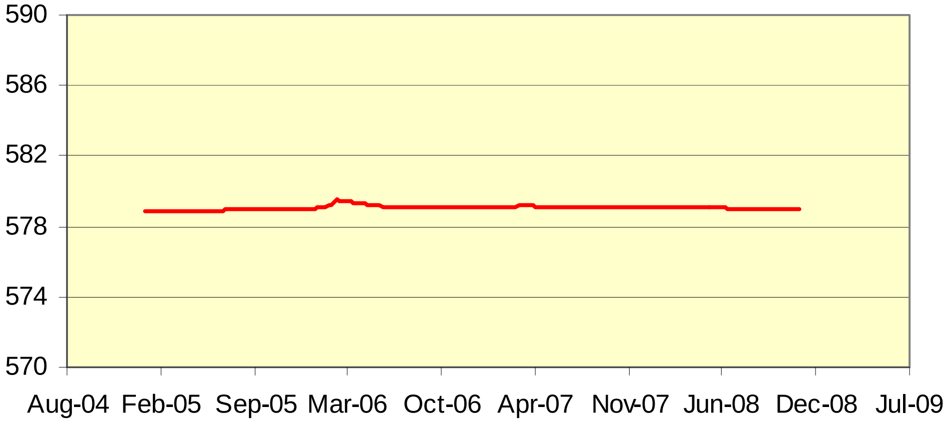

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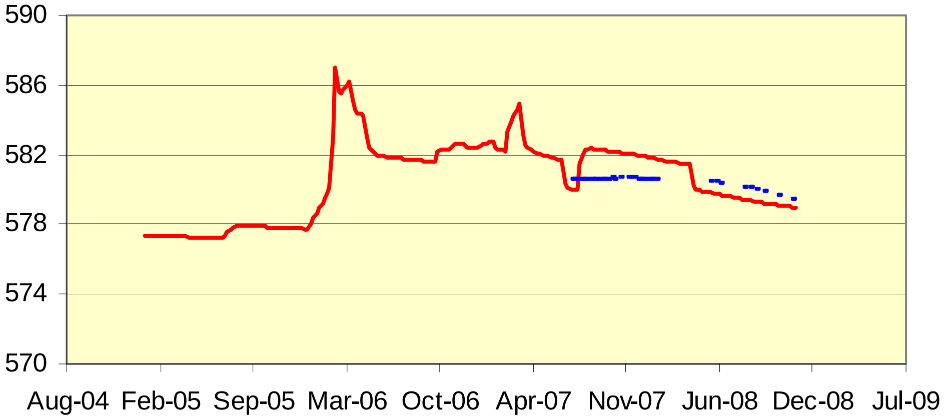

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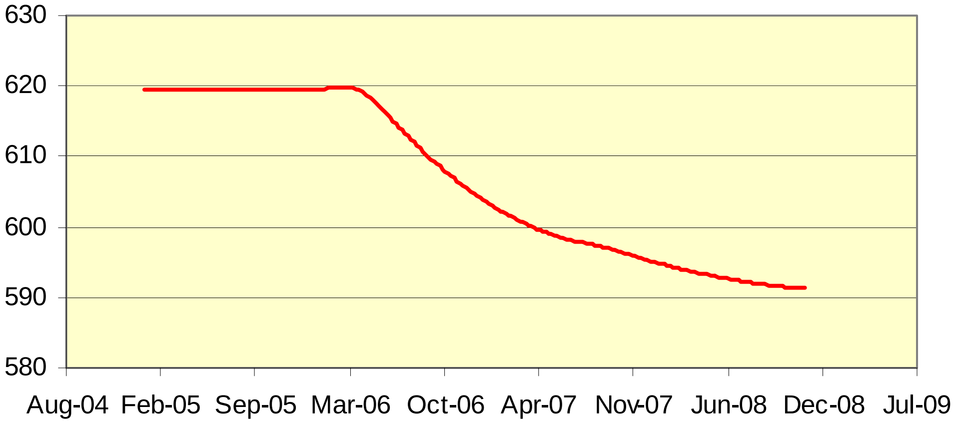

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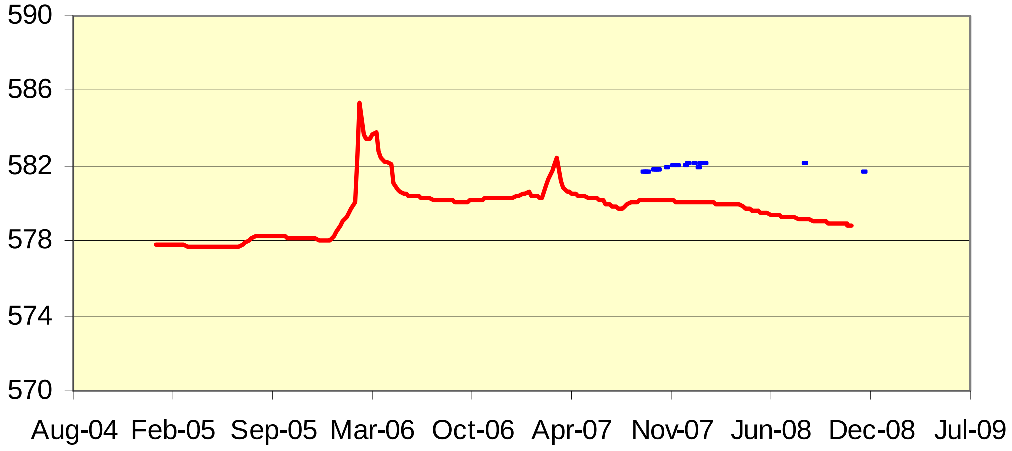

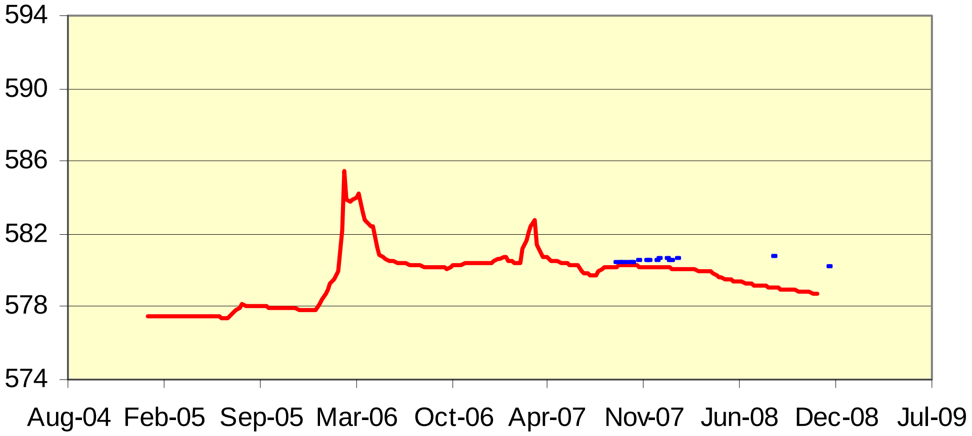

**P07NM009**

594
590
586
582
578
574
Aug-04
Feb-05
Sep-05
Mar-06
Oct-06
Apr-07
Nov-07
Jun-08
Dec-08
Jul-09

## Key Bore Locations