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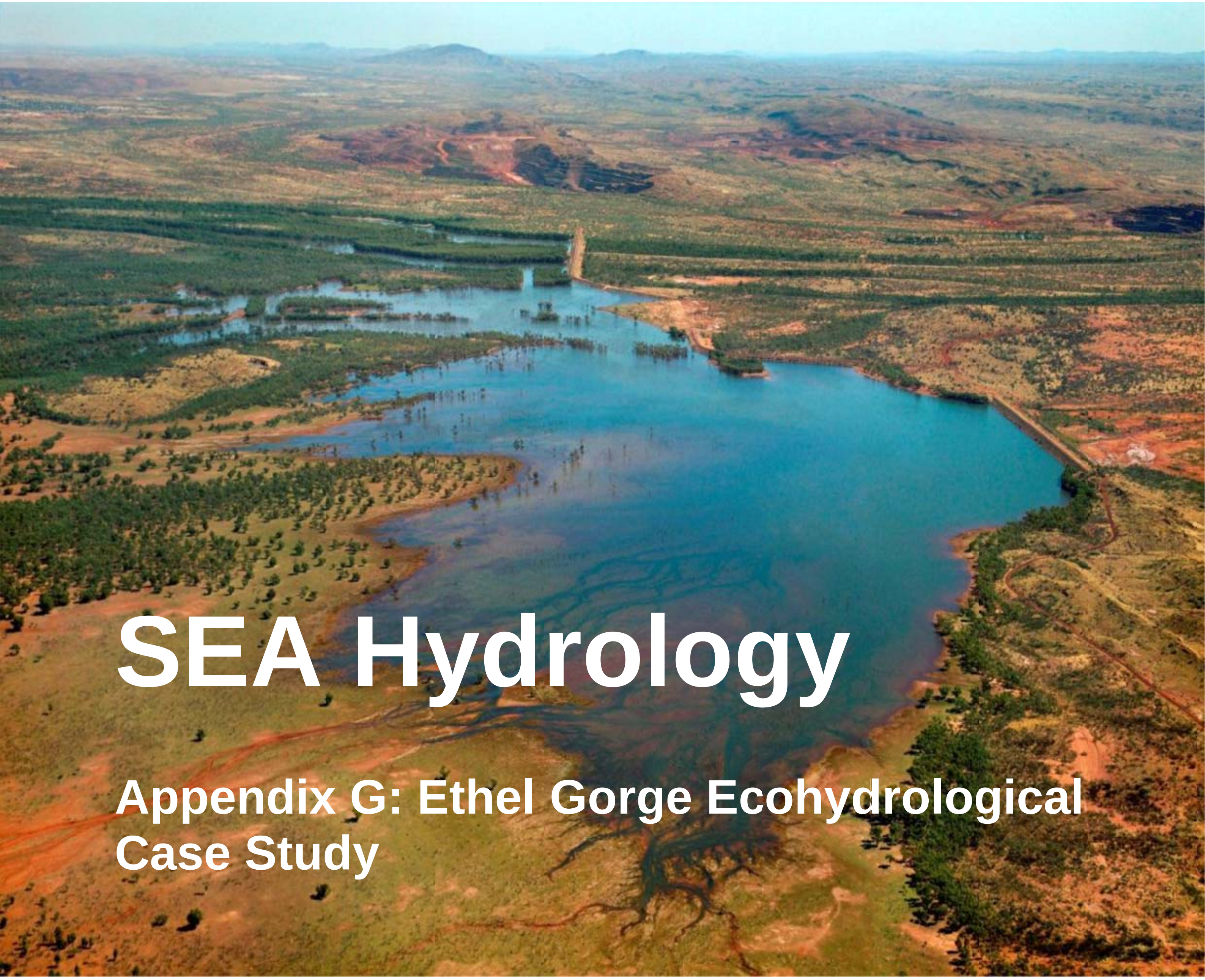

SEA Hydrology

Appendix G: Ethel Gorge Ecohydrological Case Study

Statement of limitations

This report has been prepared solely for the purposes of informing environmental impact assessment pursuant to the Environmental Protection Act 1986 (WA) and Environment Protection and Biodiversity Conservation Act 1999 (Cth) and is not intended for use for any other purpose. No representation or warranty is given that project development associated with any or all of the disturbance indicated in this report will actually proceed. As project development is dependent upon future events, the outcome of which is uncertain and cannot be assured, actual development may vary materially from this report.

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The Ethel Gorge ecohydrological case study demonstrates the application of adaptive management techniques maintain hydrological conditions within a threshold range and to mitigate potential impacts within historical baseline trends. The case study prepares the business for various and changing dewatering and surplus water scenarios and, where necessary, manages the hydrological changes associated with these activities to avoid potential impacts to ecohydrological receptors.

The Ophthalmia aquifer is the main habitat for the Ethel Gorge stygobiont community and some riparian vegetation may also be partially groundwater dependent. The three main threatening processes include groundwater drawdown associated with mine dewatering, waterlogging (water saturation within the root zone) and increased groundwater salinity. The latter two processes result from the discharge of surplus dewatering water into Ophthalmia Dam.

The Ophthalmia aquifer has historically been subjected to natural and mining-related hydrological changes, but preventative and corrective controls have been in place to manage water levels and salinity concentrations. The preventative measures entail returning surplus dewatering water back to the aquifer by means of discharge to the Ophthalmia Dam. The corrective action controls comprises the Ophthalmia Dam Managed Aquifer Recharge (MAR) facility which includes the dam, infiltration basins, recharge ponds and Ophthalmia borefield. The monitoring data suggests that the receptors have not been significantly affected by the historical changes and hydrological changes have been within the threshold limits of the receptors.

OB23 has been mined out and is currently under care and maintenance. There are currently four orebodies being mined with an additional five orebodies to be mined within the 30% development scenario. Only OB23 has a direct hydraulic connection with the Ophthalmia aquifer, but there may be indirect hydraulic connections between certain orebodies and the Ophthalmia aquifer associated with tributary palaeochannels, dolomite aquifers or geological structures.

Numerical modelling indicates that the infiltration from the Ophthalmia Dam MAR facility will offset groundwater drawdown impacts from future mining operations. However, there are uncertainties about the degree of hydraulic connection between some orebodies and the Ophthalmia aquifer, which need to be validated as part of ongoing studies, consistent with the adaptive management approach. If groundwater drawdown is more significant than anticipated, infiltration at the existing recharge ponds, infiltration basins and targeted injection bores may be used to minimise impacts on the receptors.

Numerical modelling also indicates no significant impacts related to rising groundwater levels from the discharge of surplus dewatering water to Ophthalmia Dam. If the surplus dewatering is significantly higher than anticipated, rising groundwater levels may lead to waterlogging in places which may affect the health of a portion of the riparian vegetation. Rising groundwater levels may be controlled through increased abstraction from water supply bores and the installation of engineering structures, such as subsurface drains.

The water and salt balance modelling suggests that salinity concentrations in the Ophthalmia aquifer will remain mostly within the historical ranges, but at some locations, salinity concentrations may increase to about 30% above historical maximum ranges. The operating strategy of the dam is predicted to exert a strong influence on groundwater salinity concentrations.

The increase in groundwater salinity is likely to be within the tolerance thresholds of the stygofauna community. However, as a precautionary approach, historical ranges rather than species tolerance and adaptability has been adopted for the threshold values. The elevated salinity concentrations are predicted to occur in 10 to 15 years' time, providing an adequate timeframe for progressive technical studies to address these uncertainties within the framework of BHP Billiton Iron Ore's adaptive management approach.

As a contingency measure, BHP Billiton Iron Ore has considered other surplus water management options should discharge of surplus dewatering water into Ophthalmia Dam results in undesirable effects. These options include the controlled discharge of surplus dewatering water into Jimblebar Creek and return of surplus dewatering water to the groundwater through other MAR measures.

Ethel Gorge Ecohydrological Case Study continued

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Introduction

The Ethel Gorge ecohydrological case study presents an example of the implementation of the proposed Water Regional Management Strategy (Water RMS) for the purpose of assessing and managing potential impacts on ecological receptors associated with mining-related changes to the groundwater and surface water regime in the Ethel Gorge project area.

The case study demonstrates the application of adaptive management techniques to maintain hydrological conditions within a threshold range and to mitigate potential impacts to within historical baseline trends. The case study includes the following components.

1. A description of the **adaptive management framework** consistent with the proposed Water RMS.
2. A description of the **project domain and ecological assets**, including the baseline, historical and hydrological conditions, ecological receptors and their tolerances to hydrological change
3. A **change assessment** examining potential hydrological changes caused by future BHP Billiton Iron Ore mining operations and potential impacts on ecological receptors. Where the change assessment is predicted to exceed the receptor tolerances, a range of **mitigation and management measures** have been assessed to avoid, minimise and manage the potential impacts
4. **Monitoring, review and corrective actions** in support of the overall management approach. Corrective actions may be considered and implemented in the event that thresholds are exceeded.

An adaptive management approach for the Ethel Gorge case study represents a summarised application of the proposed Water RMS, which is illustrated in Figure 1. The approach prepares the business for various and changing dewatering and surplus water scenarios and where necessary, manages the hydrological changes associated with activities including potential impacts to the Ethel Gorge stygobiont community, riparian vegetation and water resources.

The approach demonstrates that BHP Billiton Iron Ore operations can undertake various abstraction and discharge scenarios within the region, whilst effectively achieving the necessary hydrological conditions to sustain the key receptors by using a range of feasible and scalable management and mitigation controls. These controls are designed to prevent and mitigate impacts and offset the water footprint.

It is a staged and iterative process, which is responsive to the specific water requirements of the key receptors. Whereby decision making is aligned to outcome-based objectives that reflect hydrological baselines, assessment of potential hydrological changes (predicted and actual), predicted impacts on receptors, monitoring of change, and the outcomes of management actions where applied. The management approach is therefore progressively developed and refined, through the accumulation of scientific knowledge and measured outcomes.

The adaptive strategy is underpinned by a risk-based approach that focuses on the key assets of importance, and considers scientific uncertainty and outcome-based objectives. Early-warning triggers and thresholds are selected to ensure that monitoring is targeted to key hydrological change processes, in order to mitigate and manage potential impacts on receptors.

The proposed Water RMS is underpinned by current scientific understanding of the receptors' hydrological dependency and the hydrological setting, which collectively form the basis of predictive modelling. This understanding is expected to iteratively develop and evolve over time as more monitoring data is accumulated and measured hydrological changes can be compared with modelling predictions. In recognition of uncertainties related to predictive modelling, a precautionary approach for developing thresholds is adopted.

Ethel Gorge Ecohydrological Case Study continued

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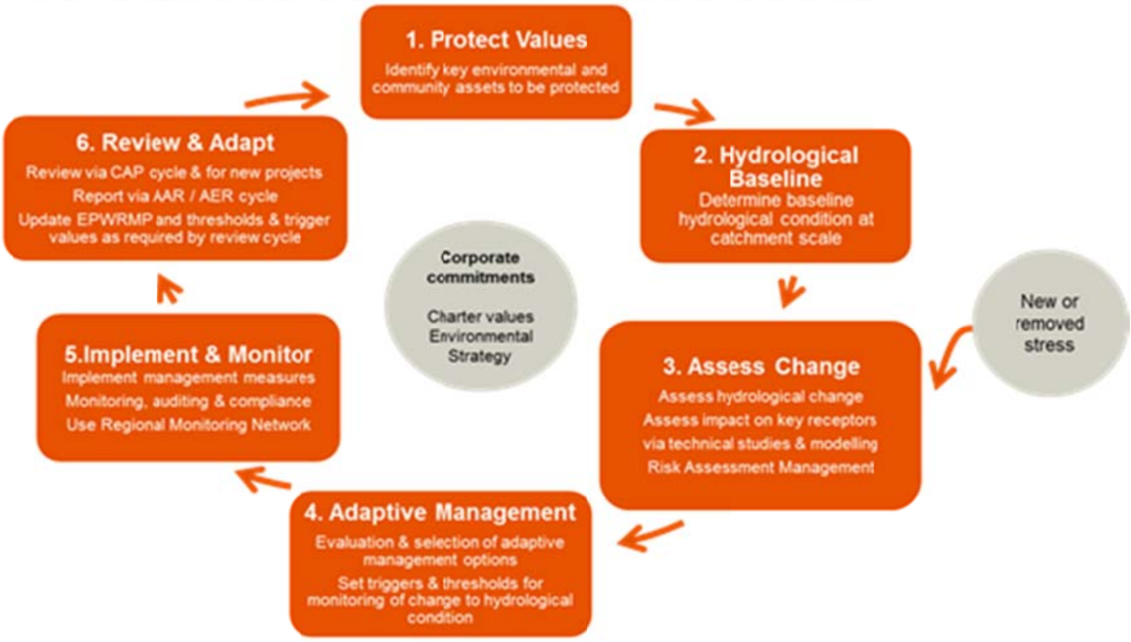

Figure 1: Schematic Presentation of the proposed Water RMS

Project domain and ecological assets

The case study provides a summary of the physical and ecological aspects at the Ethel Gorge area. A detailed description of the Eastern Pilbara ecohydrological conceptualisation is provided by RPS (Appendix C) and further supporting documentation is provided in Section 1.

Ethel Gorge is located on the Upper Fortescue River where it cuts through the Ophthalmia Range, approximately 15 km northeast of Newman and directly downstream of the confluence of several creek systems (Map 1). The Ophthalmia Dam is a purposely designed managed aquifer recharge (MAR) structure, located about 3 km upstream of Ethel Gorge. The dam captures and retains surface water flows in the Fortescue River which then infiltrates into the ground, or are discharged through controlled release to infiltration basins to replenish aquifers beneath the dam, from where groundwater is abstracted. Key features of Ethel Gorge and the Ophthalmia Dam MAR system is shown in Figure 2.

Ethel Gorge Ecohydrological Case Study continued

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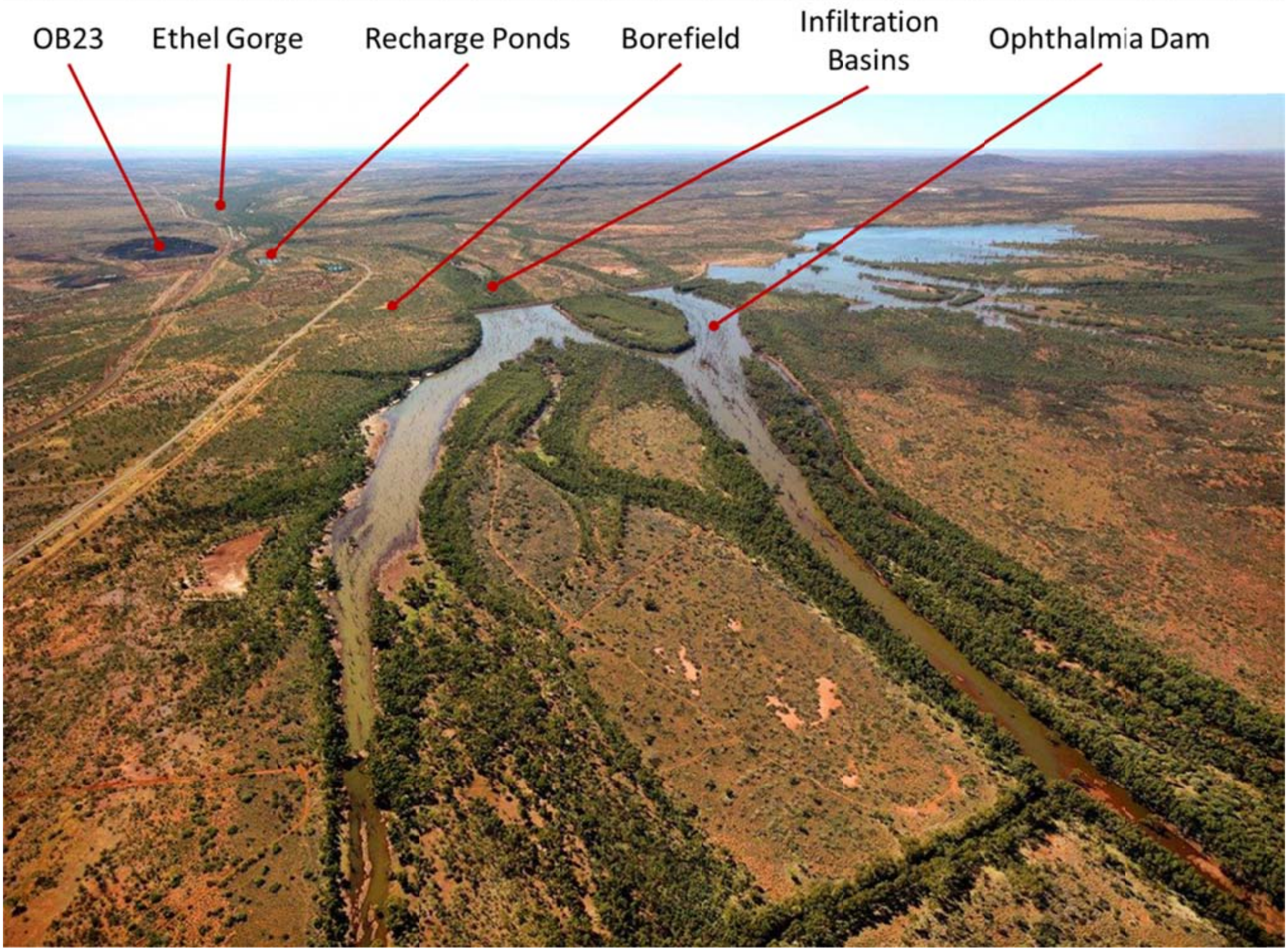

Figure 2: Key features of Ethel Gorge area and Ophthalmia Dam MAR system

BHP Billiton Iron Ore has a mining lease over Ethel Gorge (AML7000244) and owns and operates the Ophthalmia Dam and Ophthalmia Borefield, which provides potable water to the Newman Township. BHP Billiton Iron Ore has been operating in the region for more than 40 years and current operations include the Whaleback, Eastern Ridge and Jimblebar mining areas.

Hydrology and hydrogeology

Hydrology

Four creek systems flow into the Upper Fortescue River, upstream from Ethel Gorge (Map 2). The Fortescue River, Whaleback and Warrawanda Creeks flows into Ophthalmia Dam; while, Homestead and Shovelanna Creeks enter the Fortescue River downstream of Ophthalmia Dam. Upstream from its entry into Ethel Gorge, the Fortescue River has a total catchment area of 4 872 km^2. The catchment area upstream from Ophthalmia Dam is 4 319 km^2 representing 89% of the total catchment upstream from Ethel Gorge.

As with most other natural drainage systems in the Pilbara region, the Upper Fortescue River and creek systems are ephemeral and flow in direct response to rainfall in their catchments. Streamflow mainly occurs during the summer months of December through to March being associated with the large and more intense rainfall events. The annual runoff volume from the Upper Fortescue River is extremely variable. The stream flow at the DoW gauging station 708011, located upstream of Ethel Gorge, ranges between 192 and 391 000 ML per rainfall year. The median annual runoff volume is 19 000 ML (2.5% of average annual rainfall)

Ethel Gorge Ecohydrological Case Study continued

The Ophthalmia Dam MAR system comprises the Ophthalmia Dam, infiltration basins, recharge ponds and the Ophthalmia borefield (Figure 2 and Map 2). Water from the Ophthalmia Dam can be released into the infiltration basins or pumped into the recharge ponds to enhance infiltration into the underlying aquifers. When full, the water in the dam flows over the service spillway and flows into the former Warrawanda Creek before through to Ethel Gorge.

Ophthalmia Dam completely filled and overtopped the dam in 16 of the past 33 years. The dam did not overflow during seven consecutive years from 1987 to 1993. The more frequent overtopping since 1994 coincides with higher annual rainfall during this period.

The streamflow water quality is fresh (about 40 mg/L) when it enters the dam, but the dam water becomes gradually more saline (about 250 mg/L) owing to concentration effects from evaporation. During the next major runoff event, the fresh streamflow tends to mix with and dilute the more saline stored water.

Since 2007, the Ophthalmia Dam received surplus dewatering water from OB23 and OB25 mining operations and a portion of surplus dewatering water from the OB23 operations was pumped to the recharge ponds to offset groundwater drawdown in the Ophthalmia aquifer.

Hydrogeology

The Ophthalmia aquifer is the main groundwater system in the Ethel Gorge area and comprises Tertiary detritals deposited in a palaeochannel situated underneath the Upper Fortescue River (Map 3). There are also two tributary palaeochannels, associated with Homestead and Shovelanna Creeks. The Paraburdoo Member dolomite of the Wittenoom Formation underlies and is in hydraulic connection with the Tertiary detritals.

The Ophthalmia aquifer comprises an upper and lower aquifer and is mostly hydraulically separated from each other by an extensive clay layer. However, on the margins of the palaeochannel, ancient scree deposits are preserved and these can be variably permeable, hydraulically linking the upper and lower aquifers. The upper aquifer (TD3) occurs throughout the Ethel Gorge area and consists of coarse alluvium and substantial thicknesses of calcrete. The upper aquifer is a high-permeability, large storage aquifer and is the main habitat for the Ethel Gorge stygobiont TEC.

The palaeochannel aquifers and dolomite are surrounded by low-permeability lithologies comprising mainly banded iron formations and granite. There are also zones of high-permeability material associated with orebodies. The extent to which the orebody aquifers are in hydraulic connection with the regional groundwater system varies with site-specific and local geological conditions.

Groundwater recharge occurs mainly along creeks and through the Ophthalmia Dam MAR system. There is no substantial rainfall recharge. Natural groundwater discharge occurs mainly through evaporation and transpiration. Further studies is currently undertaken to better understand the transpiration controls along the extensive 3 650 ha of riparian vegetation. Groundwater abstraction from the Ophthalmia Borefield varies between 2 and 5 GL/yr. The groundwater throughflow at Ethel Gorge is estimated to be about 1 GL/yr.

Groundwater flow is generally in a north-easterly direction, converging at Ethel Gorge. Groundwater elevations range from about 514 mAHD, about 4 km upstream of Ophthalmia Dam to about 500 m AHD at Ethel Gorge. The hydraulic gradient is about 1:1000, increasing to 1:500 at Ethel Gorge. The depth to groundwater varies between 0.5 m at Ethel Gorge to 4 m upstream of Ophthalmia Dam. Groundwater quality is generally fresh with elevated calcium, magnesium and bicarbonate concentrations, which is characteristic of recharge water in the Pilbara.

Prior to the construction of Ophthalmia Dam, seasonal groundwater fluctuations were between 1 to 3 m along major drainage lines in response to creek recharge and the groundwater salinity was about 1000 mg/L total dissolved solids (TDS). Over the past 40 years, groundwater levels and salinity has been influenced by the Ophthalmia MAR system, groundwater abstraction from the Ophthalmia borefield, dewatering activities at OB23 and the expansion of riparian vegetation at Ophthalmia Dam and these are discussed in more detail later.

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Ecohydrological Receptors

Ethel Gorge stygobiont community

The Ethel Gorge stygobiont community (Tier 2) is listed as a Threatened Ecological Community (TEC) by the Department of Parks and Wildlife (DPaW) and classed as endangered (EN B) ii) (DPaW, 2014). The boundary and buffer zone of the TEC (modified by DPaW in 2013) is shown on Map 4.

The upper Ophthalmia aquifer forms the main habitat of the stygofauna community. The palaeochannel infill contains gravelly and sandy alluvium and calcrete to about 40 m depth. The highest species richness is found at Ethel Gorge and upstream to about 1.5 km below the Ophthalmia Dam wall (Map 4). Altogether, 78 stygofauna species have been collected in the vicinity, with 37 (47%) of the species thought to be restricted to the Newman area (Bennelongia 2013a). Low numbers of stygofauna occurs in the lower Ophthalmia aquifer and in hydrostratigraphic units around the Ophthalmia aquifer (Bennelongia, 2013a).

The high stygofauna abundance in the Ethel Gorge area may be associated with active creek recharge, infiltration from Ophthalmia Dam and shallower groundwater levels. Food sources are transported into the underlying aquifers through percolating creek recharge, and these sustain rich stygofauna communities (Eberhard et al. 2005, Halse et al. 2014). Also, the relatively large pore size spaces in the gravelly and sandy alluvium and calcrete forms a suitable habitat for stygofauna species (Eberhard et al. 2005, Halse et al. 2014 and Hahn and Fuchs 2009). Section 2 provides a summary of the existing scientific knowledge about the factors that control stygofauna abundance and diversity.

The groundwater salinity influences the type of stygofauna species present in the aquifer. The groundwater salinity in the upper Ophthalmia aquifers is variable both spatially and temporarily; however, the stygofauna community is likely to be resilient to changes in groundwater salinity (Halse et al. 2014, Reeves et al. 2007, Pinder et al. 2005).

BHP Billiton Iron Ore is progressively developing an improved understanding of the upper Ophthalmia aquifer geometry and habitat factors for the stygofauna community. Map 5 shows the saturated thickness profile of the upper Ophthalmia aquifer for March 2014. The map shows that portions of the Ethel Gorge stygobiont community TEC are located in areas underlain by completely desaturated alluvium or calcrete areas with a thin saturated thickness, which are prone to complete desaturation from natural groundwater fluctuations. These areas are likely to be unsuitable habitat for stygofauna, as supported by the low species richness from stygofauna sampling locations. There are also areas with a significant saturation thickness which occur outside the TEC boundary, which may be considered by DPaW for future updates and refinements of the TEC boundary.

Riparian and woodland vegetation

There are uncommon communities of dense riparian and woodland vegetation occurring along the drainage lines in the Ethel Gorge area (Map 4). The vegetation is a Tier 3 ecological asset and comprises:

- Along major drainage lines, open forest of *Eucalyptus victrix* (Coolibah) and *Eucalyptus camaldulensis* (River Red Gum) over sedges of *Cyperus Vainatus* and *Typha Domingensis*.
- Open woodland of *Eucalyptus victrix* over low open woodland of *Acacia citrinoviridis* over scattered tussock grasses of *Cenchrus ciliaris*.
- Open mallee of *Eucalyptus socialis subsp. Eucentrica* over very open hummock grassland of *Triodia pungens* on floodplains.

The riparian communities comprise vadophytic and opportunistic phreatophytic riparian vegetation types, which rely predominantly on seasonal creek recharge to replenish soil moisture in the vadose zone. Where the depth to groundwater is less than 10 mbgl, groundwater may be accessed by opportunistic phreatophytic vegetation such as Coolibah and River Red Gum.

Threatening processes

There are two main threatening processes to the stygofauna community associated with mining developments in the Ethel Gorge project area.

Ethel Gorge Ecohydrological Case Study continued

- Groundwater drawdown associated with dewatering activities has the potential to decrease the available habitat for stygofauna, and
- The stygofauna community may be affected by changes to groundwater quality associated with the discharge of surplus dewatering water into Ophthalmia Dam.

As part of the existing ministerial conditions (Ministerial Statement 712), BHP Billiton Iron Ore has implemented the subterranean fauna survey plan that outlines the procedures and measures to monitor the distribution and abundance of species and/or communities of subterranean fauna. It also addresses timely remedial action in the event that monitoring demonstrates that project operations are compromising the long-term survival of subterranean fauna and/or communities.

The main threatening processes with the potential to affect the riparian vegetation are:

- A reduction in the frequency of flooding events, which contribute to the ecological water requirements of the vegetation by replenishing moisture stores in the vadose zone.
- Groundwater drawdown may also reduce water accessibility for some opportunistic phreatophytic vegetation. However, the degree of groundwater dependency is unknown and therefore the potential impact of drawdown on vegetation health is subject to a high degree of uncertainty.
- Rising groundwater levels may result in groundwater to move into the root zone leading to waterlogging and affecting riparian vegetation health.

As part of the existing ministerial conditions (Ministerial Statement 478), BHP Billiton Iron Ore has been monitoring the vegetation health adjacent to OB25 to assess the potential impacts from drawdown around OB25. However, to date, the groundwater drawdown has not extended beneath the riparian vegetation.

Historical groundwater level and salinity changes

Over the past 40 years, groundwater levels and salinities have been influenced by mining-related activities and are described in detail in Section 1. The historical changes in groundwater levels are summarised in Table 1 and Table 2 summarises the historical changes in groundwater salinity.

Ethel Gorge Ecohydrological Case Study continued

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Table 1: Historical groundwater level changes

Phase	Description	Groundwater level changes
Phase 0: Prior to 1970	Pre-mining Baseline conditions	Natural groundwater fluctuations along drainage lines were between 1 and 3 m in response to creek flow events
Phase 1 1970-1982	Establishment of groundwater borefield	Between Ophthalmia Dam and Ethel Gorge, groundwater levels decreased between 10 and 14 m over 10 years. Groundwater levels decreased about 2 m upstream of borefield
Phase 2 1982 to 1998	Construction of Ophthalmia Dam and implementation of MAR	Groundwater levels increased between 3 and 14 m in response to infiltration of water from Ophthalmia Dam, recharge ponds and infiltration basins
Phase 3 1999-2006	High rainfall period	Above average rainfall and creek flow caused groundwater level increases of between 2 and 5 m. Groundwater levels remain at high levels
Phase 4 2006-2014	Dewatering of OB23 and groundwater drawdown	Dewatering activities at the OB23 orebody caused groundwater drawdown in a small portion of the Ophthalmia aquifer. Surplus dewatering water from OB23 and OB25 operations was discharged to the recharge ponds and Ophthalmia Dam and infiltration from these facilities sustained groundwater levels in the remainder of the aquifer.

Table 2: Historical groundwater salinity concentration changes

Phase	Description	Groundwater level changes
Phase 0: Prior to 1970	Pre-mining Baseline conditions	Natural groundwater salinity concentrations were about 1000 mg/L TDS. Groundwater salinity was higher in the region of the Warrawanda Creek and lower under the Upper Fortescue River.
Phase 1 1970-1982	Establishment of groundwater borefield	Groundwater salinity increased gradually, probably caused by a larger groundwater inflow contribution from the adjacent, higher salinity hydrostratigraphic units.
Phase 2 1982 to 1998	Construction of Ophthalmia Dam and implementation of MAR	Groundwater salinity decreased rapidly after the Ophthalmia dam was constructed, representing infiltration of good quality surface water. Salinity directly down-gradient of the dam continue to decrease and remained a low salinity. However, the salinity in Ethel Gorge gradually increased caused possibly by a combination of the concentration effects from transpiration from riparian woodland and mixing from adjacent higher salinity hydrostratigraphic units. In addition, there were very few instances that the dam overflowed, which limited the infiltration of fresh surface water along the down-gradient portion of the creek.
Phase 3 1999-2006	High rainfall period	The high rainfall period caused significant inflows into the Ophthalmia Dam, which overflowed into the down-gradient creek which then infiltrated the alluvium aquifer, resulting in a significant dilution of groundwater salinity. After the 1999/2000 freshening event production bores in Ethel Gorge showed an increasing in salinity trend while bores at Ophthalmia Dam remained below 1000 mg/L TDS.
Phase 4 2006-2014	Dewatering of OB23 and groundwater drawdown	Salinity trends showed substantial variability and reflects the variability of overflows from the Ophthalmia Dam and discharge of higher salinity surplus dewatering water into Ophthalmia Dam and the recharge ponds. Salinity concentrations generally increased between 2006 and 2010 and then decreased between 2010 and 2014 when dewatering operations at OB23 stopped.

Ethel Gorge Ecohydrological Case Study continued

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Change assessment and adaptive management

Description of operations

In accordance with the indicative SEA mine schedule, BHP Billiton Iron Ore proposes to mine nine orebodies situated in the Ethel Gorge project area between 2014 and 2030, most of which will require dewatering to facilitate below watertable mining (Map 7). One orebody, OB23, has been already been mined and BHP Billiton is considering to backfill the mine void. Four of the orebodies (OB17, OB18, OB24 and OB25) are currently being mined. OB31 is scheduled to commence mining by 2016 (pending approvals), while the remainder of the orebodies will commence with mining within the next 5 to 10 years.

This schedule provides sufficient time to better understand and model the system dynamics; address uncertainties related to the potential water-related impacts on ecological receptors; assess and test management responses to hydrological changes; and identify alternative surplus dewatering management options, if required.

BHP Billiton Iron Ore has been moving surplus dewatering water to Ophthalmia Dam and the four recharge ponds since 2006 with the development of the OB23 and OB 25 orebodies. It is planning to continue pumping surplus dewatering water from the proposed future operations in the Eastern Pilbara region into Ophthalmia Dam. The surplus dewatering rates and quality will be the subject of ongoing, progressive technical studies.

Groundwater is also used to provide potable water to the Newman Township. BHP Billiton Iron Ore estimated that the future Newman Township water demand will be about 9 GL/yr, of which 4 GL/yr is planned to be supplied by Ophthalmia borefield and the remainder by the Homestead borefield and/or other as yet identified borefields.

Groundwater drawdown

Historically, groundwater drawdown occurred in parts of the Ophthalmia aquifer caused by groundwater abstraction and dewatering from the OB23 open-cut mine, but groundwater drawdown was offset through infiltration from Ophthalmia Dam and the four recharge ponds (Section 1). No groundwater drawdown from the current operations has been observed to date.

BHP Billiton Iron Ore is progressing with technical studies to determine the degree of hydraulic connection between the proposed open pits and Ophthalmia aquifer. Map 7 and Table 3 present the current understanding of the degree of hydraulic connection between the orebodies and the Ophthalmia aquifer.

Table 3: Degree of hydraulic connection between orebodies and the Ophthalmia aquifer

Zone	Description	Uncertainties
OB23 (mined)	The mined OB23 has a full hydraulic connection with the Ophthalmia aquifer. Dewatering will be required to allow the placement of backfill.	The drawdown caused by dewatering from OB23 is well understood from past mining. Existing management practices will ensure that groundwater levels in the Ophthalmia aquifer is maintained in the vicinity of the OB23 mine void.
OB17 and OB18 (active)	Limited hydraulic connection with the Shovelanna tributary palaeochannel but there is a potential hydraulic connection with OB31.	The degree of hydraulic connection between OB17, OB18 and OB31 is poorly understood and its influence on water levels in the Ophthalmia aquifer presents a moderate to low uncertainty
OB25 pit 3 (active)	OB25 pit 3 is hydraulically connected to the Homestead tributary palaeochannel aquifer and is also in close proximity to the Ophthalmia aquifer.	There has been no drawdown as yet recorded in the Ophthalmia aquifer, but some degree of drawdown is possible as mining progresses.
OB24 and OB25 pit 1 (active)	Both pits are completely surrounded by low permeability lithologies.	There might be a degree of hydraulic connection between the pits and the dolomite and tributary palaeochannel aquifers through geological structures which presents a low uncertainty.

Ethel Gorge Ecohydrological Case Study continued

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OB31	Bound by low permeability lithologies, but potential hydraulic connectivity with the dolomite aquifer and Shovelanna tributary palaeochannel through geological structures.	The degree of hydraulic connection between the pit and the dolomite and tributary palaeochannel presents a high uncertainty.
OB32 and OB32 west	Partial to moderate connection with the Paraburdoo Member dolomite, but distant to the Ophthalmia aquifer.	The degree of hydraulic connection with the Homestead tributary palaeochannel and the Ophthalmia aquifers presents a high uncertainty.
OB37 North	Full hydraulic connection with the Homestead tributary palaeochannel aquifer, but distant to the Ophthalmia aquifer.	OB37 may have a good hydraulic connection with the Homestead tributary palaeochannel aquifer, but the degree of hydraulic connection between the Homestead tributary palaeochannel aquifer and Ophthalmia aquifer is a significant uncertainty
OB37 South	Limited hydraulic connection with the Ophthalmia aquifer due to the presence of low permeability Jeerinah Formation and other lithologies on the footwall on the proposed pit	There may be a degree of hydraulic connection with the Ophthalmia aquifer e.g. through unknown geological structures. Due to the proximity of the pit to the TEC, the degree of hydraulic connection is a critical uncertainty.
OB34 and OB39	Full hydraulic connection with the Shovelanna tributary palaeochannel, but distant to the Ophthalmia aquifer.	The pits may have a good hydraulic connection with the Shovelanna tributary palaeochannel aquifer, but the degree of hydraulic connection between the Shovelanna tributary palaeochannel aquifer and Ophthalmia aquifer is uncertain.

The content of the table is conceptual only, of a general nature and does not purport to contain all information relevant to future project development associated with the Project. This table has been prepared solely for the purposes of informing environmental impact assessment pursuant to the Environmental Protection Act 1986 (WA) and Environment Protection and Biodiversity Conservation Act 1999 and is not intended for use for any other purpose. No representation or warranty is given that project development will actually proceed. As project development is dependent upon future events, the outcome of which is uncertain and cannot be assured, actual development may vary materially from the contents of the table.

Groundwater abstraction from the Ophthalmia borefield may result in additional groundwater drawdown in parts of the Ophthalmia aquifer, in addition to drawdown associated with dewatering activities. BHP Billiton Iron Ore identified that the Homestead borefield will need to be replaced owing to drawdown in the Homestead tributary palaeochannel aquifer associated with the dewatering of OB37. For the purpose of this case study, it was assumed that the new borefield will not be situated in the vicinity of the Ophthalmia aquifer.

Waterlogging

Waterlogging occurs when there is a high degree of water saturation in the plant root zone and as a result, there is insufficient oxygen in the pore space for plant roots to adequately respire to the detriment of the vegetation health. Waterlogging tolerances varies between plant species but studies carried out on behalf BHP Billiton Iron Ore indicate that rising groundwater levels to less than 2 m depth could potentially affect vegetation health (BHP Billiton Iron Ore, in preparation).

Waterlogged conditions have not been observed to date (other than within the dam basin), despite groundwater levels increasing substantially after the construction of Ophthalmia Dam, and more noticeably, after the above average wet conditions in 1999/2000. Nevertheless, there is potential for waterlogging associated with sustained discharge of large surplus dewatering water volume into the Ophthalmia Dam and recharge ponds.

Numerical groundwater modelling: Groundwater levels

Model development

A numerical groundwater model was developed for the Ethel Gorge area and calibrated with respect to historical conditions. The model was used to estimate the range of groundwater levels in the Ophthalmia aquifer, considering dewatering in accordance of the SEA mining schedule, groundwater abstraction and a range of other factors such as leakage from Ophthalmia dam, transpiration from the riparian vegetation and groundwater throughflow. A summary of the

Ethel Gorge Ecohydrological Case Study continued

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groundwater model development and results are presented in Section 3 and a detailed groundwater modelling report is provided by RPS (in progress).

The model has been used to demonstrate that it is capable of simulating a range of historical groundwater conditions and is able to provide the predictions required. The significance of model uncertainties has not been extensively tested and only limited sensitivity analysis has been carried out to date. The intention is to continue improving the model as more data is collected and more is known about the potential uncertainties of the system, providing validation of the model results. The model may be continuously updated, refined and the uncertainty in the system.

The numerical groundwater model was developed using the Modflow-Surfact groundwater modelling code comprising calibration and prediction models. The predictive models represent the SEA mining schedule and a hypothetical post-closure scenario following 2033.

The model domain is shown in Map 1 and comprises four layers which include both the upper and lower Ophthalmia aquifers, clay aquitard that separates the upper and lower aquifers, and the underlying bedrock. Section 3 provides additional technical detail on flow processes and boundary conditions.

The groundwater model was calibrated against nearly 150 calibration bores over a 44 year period. The calibration incorporated various hydraulic stresses imposed on the aquifer including groundwater abstraction, dewatering, aquifer recharge from the Ophthalmia MAR scheme and various climates. In general, the model calibration for the entire model domain is considered representative with groundwater levels and trends being simulated for the calibration period (Section 3).

During the course of the study, groundwater studies related to the OB31 approvals project suggested that dewatering rates from OB31 may be significantly higher than initial estimates. As such, two scenarios have been presented:

- Low surplus dewatering rates based on initial dewatering estimates;
- High surplus dewatering rates based on updated dewatering estimates from the OB31 study.

The two scenarios represent the upper and lower bounds of surplus dewatering rates. As such, the case study highlights the flexibility of the management tools to address a range of surplus dewatering rates.

The predicted groundwater level changes associated with the OB23 backfilling was excluded from the case study, as these form part of a separate approvals process. Therefore, the case study presents the predicted groundwater levels for the period 2018 to 2033. Also, it was assumed that no open pits, other than OB23, will be backfilled for the closure period; however, one additional model scenario run was performed assuming that OB37 is backfilled to pre-mining groundwater levels.

Model results

This section presents the model results relevant to the ecological receptors. Detailed modelling results including groundwater drawdown contours and hydrographs are presented in Section 3 and RPS (2014a, BHP Billiton Iron Ore 2014).

Significant groundwater drawdown is predicted in the Homestead and Shovelanna tributary palaeochannels due to dewatering from orebodies situated on the flanks of these tributary palaeochannels. The impacts of the drawdowns on the Ophthalmia aquifer are predicted to be offset by leakage from the Ophthalmia Dam. For the low surplus dewatering scenario, localised drawdown is predicted at the convergence of the Homestead and Fortescue River palaeochannels.

Figure 3 provides a long section through Ophthalmia aquifer showing the range of predicted groundwater levels, compared to the historical range of groundwater levels for the period 2018 to 2033. The upper predicted groundwater level bound reflects the maximum groundwater levels for the high surplus dewatering scenario, while the lower predicted groundwater level bound reflects the low surplus dewatering scenario. Map 7 shows the location of the transect through the Ophthalmia aquifer.

Ethel Gorge Ecohydrological Case Study continued

4.95cm

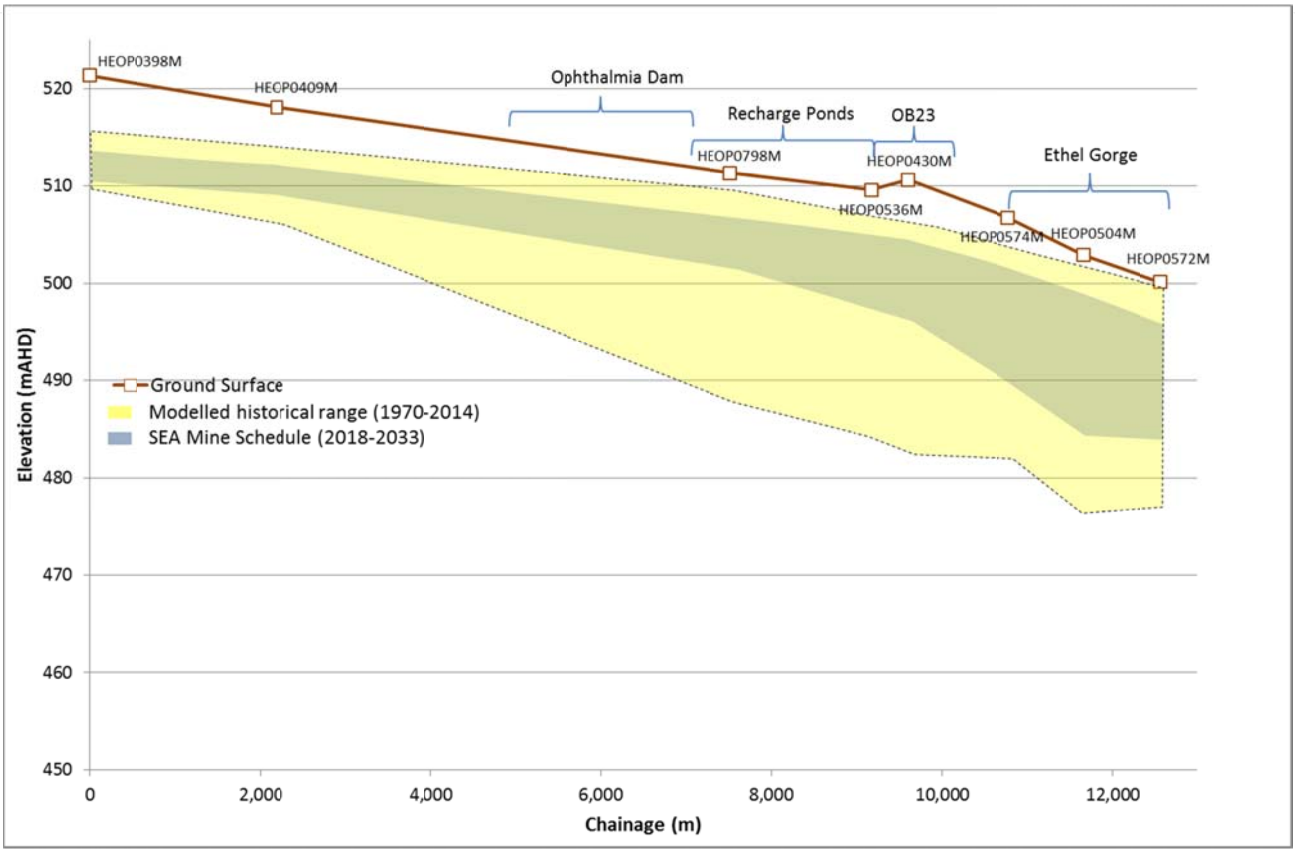

Figure 3: Predicted range of groundwater levels in the Ophthalmia aquifer

The model result suggests that groundwater levels will remain within the historical range throughout the SEA mining period, irrespective of the surplus dewatering scenario. Drawdown in the Ophthalmia aquifer is offset by leakage from the Ophthalmia Dam which maintains high groundwater levels in the Ophthalmia aquifer. Groundwater levels will also increase caused by the discharge of surplus dewatering water into Ophthalmia Dam and the recharge ponds causing higher infiltration rates, but groundwater levels is predicted to be maintained within the historical range.

Maps 8 show the predicted saturated thickness throughout the Ophthalmia aquifer in 2030 for the low surplus dewatering scenario. The saturated thickness in 2030 is very similar to the saturated thickness in March 2014, which implies that the stygofauna habitat will not be significantly affected by the drawdown from mining activities. Map 9 shows the depth to groundwater throughout the Ophthalmia aquifer in 2030 for the high surplus dewatering scenario. The depth to groundwater in October 2030 is about 2 m lower compared to in March 2014, but there is no significant change of the size of the area where groundwater levels are less than 2m depth to groundwater. This implies that the riparian vegetation will not be significantly affected by the drawdown from mining activities nor will it be affected by rising groundwater levels caused by the discharge of surplus dewatering water into Ophthalmia Dam.

Figure 4 is a transect through Ophthalmia aquifer showing the range of predicted groundwater levels for the closure scenario, compared to the historical range of groundwater levels.

Ethel Gorge Ecohydrological Case Study continued

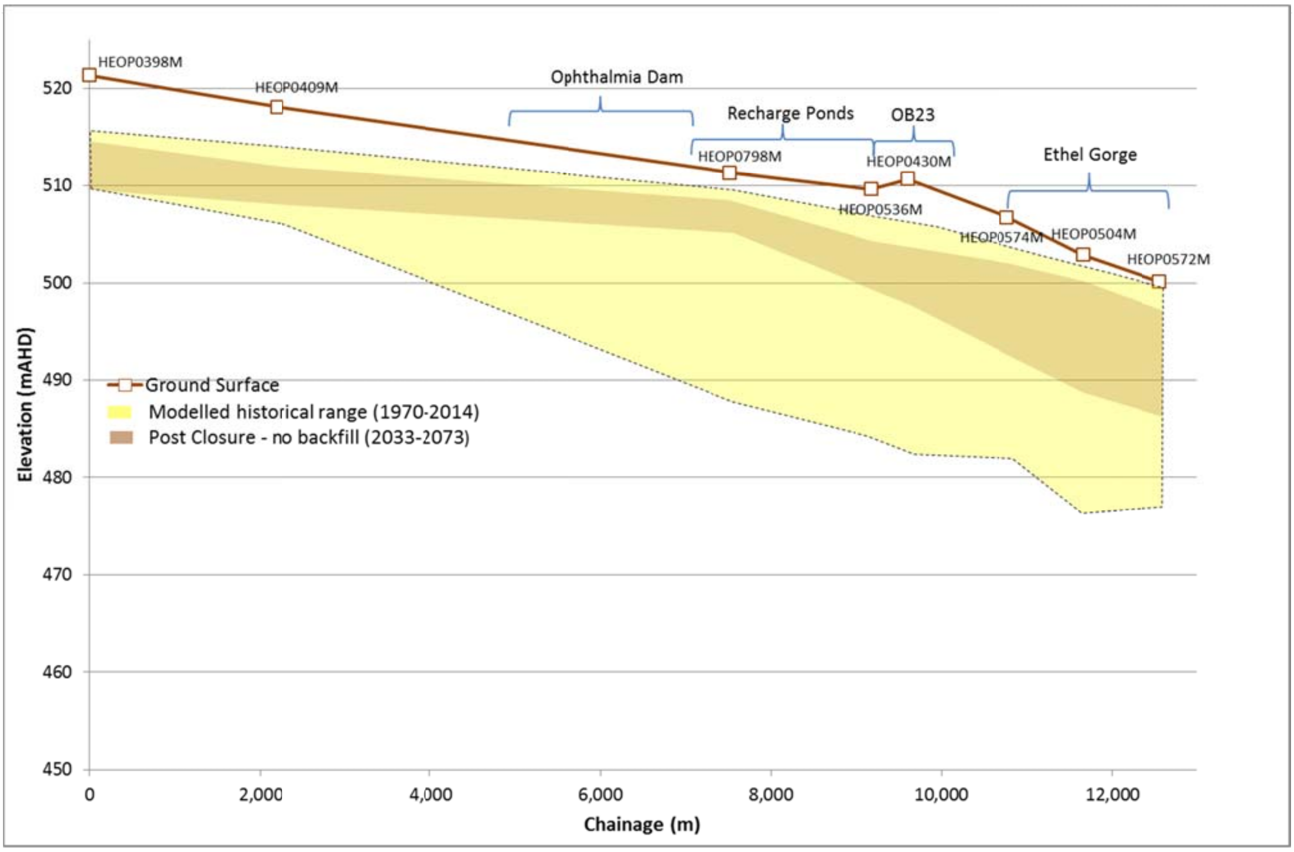

Figure 4: Predicted range of groundwater levels in the Ophthalmia aquifer after closure

The model result shows that groundwater water levels will remain within the historical range throughout the closure period. Groundwater levels recover rapidly (within a couple of years) once groundwater from the Ophthalmia borefield ceases and then remain almost constant throughout the closure period.

Maps 10 and 11 show the predicted saturated thickness and depth to groundwater throughout the Ophthalmia aquifer at 2072 respectively. The saturated thickness in 2072 is very similar to the saturated thickness in 2014, which implies that the stygofauna habitat will not be significantly affected during the closure phase. The depth to groundwater is also similar to 2014 which implies that the riparian vegetation will not be significantly affected during the closure phase.

For the scenario where it was assumed that OB37 will also be backfilled after closure, there were almost no changes to the predicted groundwater levels. Groundwater level ranges, saturated thickness and depth to groundwater levels were almost exactly the same as the case where OB37 is not backfilled.

Uncertainties and management response: Groundwater levels

Even though the numerical model predicts no significant changes in groundwater levels, there remain considerable uncertainties which should be considered in the framework of adaptive management.

Table 4 presents various scenarios related to the uncertainty of the groundwater system, its implications in terms of potential groundwater level changes and possible management responses to mitigate against unacceptable groundwater level changes.

Ethel Gorge Ecohydrological Case Study continued

4.95cm

Table 4: Uncertainties, implications and management responses related to changes in groundwater levels

Scenario	Implication	Management response
Higher than expected dewatering rates	Higher discharge rates to Ophthalmia Dam causing higher groundwater levels and more frequent overflows	Increase groundwater abstraction from production bores at Ophthalmia Dam to lower groundwater levels. Installation of subsurface drains along the perimeter of the Ophthalmia Dam wall
Lower than expected dewatering rates	Lower discharge rates to Ophthalmia Dam causing less frequent overflows, but frequency of overflows will still be higher than the “no discharge scenario”	Groundwater levels expected to remain in historical ranges and no management action is required.
Greater hydraulic connection between Ophthalmia aquifer and Homestead tributary palaeochannel	Greater but localised drawdown along the north-western part of the Ophthalmia aquifer and Ethel Gorge	Pump surplus dewatering water to the recharge ponds to offset groundwater drawdown Decrease abstraction rates for production bores situated in the affected area
Greater hydraulic connection between Ophthalmia aquifer and Shovelanna tributary palaeochannel	Greater but localised drawdown along the north-eastern part of the Ophthalmia aquifer and Ethel Gorge	Some groundwater drawdown will be offset by infiltration from Ophthalmia Dam Consider implementation of aquifer recharge through infiltration ponds and/or groundwater injection bores
Greater hydraulic connection between Ophthalmia aquifer and OB37	Greater drawdown along the north-western part of the Ophthalmia aquifer and Ethel Gorge	Some groundwater drawdown will be offset by infiltration from Ophthalmia Dam Consider implementation of aquifer recharge through infiltration ponds and/or groundwater injection bores
Greater hydraulic connection between Ophthalmia aquifer and OB37	After closure, groundwater drawdown along the north-western part of the Ophthalmia aquifer and Ethel Gorge will be sustained	Consider passive aquifer recharge infrastructure such as recharge ponds Install hydraulic barrier to decrease hydraulic connection with OB37 Backfill OB37
Wetter than normal conditions	Higher groundwater levels and more frequent overflows from Ophthalmia Dam	Increase groundwater abstraction from production bores at Ophthalmia Dam to lower groundwater levels.
Drier than normal conditions	Lower discharge rates to Ophthalmia Dam causing less frequent overflows, but frequency of overflows will still be higher than the “no discharge scenario”	Groundwater levels expected to remain in historical ranges and no management action is required.
Greater than expected groundwater dependency by riparian vegetation	Vegetation health might be affected if groundwater drawdown takes place down stream of Ophthalmia Dam	Not applicable as no significant drawdown is expected or groundwater levels will be maintained through infiltration/injection. Some decreasing tree health expected in localised areas.
Greater than expected riparian impacts caused by waterlogging	Vegetation health might be affected by rising groundwater levels down stream of Ophthalmia Dam	Reduce or stop discharge to recharge ponds and/or infiltration basins Increase groundwater abstraction from production bores at Ophthalmia Dam to lower groundwater levels. Installation of subsurface drains along the perimeter of the Ophthalmia Dam wall

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Ethel Gorge Ecohydrological Case Study continued

4.95cm

Groundwater salinity[1]

Historically, groundwater salinity ranged considerably in the Ophthalmia aquifer caused by both natural and mining related activities. Pre-mining salinity concentrations varied between 1000 and 1400 mg/L, though salinity mapping showed that salinity varied significantly across the Ophthalmia aquifer (Section 2).

Since the 1970s, changes in groundwater salinity concentrations occurred mostly because of the construction of the Ophthalmia Dam which caused a freshening of groundwater close to the Ophthalmia Dam (due to the infiltration of fresh surface water into the aquifer) and increased salinity towards Ethel Gorge (caused by reduced creek recharge). The processes causing changes in groundwater salinity is summarised in Figure 5 and described in more detail in Section 2.

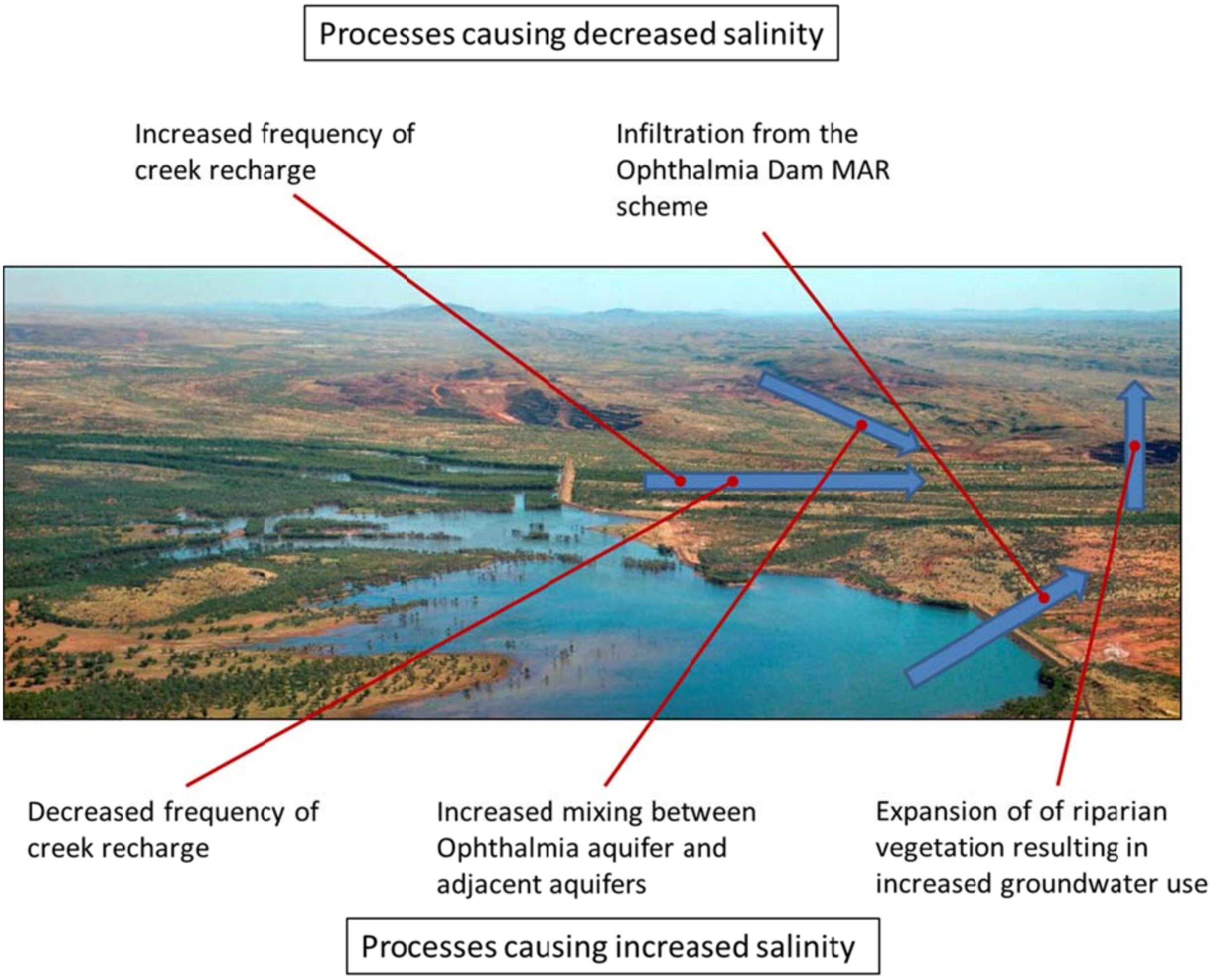

Figure 5: Processes causing changes in groundwater salinity

The surplus dewatering water is likely to have salinity concentrations of around 1000 mg/L TDS, which is similar or lower to the pre-dam groundwater quality. However, the system dynamics controlling the salinity concentrations in the Ophthalmia aquifer is complex and progressive studies are undertaken to better understand these processes.

Table 5 is a comparison of the ‘no discharge’ and ‘discharge’ scenarios and its implications on groundwater salinity.

[1] For the purposes of the case study, salinity concentrations are expressed as the Total Dissolved Solids (TDS) concentrations to account for the variety of water types present in the study area.

Ethel Gorge Ecohydrological Case Study continued

4.95cm

Table 5: Processes causing changes groundwater salinity

No discharge scenario	Discharge scenario
During the wet season, fresh surface runoff is captured in the dam and infiltrates the Ophthalmia aquifer, causing decrease in groundwater salinity.	During the wet season, fresh surface runoff is mixed with dewatering discharge water and infiltrates the Ophthalmia aquifer. The Ophthalmia Dam salinity concentrations is higher than the 'no discharge' scenario, but lower than the groundwater salinity concentrations, hence the infiltration still cause a decrease in groundwater quality
During the dry season, salinity concentrations in the Ophthalmia Dam increases due to evapoconcentration causing an increase in groundwater salinity, but infiltration rates are lower.	During the dry season, salinity concentrations in the Ophthalmia Dam mixes with dewatering water and salinity concentrations are lower compared to the 'no discharge scenario', causing decrease in groundwater salinity.
The frequency of overflow is lower compared to the 'discharge' scenario. As such, there is less creek recharge downstream of the dam and groundwater salinity increases due to the combined effect of increased mixing with groundwater from adjacent aquifers and transpiration from riparian vegetation.	The frequency of overflow is higher compared to the 'no discharge' scenario and the creek recharge downstream of the dam causes a decrease on groundwater salinity
The extent of riparian vegetation is smaller compared to the discharge scenario, hence transpiration rates are lower and groundwater salinity concentrations are lower compared to the discharge scenario	The riparian vegetation is likely to cover a larger area, taking advantage of the higher water availability. The higher riparian vegetation density causes an increase in transpiration rates concentrating groundwater salinity.

Table 5 only describes the relative changes in groundwater salinity between the discharge and no discharge scenario. Climate is predicted to exert a significant impact on groundwater salinity, for example, the 1999/2000 wet season caused a marked decrease in groundwater salinity across the entire Ophthalmia aquifer.

Analytical salinity modelling

An analytical flow and salinity load balance model was developed to predict and quantify the potential changes in salinity concentrations in the upper Ophthalmia aquifer. The analytical model was validated to the historical salinity concentration trends and was then used to predict the potential changes in salinity concentrations resulting from the discharge of surplus dewatering water to Ophthalmia Dam.

As with the numerical groundwater modelling, the analytical salinity modelling was updated during the course of the study after groundwater studies related to the OB31 approvals project indicated that dewatering rates from OB31 could be significantly higher compared to initial estimates. The two scenarios considered were:

- Low surplus dewatering rates based on initial dewatering estimates;
- High surplus dewatering rates based on updated dewatering estimates from the OB31 study.

For the purpose of the case study, the high surplus dewatering rates scenario was adopted as this scenario will results in higher salinity concentrations and are therefore considered conservative. A summary of the salinity model development and model results are presented in Section 4 and detailed reports are provided by RPS (2014b, 2014c, 2014d and 2015)

The model has been used to demonstrate that it is capable of simulating the processes which causes the changes groundwater salinity levels. The significance of model uncertainties has not been tested and no sensitivity analysis has been carried out to date. As with the numerical groundwater model, the intention is to continue improving the model as more data is collected and more is known about the potential uncertainties of the system. Consistent with the adaptive management approach, the model can be updated and refined and used to assess a range of possible outcomes given the uncertainty in the system.

The analytical low and salinity load model was developed using Microsoft Excel spreadsheet incorporating the key processes described earlier (Section 4). The analytical flow and salinity balance model were calibrated to selected water quality data sets for the period 1981 to 2011. The model was used to simulate the freshening effects caused by the infiltration of captured surface water after the construction of Ophthalmia Dam. The model also simulated the freshening

Ethel Gorge Ecohydrological Case Study continued

4.95cm

effects related to the large rainfall period in late 1990 to mid-2000. More information about the model calibration, including hydrographs showing the modelled and measured salinity concentrations at selected monitoring bores are provided in Section 4.

Model results

Figure 6 shows the range of predicted salinity concentrations compared to the historical range of groundwater levels. The figure represents an averaged salinity concentration range throughout the Ophthalmia aquifer for the zone between the dam and Ethel Gorge.

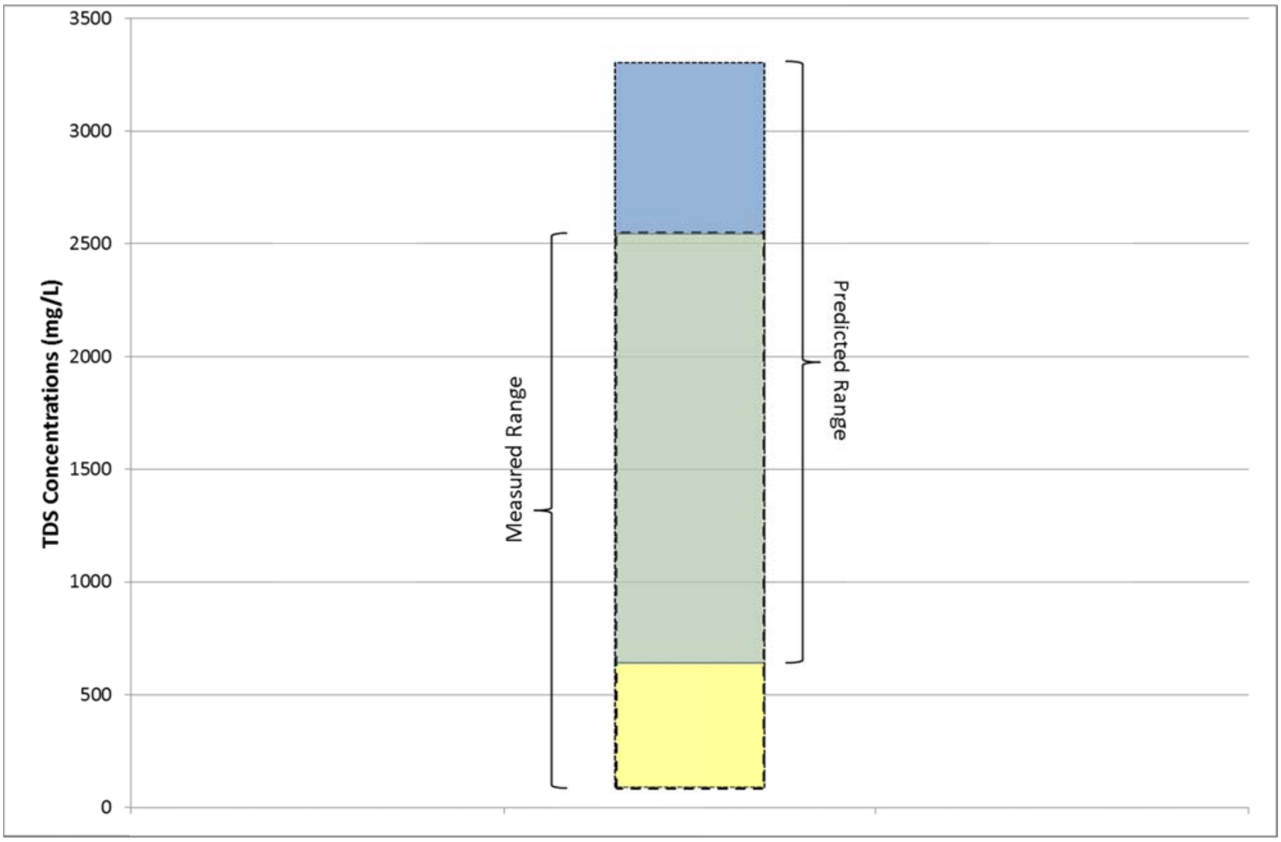

Figure 6: Predicted range of salinity concentrations in Ophthalmia aquifer

The predicted salinity concentrations directly underneath the Ophthalmia Dam remain below 1 000 mg/L and within the range that has been historically recorded within this zone since construction of the dam. The values are and well below the maximum values that have already been experienced elsewhere within the TEC.

The predicted salinity concentrations directly down-gradient of the dam will have higher salinity concentrations with a maximum predicted value of about 2400 mg/L. This value is below the historical maximum salinity concentrations.

At Ethel Gorge, higher salinity concentrations are predicted with a maximum value of 3300 mg/L which is about 30% higher than the maximum historical salinity concentration. By comparison, for the low surplus dewatering scenario, salinity concentrations are predicted with a maximum value of 2800 mg/L. The historical groundwater salinity concentrations ranges between 92 and 2550 mg/L and stygofauna communities are likely to be tolerant to a range of salinity concentrations. However, as a precautionary measure, management responses aim to address these maximum salinity concentrations as discussed below.

The model results also show that salinity concentrations are affected by the management and operating strategy of the Ophthalmia Dam, for example, if 50% of surplus dewatering is released from the Ophthalmia Dam, salinity concentrations

Ethel Gorge Ecohydrological Case Study continued

could potentially increase to 6000 mg/l. The operating strategy should therefore be carefully considered so that it does not impact on the groundwater quality.

Uncertainties and management response: salinity concentrations

The water and salinity load balance model shows that salinity concentration is likely to remain within the stygofauna tolerance ranges and as such, no management or remediation measures were incorporated in the model. However, there remain some uncertainties which should be considered in the framework of adaptive management.

Table 4 presents various scenarios related to the uncertainty of the groundwater system, its implications in terms of potential salinity concentration changes and possible management responses to mitigate against unacceptable salinity concentration changes.

Table 4: Uncertainties, implications and management responses related to changes in salinity concentrations

Action	Implication	Management response
Higher dewatering rates	Higher discharge rates to Ophthalmia Dam causing higher groundwater salinity	Increase groundwater abstraction from abstraction bores at Ophthalmia Dam to remove salt loads from the aquifer. During high rainfall periods, release fresh water into infiltration basins to allow infiltration of fresh water to aquifer Consider alternative water discharge options
Surplus dewatering has a higher salinity	Higher salinity loads are pumped to Ophthalmia Dam causing higher groundwater salinity	Increase groundwater abstraction from abstraction bores at Ophthalmia Dam to remove salt loads from the aquifer. During high rainfall periods, release fresh water into infiltration basins to allow infiltration of fresh water to aquifer Consider alternative water discharge options
Corrective actions aimed to mitigate against decreasing water levels, e.g. pump surplus dewatering water to recharge ponds	Infiltration of higher salinity mine water infiltrate aquifer	Pump fresher runoff water from Ophthalmia Dam to recharge ponds instead. During high rainfall periods, release fresh water into infiltration basins to allow infiltration of fresh water to aquifer Consider alternative water discharge options
Riparian vegetation evapotranspiration rates are lower than expected	salinity concentrations could be lower than expected.	Management responses to mitigate to high salinity concentrations can be relaxed.
Stygofauna communities are tolerant to salinity increases	Stygofauna communities are unaffected by salinity increases	Management responses to mitigate to high salinity concentrations can be relaxed.

Monitoring, review and corrective actions

BHP Billiton Iron Ore is maintaining a groundwater and surface water monitoring program in the Ethel Gorge project area, and also monitoring the health of the Ethel Gorge stygofauna community and riparian vegetation. The groundwater and surface water monitoring findings are included in company annual aquifer reviews. The stygofauna and riparian vegetation monitoring findings are included in company annual environmental reviews.

As part of the existing ministerial conditions (Ministerial Statement 712), BHP Billiton Iron Ore will continue to monitor the distribution and abundance of species and/or communities of subterranean fauna and take timely remedial action in the event that monitoring indicate that project operations may compromise the long-term survival of subterranean fauna and/or communities.

As part of the existing ministerial conditions (Ministerial Statement 478), BHP Billiton Iron Ore will also continue to monitor the vegetation health adjacent to OB25 to assess the potential impacts from drawdown around OB25. However, to date, the drawdown cone has not extended to the riparian vegetation.

Ethel Gorge Ecohydrological Case Study continued

BHP Billiton Iron Ore will continue with the adaptive management to protect the ecological receptors as laid out in the existing ministerial conditions. The remainder of the orebodies will commence with mining within 5 to 10 years, providing an adequate timeframe to better understand the potential drawdown and salinity impacts related from the proposed pits.

BHP Billiton Iron Ore is in the process of modifying the Ethel Gorge project area monitoring and management strategy to better align with the predicted changes caused by proposed future operations included in the SEA. It is proposed that the Ethel Gorge project area will be divided into a number of management zones, which represent the groundwater conditions in and around the Ethel Gorge project area.

Based on the outcome of the technical studies, investigation triggers and mitigation triggers will be developed for these management zones. These will provide the basis for ongoing adaptive management of the Ethel Gorge ecological receptors. It is anticipated that the trigger values will be regularly reviewed and updated, as informed by ongoing monitoring and the outcomes of progressive technical studies addressing the hydrological regime and ecological responses to the regime.

Predictive modelling runs will be progressively validated and updated as more information becomes available from ongoing technical studies. Where predictive modelling findings indicate that defined trigger values could potentially be exceeded, appropriate mitigation measures will be identified.

The existing preventative management and corrective action controls comprise:

- Ophthalmia Dam with an infiltration capacity of about 30 to 80 ML/d and four overflow values to allow controlled discharge to the infiltration basins and into Ethel Gorge
- Two Infiltration basins with a combined infiltration capacity of about 60 ML/d
- Four existing recharge ponds with a combined infiltration capacity of about 64 ML/d
- Ophthalmia borefield with a capacity to pump 16 ML/d which can be used to mitigate elevated water levels and abstract higher salinity groundwater if required.

If trigger values are exceeded and predictive modelling findings indicate that threshold values might be exceeded, appropriate contingency measures will be implemented. For the proposed OB31 operations, the backup option for managing surplus water comprises the controlled release of surplus dewatering water into the Jimblebar Creek while other options, such as MAR are being evaluated.

Further potential mitigation measures will be aligned with the feasible water options as outlined in the water RMS. Where implemented, the effectiveness of mitigation measures will be evaluated and optimised using predictive modelling. This approach will ensure that residual risks to ecological receptors are minimised throughout the implementation of the SEA mine schedule.

LEGEND

- Production Bore (in use) (86)
- Production Bore (not in use) (63)
- DoW Streamflow Gauging Stations

Existing Development
- OSAs
- Pits

- Numerical Model Boundary
- Ophthalmia Aquifer
- Threatended Ecological Community
- Threatended Ecological Community Buffer
- Tributary Palaeochannels

- Townships
- BHPBIO Rail Corridor
- Great Northern Highway
- Other Roads
- Major Drainage Lines
- Minor Drainage Lines

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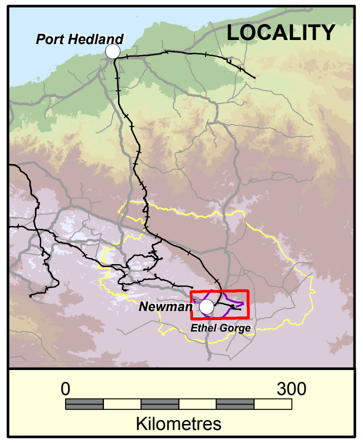

Resource Planning Hydrology
BHP BILLITON IRON ORE

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ETHEL GORGE CASE STUDY
Location

N

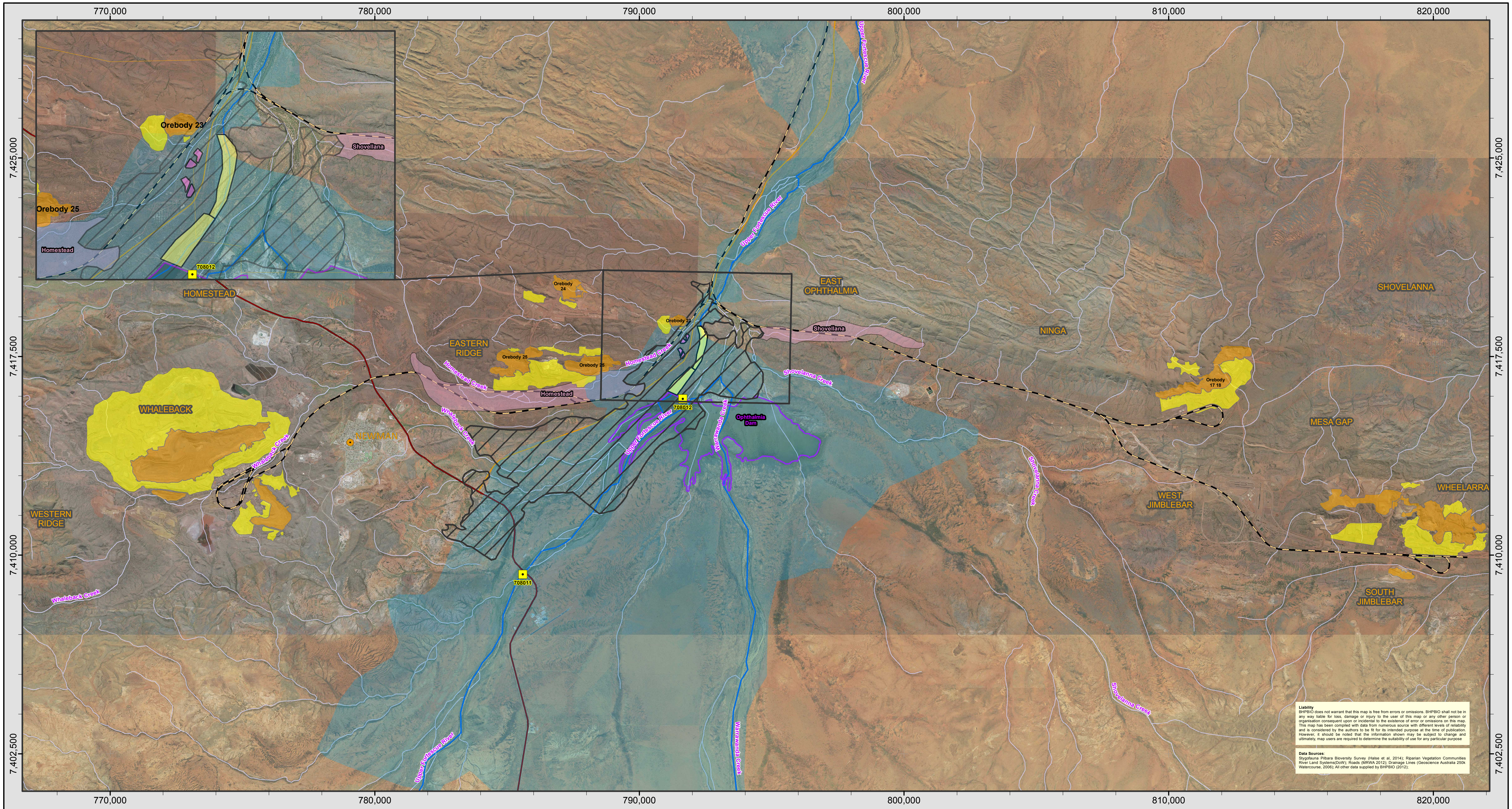
0 1 2 4 6 8 10 12
Kilometres

Coordinate System: GDA 1994 MGA Zone 50
Projection: Transverse Mercator, Datum: GDA 1994, Units: Meter

Scale @ A3: 1:175,000	Prepared: J Botterill	Revision: Rev F
Date: 1/09/2015	Checked: J Vermaak	Map: 1
	Reviewed: J Youngs	

Ethel Gorge Case Study

Document Name: \\entper-fil01\2groups\TSRD Application Drive\Resource Planning\Hydro\WAIO-wide Projects\Strategic Environmental Approval\1 Hydrology all\4 GIS\Maps\ EthelGorge_case_study01_Location.mxd



LEGEND

- DoW Streamflow Gauging Stations
- Existing Development
- OSAs
- Pits
- Ophthalmia Aquifer
- Threatended Ecological Community
- Tributary Palaeochannels
- Recharge Ponds
- Infiltration Basins
- Ophthalmia Dam
- Townships
- BHPBIO Rail Corridor
- Great Northern Highway
- Other Roads
- Major Drainage Lines
- Minor Drainage Lines

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LOCALITY

Newman
Ethel Gorge
0 250
Kilometres

Resource Planning Hydrology
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ETHEL GORGE CASE STUDY
Hydrology

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Projection: Transverse Mercator, Datum: GDA 1994, Units: Meter

Scale @ A3: 1:140,000	Prepared: J Botterill	Revision: Rev F
Date: 1/09/2015	Checked: J Vermaak	Map: 2
	Reviewed: J Youngs	

Ethel Gorge Case Study

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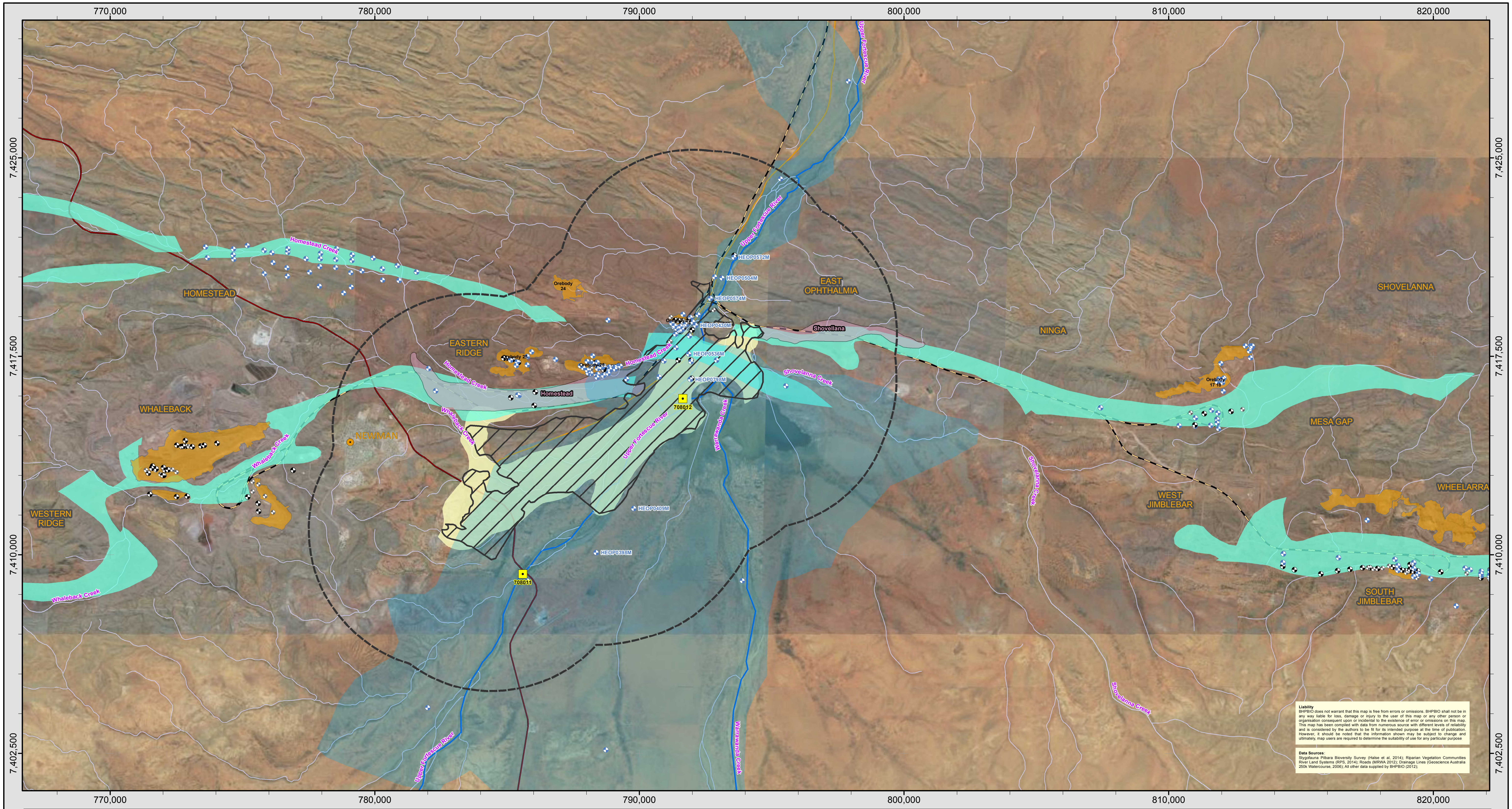

LEGEND

Monitoring Bore (196)	Existing Development	Ophthalmia Aquifer	Townships
Production Bore (in use) (85)	Pits	Threatended Ecological Community	BHPBIO Rail Corridor
Production Bore (not in use) (62)		Threatended Ecological Community Buffer	Great Northern Highway
DoW Streamflow Gauging Stations		Tributary Palaeochannels	Other Roads
		Wittenoom Formation	Major Drainage Lines
		Surface Calcrete	Minor Drainage Lines

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LOCALITY

Newman

Ethel Gorge

0 250

Kilometres

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Resource Planning Hydrology
BHP BILLITON IRON ORE

ETHEL GORGE CASE STUDY
Hydrogeology

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Kilometres

Coordinate System: GDA 1994 MGA Zone 50
Projection: Transverse Mercator, Datum: GDA 1994, Units: Meter

Scale @ A3: 1:140,000	Prepared: J Botterill	Revision: Rev F
Date: 1/09/2015	Checked: J Vermaak	Map: 3
	Reviewed: J Youngs	

Ethel Gorge Case Study

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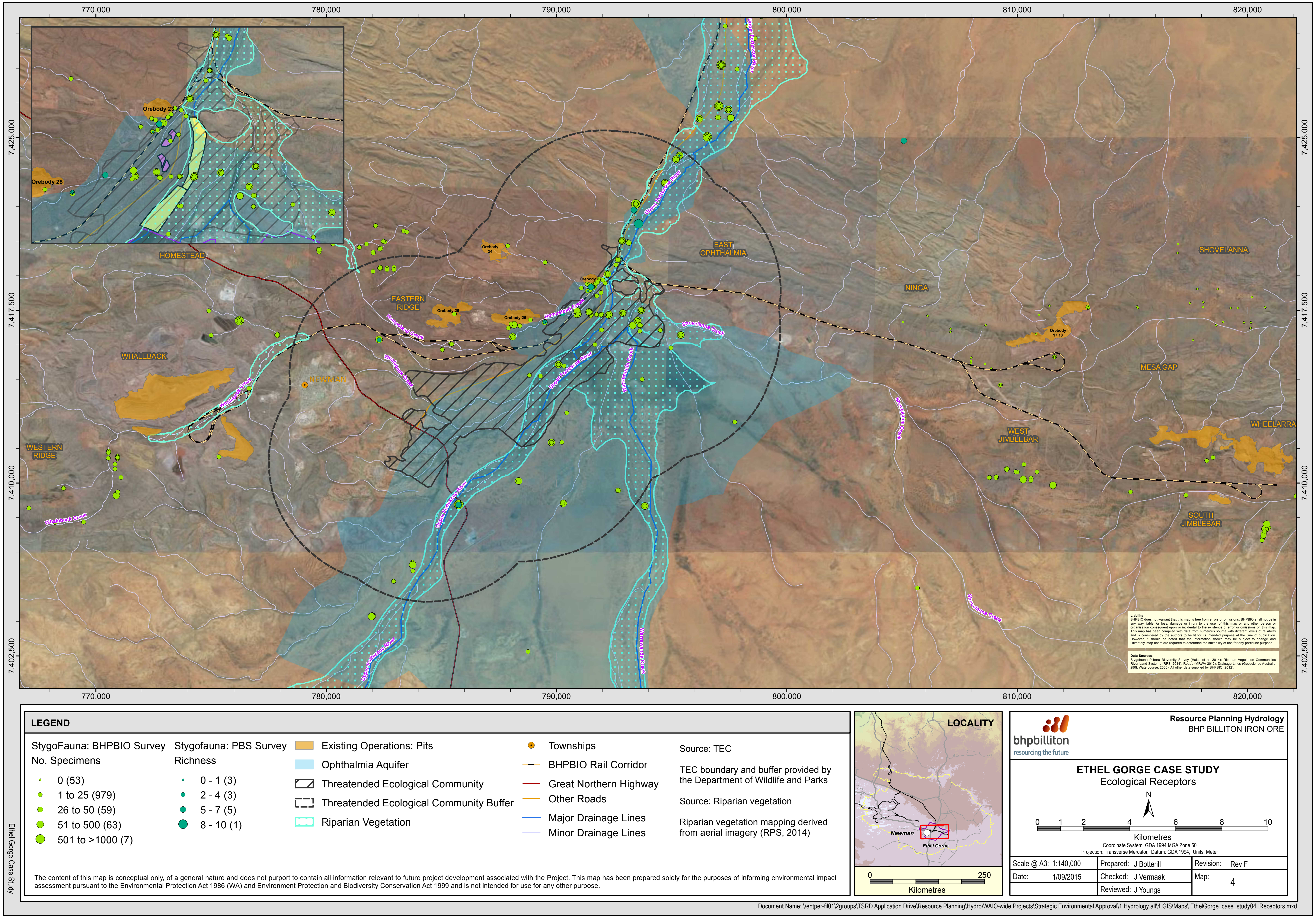

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Orebody 23
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HOMESTEAD
EASTERN RIDGE
Orebody 24
Orebody 25
EAST OPHTHALMIA
NINGA
SHOVELANNA
Orebody 17 18
MESA GAP
WHALEBACK
NEWMAN
WESTERN RIDGE
WEST JIMBLEBAR
WHEELARRA
SOUTH JIMBLEBAR
Homestead Creek
Whaleback Creek
Shovelanna Creek
Upper Fortescue River
Warrawanda Creek
LEGEND
StygoFauna: BHPBIO Survey No. Specimens
0 (53)
1 to 25 (979)
26 to 50 (59)
51 to 500 (63)
501 to >1000 (7)
Stygofauna: PBS Survey Richness
0 - 1 (3)
2 - 4 (3)
5 - 7 (5)
8 - 10 (1)
Existing Operations: Pits
Ophthalmia Aquifer
Threatened Ecological Community
Threatened Ecological Community Buffer
Riparian Vegetation
Townships
BHPBIO Rail Corridor
Great Northern Highway
Other Roads
Major Drainage Lines
Minor Drainage Lines
Source: TEC
TEC boundary and buffer provided by the Department of Wildlife and Parks
Source: Riparian vegetation
Riparian vegetation mapping derived from aerial imagery (RPS, 2014)
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LOCALITY
Newman
Ethel Gorge
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Kilometres
bhpbilliton
resourcing the future
Resource Planning Hydrology
BHP BILLITON IRON ORE
ETHEL GORGE CASE STUDY
Ecological Receptors
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Projection: Transverse Mercator, Datum: GDA 1994, Units: Meter
Scale @ A3: 1:140,000
Date: 1/09/2015
Prepared: J Botterill
Checked: J Vermaak
Reviewed: J Youngs
Revision: Rev F
Map: 4
Ethel Gorge Case Study
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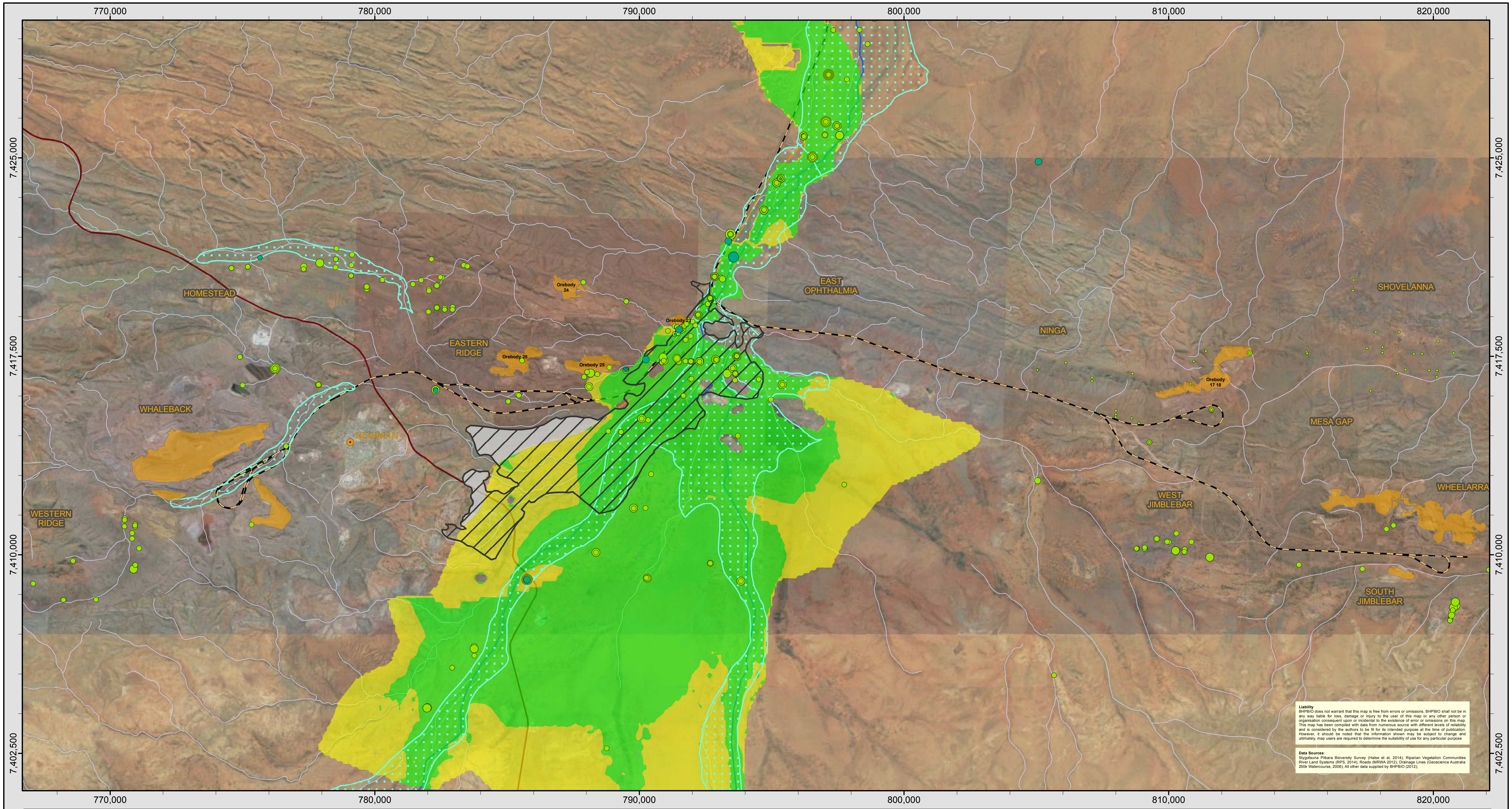

LEGEND

Stygofauna: BHPBIO Survey No. Specimens
- 0 (53)
- 1 to 25 (979)
- 26 to 50 (59)
- 51 to 500 (63)
- 501 to >1000 (7)

Stygofauna: PBS Survey Richness
- 0 - 1 (3)
- 2 - 4 (3)
- 5 - 7 (5)
- 8 - 10 (1)

- Existing Development: Pits
- Threatended Ecological Community
- Riparian Vegetation
- Zones with completely desaturated alluvium and calcrete
- Saturated thickness less than 6m
- Saturated thickness more than 6m

- Townships
- BHPBIO Rail Corridor
- Great Northern Highway
- Other Roads
- Major Drainage Lines
- Minor Drainage Lines

Notes:

Aquifer with saturated thickness of less than 6m (yellow and red) may become desaturated from time to time due to changes in groundwater levels

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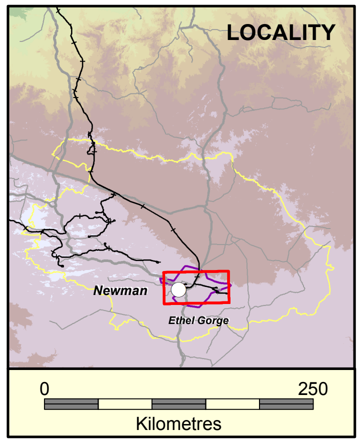


Resource Planning Hydrology
BHP BILLITON IRON ORE

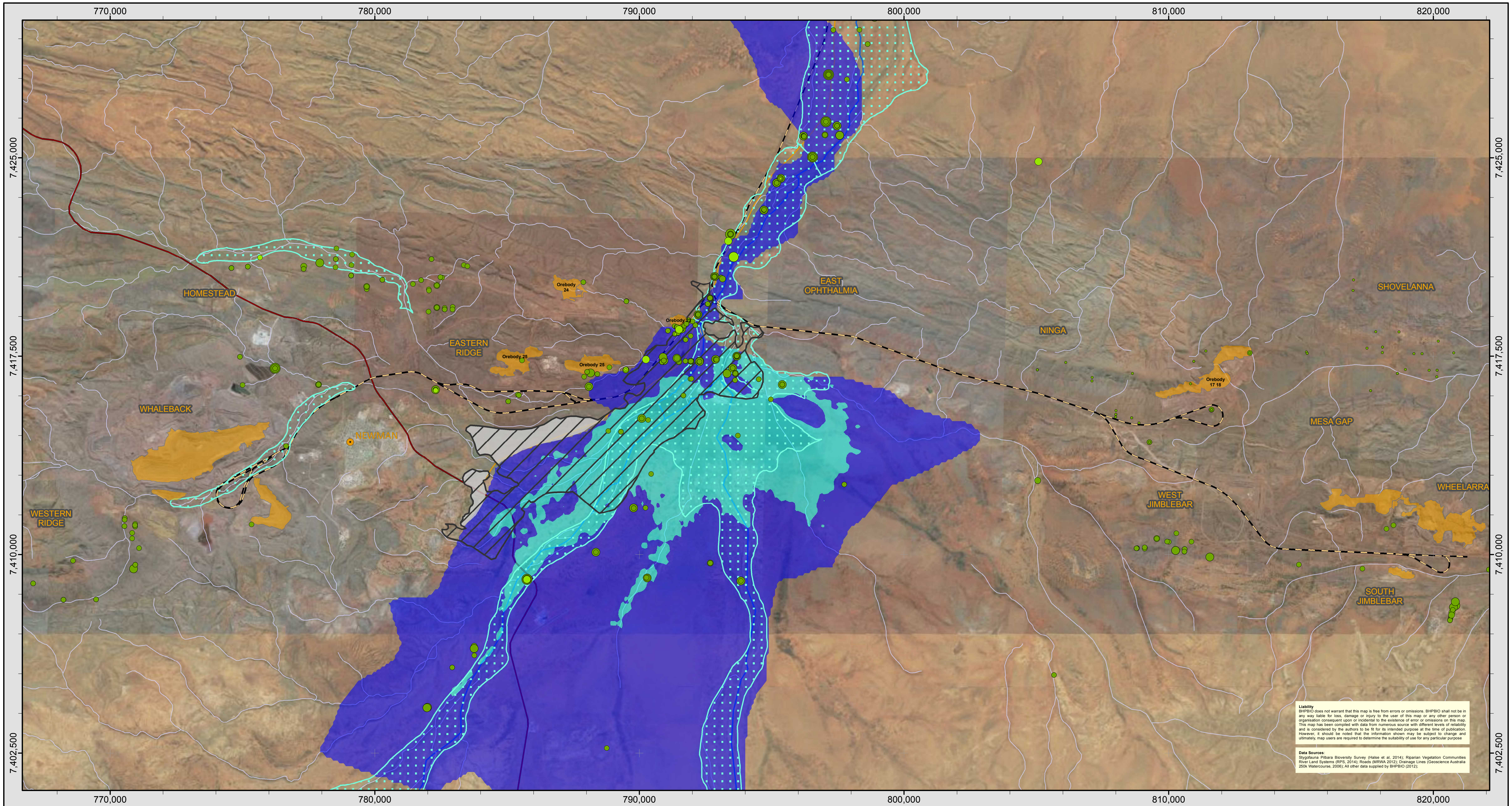
ETHEL GORGE CASE STUDY
Saturated Thickness in the Upper Ophthalmia Aquifer: 2014

N
0 1 2 4 6 8 10
Kilometres
Coordinate System: GDA 1994 MGA Zone 50
Projection: Transverse Mercator, Datum: GDA 1994, Units: Meter

Scale @ A3: 1:140,000	Prepared: J Botterill	Revision: Rev E
Date: 1/09/2015	Checked: J Vermaak	Map: 5
	Reviewed: J Youngs	

Ethel Gorge Case Study

Document Name: \\entper-fil01\2groups\TSRD Application Drive\Resource Planning\Hydro\WAIO-wide Projects\Strategic Environmental Approval\1 Hydrology all\4 GIS\Maps\ EthelGorge_case_study05_SatThick2014_RevE.mxd



LEGEND

Stygofauna: BHPBIO Survey No. Specimens
- 0 (53)
- 1 to 25 (979)
- 26 to 50 (59)
- 51 to 500 (63)
- 501 to >1000 (7)

Stygofauna: PBS Survey Richness
- 0 - 1 (3)
- 2 - 4 (3)
- 5 - 7 (5)
- 8 - 10 (1)

- Existing Development: Pits
- Threatended Ecological Community
- Riparian Vegetation
- Zones with completely desaturated alluvium and calcrete
- Depth to water table greater than 2m
- Depth to water table less than 2m

- Townships
- BHPBIO Rail Corridor
- Great Northern Highway
- Other Roads
- Major Drainage Lines
- Minor Drainage Lines

Notes:

Some facultative phreatophytes riparian vegetation may use both groundwater and soil moisture where the depth to groundwater is less than 10 m

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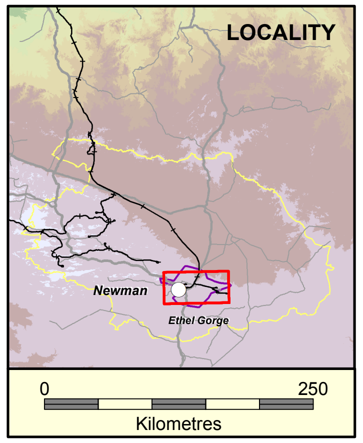
LOCALITY



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Resource Planning Hydrology
BHP BILLITON IRON ORE

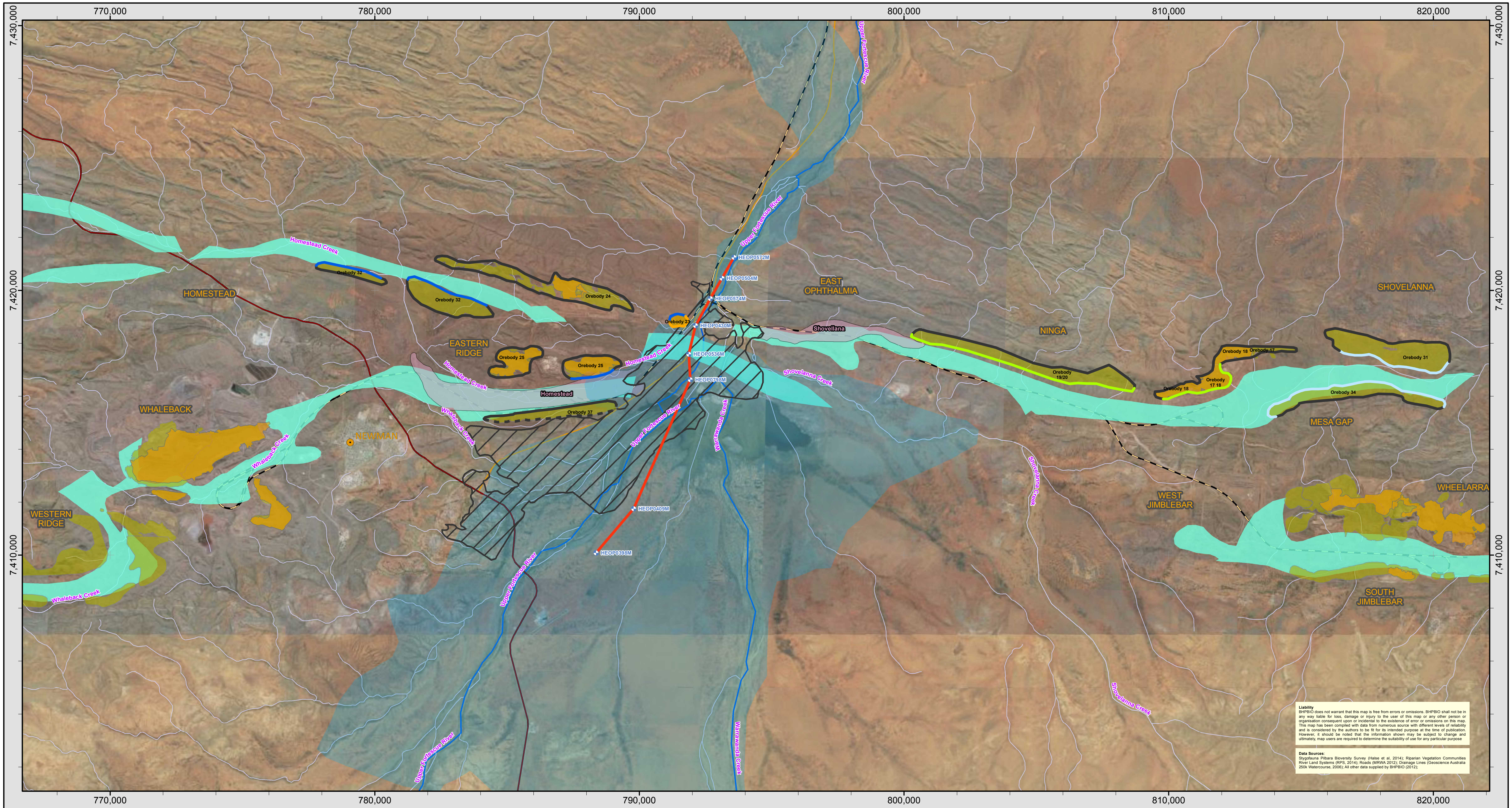
ETHEL GORGE CASE STUDY
Depth to Groundwater in the Upper Ophthalmia Aquifer: 2014

N
0 1 2 4 6 8 10
Kilometres

Coordinate System: GDA 1994 MGA Zone 50
Projection: Transverse Mercator, Datum: GDA 1994, Units: Meter

Scale @ A3: 1:140,000	Prepared: J Botterill	Revision: Rev E
Date: 1/09/2015	Checked: J Vermaak	Map: 6
	Reviewed: J Youngs	

Document Name: \\entper-fil01\2groups\TSRD Application Drive\Resource Planning\Hydro\WAIO-wide Projects\Strategic Environmental Approval\1 Hydrology all\4 GIS\Maps\ EthelGorge_case_study06_DTW2014_RevE.mxd



LEGEND

Hydraulic Connection
- No hydraulic connection
- Low permeability lithologies
- Connected via tributary palaeochannel
- Partially connected
- Fully connected to tributary palaeochannel
- Fully connected to Ophthalmia aquifer

Monitoring Bore (8)

Existing Development
- Pits

30% Development Scenario
- Pits

- Ophthalmia Aquifer Transect
- Ophthalmia Aquifer
- Threatended Ecological Community
- Tributary Palaeochannels
- Wittenoom Formation

- Townships
- BHPBIO Rail Corridor
- Great Northern Highway
- Other Roads
- Major Drainage lines
- Minor Drainage lines

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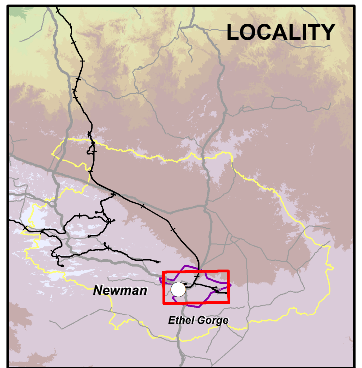
LOCALITY



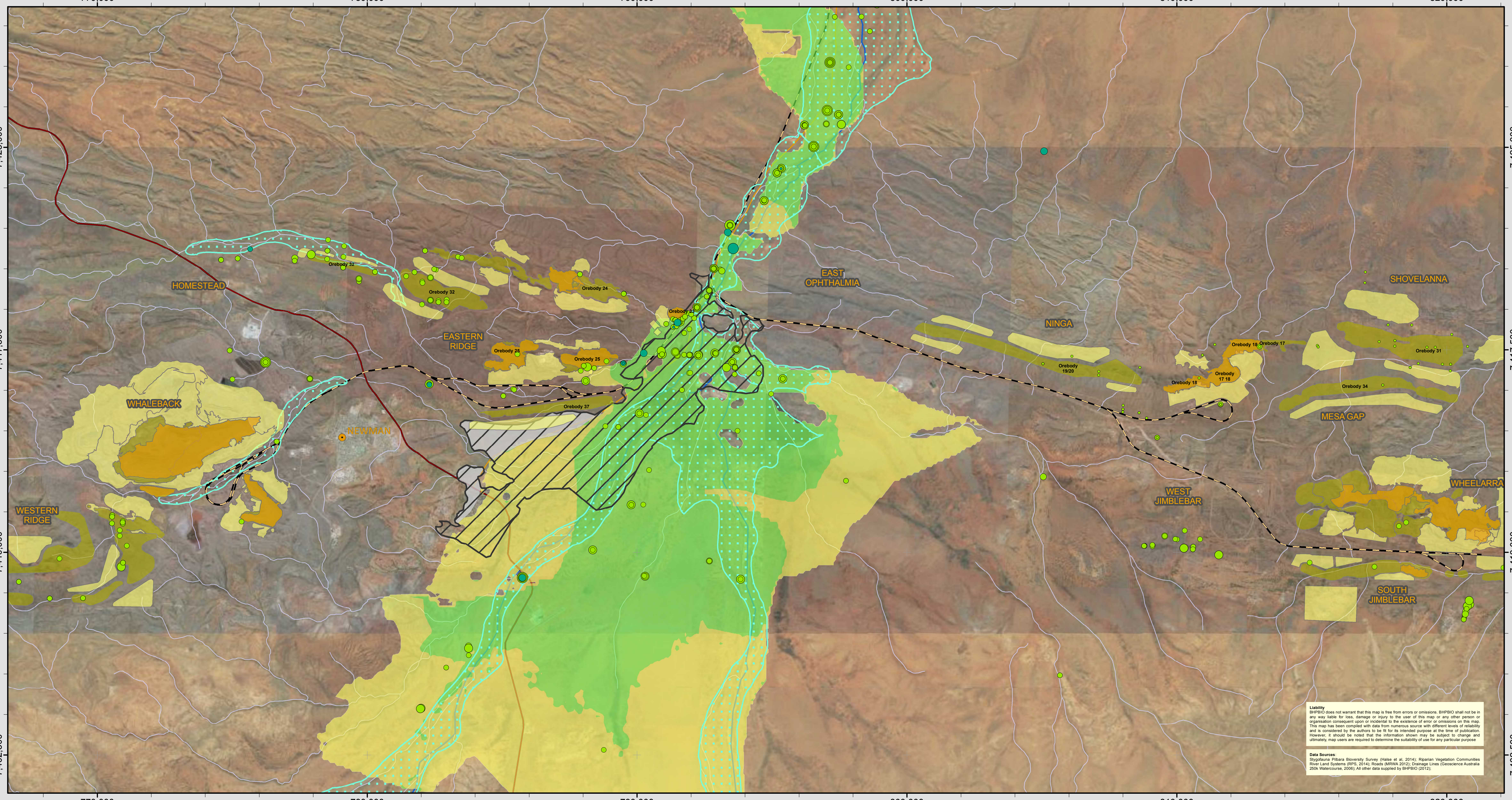
Resource Planning Hydrology
BHP BILLITON IRON ORE

ETHEL GORGE CASE STUDY
SEA orebodies and hydraulic connectivity

N
0 1 2 4 6 8 10
Kilometres
Coordinate System: GDA 1994 MGA Zone 50
Projection: Transverse Mercator, Datum: GDA 1994, Units: Meter

Scale @ A3: 1:140,000	Prepared: J Botterill	Revision: Rev F
Date: 1/09/2015	Checked: J Vermaak	Map: 7
	Reviewed: J Youngs	

Document Name: \\entper-fil01\2groups\TSRD Application Drive\Resource Planning\Hydro\WAIO-wide Projects\Strategic Environmental Approval\1 Hydrology all\4 GIS\Maps\ EthelGorge_case_study07_Hydraulic_Connectivity.mxd



LEGEND

Stygofauna: BHPBIO Survey No. Specimens
- 0 (53)
- 1 to 25 (979)
- 26 to 50 (59)
- 51 to 500 (63)
- 501 to >1000 (7)

Stygofauna: PBS Survey Richness
- 0 - 1 (3)
- 2 - 4 (3)
- 5 - 7 (5)
- 8 - 10 (1)

- Existing Development: Pits
- 30% Development Scenario: OSAs
- 30% Development Scenario: Pits
- Threatended Ecological Community
- Riparian Vegetation
- Zones with completely desaturated alluvium and calcrete
- Saturated thickness less than 6m
- Saturated thickness more than 6m

- Townships
- BHPBIO Rail Corridor
- Great Northern Highway
- Other Roads
- Major Drainage Lines
- Minor Drainage Lines

Notes:

Aquifer with saturated thickness of less than 6m (yellow and red) may become desaturated from time to time due to changes in groundwater levels.

Localised decrease of saturated thickness at Homestead tributary palaeochannel confluence.

Localised increase of saturated thickness adjacent to OB23.

Localised decrease of saturated thickness along western margin of Ophthalmia aquifer.

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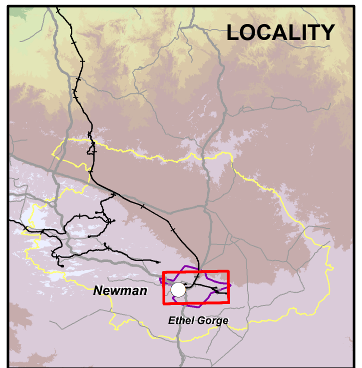
LOCALITY



Resource Planning Hydrology
BHP BILLITON IRON ORE

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ETHEL GORGE CASE STUDY

Saturated Thickness in the Upper Ophthalmia Aquifer: 2030

N

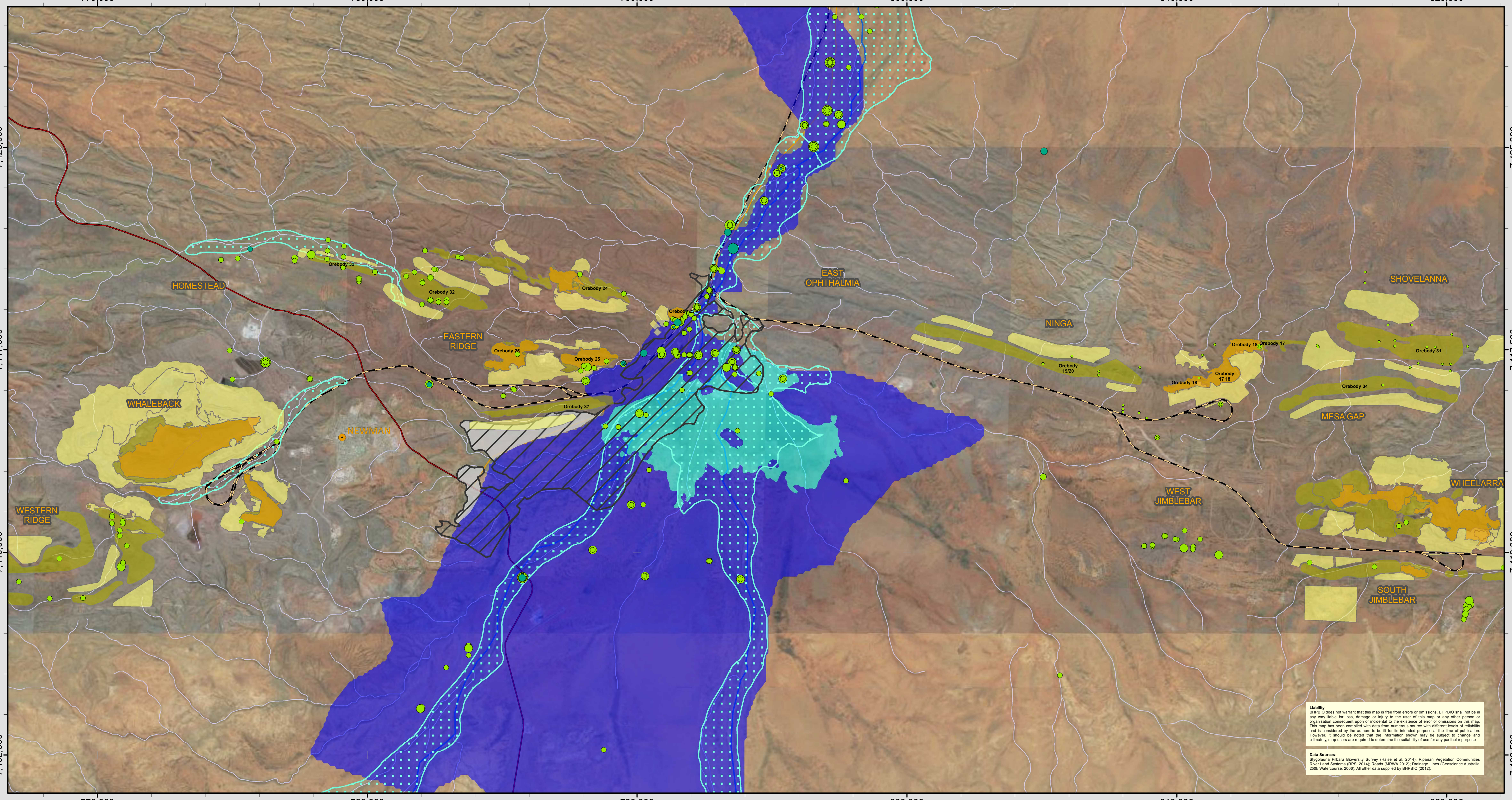
0 1 2 4 6 8 10
Kilometres

Coordinate System: GDA 1994 MGA Zone 50
Projection: Transverse Mercator, Datum: GDA 1994, Units: Meter

Scale @ A3: 1:140,000	Prepared: J Botterill	Revision: Rev E
Date: 1/09/2015	Checked: J Vermaak	Map: 8
	Reviewed: J Youngs	

Ethel Gorge Case Study

Document Name: \\entper-fil01\2groups\TSRD Application Drive\Resource Planning\Hydro\WAIO-wide Projects\Strategic Environmental Approval\1 Hydrology all\4 GIS\Maps\ EthelGorge_case_study08_SatThick2030_RevE.mxd



LEGEND

Stygofauna: BHPBIO Survey No. Specimens
- 0 (53)
- 1 to 25 (979)
- 26 to 50 (59)
- 51 to 500 (63)
- 501 to >1000 (7)

Stygofauna: PBS Survey Richness
- 0 - 1 (3)
- 2 - 4 (3)
- 5 - 7 (5)
- 8 - 10 (1)

- Existing Development: Pits
- 30% Development Scenario: OSAs
- 30% Development Scenario: Pits
- Threatended Ecological Community
- Riparian Vegetation
- Zones with completely desaturated alluvium and calcrete
- Depth to water table greater than 2m
- Depth to water table less than 2m

- Townships
- BHPBIO Rail Corridor
- Great Northern Highway
- Other Roads
- Major Drainage Lines
- Minor Drainage Lines

Notes:

Some facultative phreatophytes riparian vegetation may use both groundwater and soil moisture where the depth to groundwater is less than 10 m.

Localised increase of depth to groundwater at Homestead tributary palaeochannel confluence.

Localised decrease of depth to groundwater adjacent to OB23.

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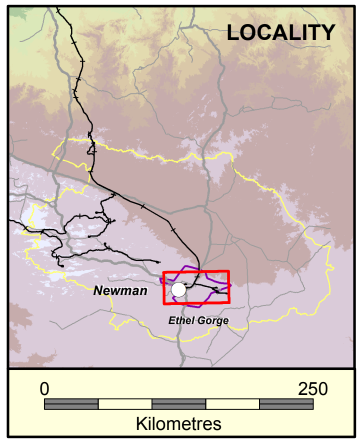
LOCALITY



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ETHEL GORGE CASE STUDY

Depth to Groundwater in the Upper Ophthalmia Aquifer: 2030

N

0 1 2 4 6 8 10
Kilometres

Coordinate System: GDA 1994 MGA Zone 50
Projection: Transverse Mercator, Datum: GDA 1994, Units: Meter

Scale @ A3: 1:140,000	Prepared: J Botterill	Revision: Rev E
Date: 1/09/2015	Checked: J Vermaak	Map: 9
	Reviewed: J Youngs	

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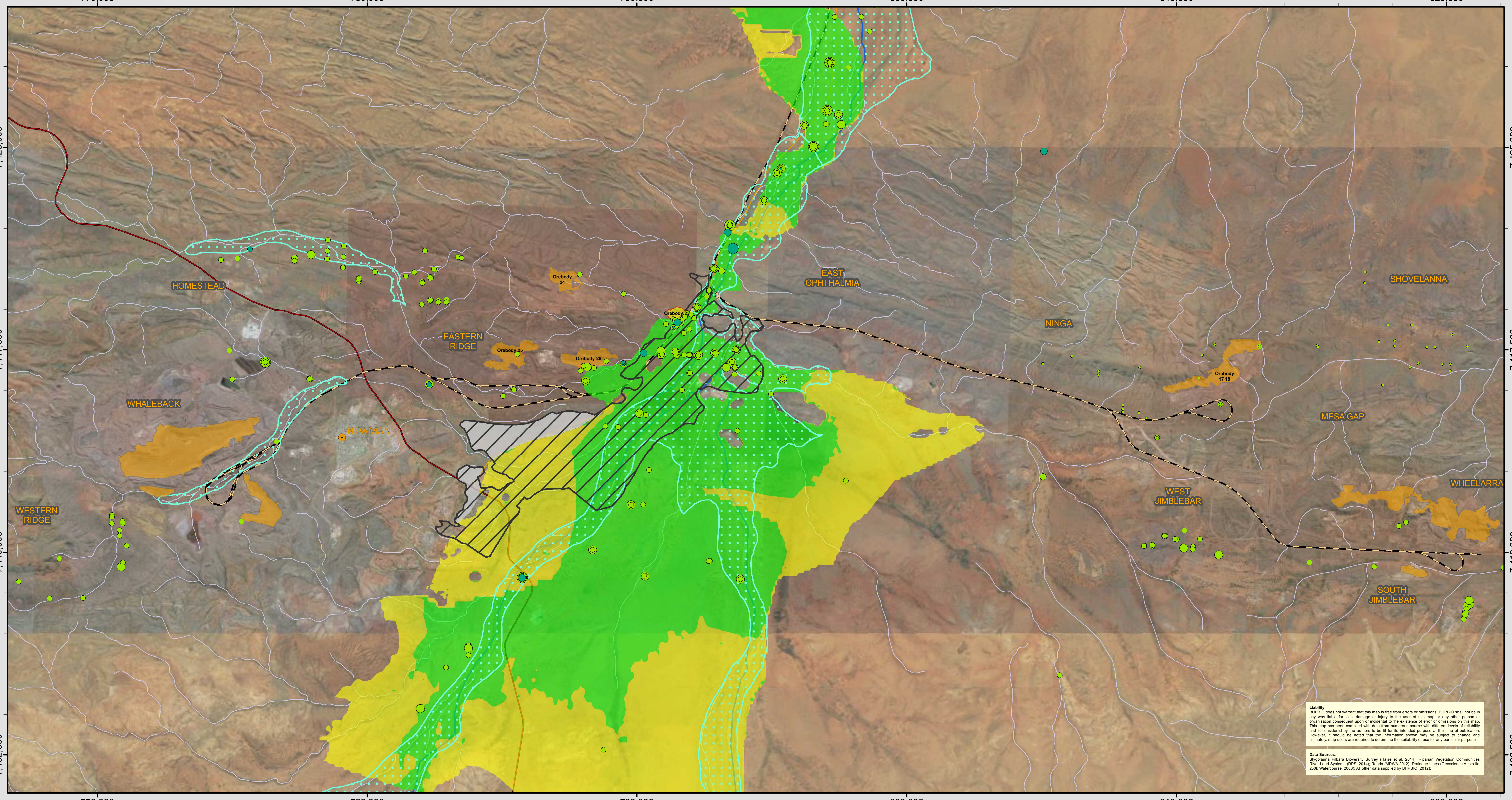

LEGEND

Stygofauna: BHPBIO Survey No. Specimens
- 0 (53)
- 1 to 25 (979)
- 26 to 50 (59)
- 51 to 500 (63)
- 501 to >1000 (7)

Stygofauna: PBS Survey Richness
- 0 - 1 (3)
- 2 - 4 (3)
- 5 - 7 (5)
- 8 - 10 (1)

Existing & 30% Development Scenario
- Backfilled: OB23 (1)
- Open: all other orebodies (11)
- Threatended Ecological Community
- Riparian Vegetation
- Zones with completely desaturated alluvium and calcrete
- Saturated thickness less than 6m
- Saturated thickness more than 6m

- Townships
- BHPBIO Rail Corridor
- Great Northern Highway
- Other Roads
- Major Drainage Lines
- Minor Drainage Lines

Notes:

Aquifer with saturated thickness of less than 6m (yellow and red) may become desaturated from time to time due to changes in groundwater levels.

Localised increase of saturated thickness adjacent at Ethel Gorge.

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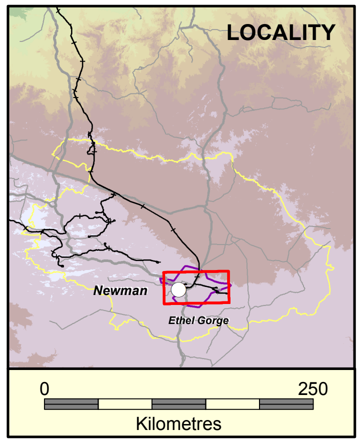

Resource Planning Hydrology
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ETHEL GORGE CASE STUDY

Saturated Thickness in the Upper Ophthalmia Aquifer: 2072

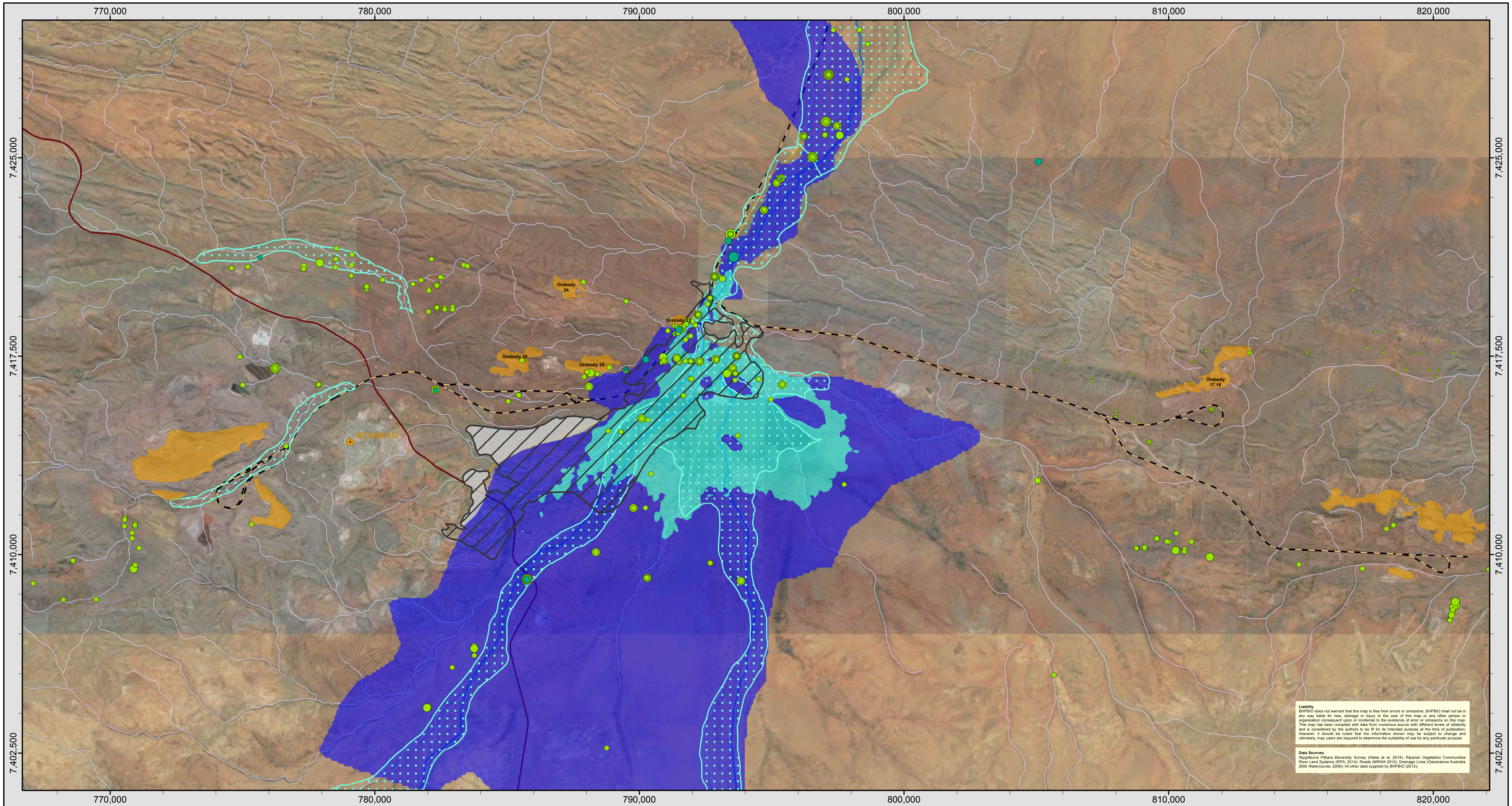
N

0 1 2 4 6 8 10
Kilometres

Coordinate System: GDA 1994 MGA Zone 50
Projection: Transverse Mercator, Datum: GDA 1994, Units: Meter

Scale @ A3: 1:140,000	Prepared: J Botterill	Revision: Rev E	
Date: 1/09/2015	Checked: J Vermaak	Map:	10
	Reviewed: J Youngs		

Document Name: \\entper-fil01\2groups\TSRD Application Drive\Resource Planning\Hydro\WAIO-wide Projects\Strategic Environmental Approval\1 Hydrology all\4 GIS\Maps\ EthelGorge_case_study10_SatThick2072_RevE.mxd



LEGEND

Stygofauna: BHPBIO Survey No. Specimens

- 0 (53)
- 1 to 25 (979)
- 26 to 50 (59)
- 51 to 500 (63)
- 501 to >1000 (7)

Stygofauna: PBS Survey Richness

- 0 - 1 (3)
- 2 - 4 (3)
- 5 - 7 (5)
- 8 - 10 (1)

- Existing Development: Pits
- Threatended Ecological Community
- Riparian Vegetation
- Zones with completely desaturated alluvium and calcrete
- Depth to water table greater than 2m
- Depth to water table less than 2m

- Townships
- BHPBIO Rail Corridor
- Great Northern Highway
- Other Roads
- Major Drainage Lines
- Minor Drainage Lines

Notes:

Some facultative phreatophytes riparian vegetation may use both groundwater and soil moisture where the depth to groundwater is less than 10 m.

Localised decrease of depth to groundwater adjacent at Ethel Gorge.

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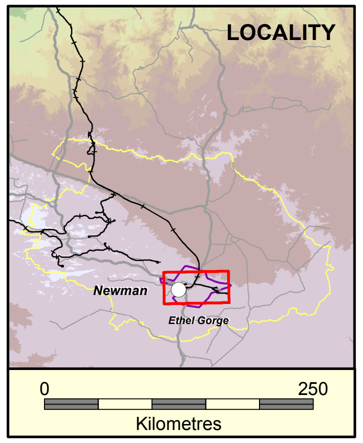

Resource Planning Hydrology
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ETHEL GORGE CASE STUDY

Depth to Groundwater in the Upper Ophthalmia Aquifer: 2072

N

0 1 2 4 6 8 10
Kilometres

Coordinate System: GDA 1994 MGA Zone 50
Projection: Transverse Mercator, Datum: GDA 1994, Units: Meter

Scale @ A3: 1:140,000	Prepared: J Botterill	Revision: Rev E
Date: 1/09/2015	Checked: J Vermaak	Map: 11
	Reviewed: J Youngs	

Document Name: \\entper-fil01\2groups\TSRD Application Drive\Resource Planning\Hydro\WAIO-wide Projects\Strategic Environmental Approval\1 Hydrology all\4 GIS\Maps\ EthelGorge_case_study11_DTW2072_RevE.mxd

Ethel Gorge Case Study

4.95cm

Section 1: Historical groundwater level and salinity changes

Introduction

This section provides a summary of the historical ranges in groundwater levels and salinity at Ethel Gorge. The purpose of the analysis is to determine the observed range of groundwater conditions under which ecological communities have remained resilient to changing climate and water conditions associated with natural and anthropological influences.

A number of key indicators have been identified defining the observed ranges at Ethel Gorge including groundwater levels and quality, as well as subterranean fauna abundance, diversity and health. The analysis has considered the range, trend and rate of changes for these key indicators. The key indicators will form the basis for developing early-warning triggers and thresholds for potential impacts on the Ethel Gorge subterranean ecological community.

The Ethel Gorge stygobiont community is a rich and diverse stygofauna grouping that occurs in the Ophthalmia aquifer situated upgradient of Ethel Gorge within the Ophthalmia Valley. It is listed as a Threated Ecological Community (TEC) by the Department of Parks and Wildlife (DPaW) with some stygofauna species endemic to Ethel Gorge. The stygofaunal habitat comprises calcrete and alluvium aquifers, which underlies the broad Ophthalmia Valley and Ethel Gorge, the latter containing the most abundant and diverse community.

The Ophthalmia Dam Recharge Scheme was developed in the 1980s to replenish groundwater resources through artificial recharge. Runoff from the Fortescue River flows into the Ophthalmia Dam and then recharges the groundwater resource providing an offset effect with respect to groundwater abstraction. Since 2006, mine dewatering at OB23 and OB25 has resulted in localised groundwater drawdown; however, these impacts have been offset by infiltration from Ophthalmia Dam as well as three recharge ponds situated close to OB23.

BHP Billiton Iron Ore plans to manage future surplus mine water, which may contain higher water salinities, by discharging the water into Ophthalmia Dam. This discharge of mine water will be conducted in accordance to the Ophthalmia Dam Water Management Plan (ODWMP), so that key indicators will remain within the threshold values.

Hydrogeology

The main aquifers at the Ethel Gorge region comprise alluvial sediments that infill the floodplain and channels of the Fortescue River and its tributaries. There are upper and lower alluvium and calcrete aquifers being separated by a thick clay layer. Stygofauna sampling suggests that the stygofauna tend to occur mainly in the upper alluvium and calcrete aquifer.

The upper aquifer comprising sand, gravel and calcrete is present across the Fortescue River floodplain. The thickness of the upper aquifer varies between 10 and 30 m with calcrete being developed in this sequence. Calcrete is particularly well developed in Ethel Gorge being up to 30 m thick. The sand, gravel and calcrete form a high permeability, unconfined aquifer.

An extensive clay layer separates the upper and lower alluvium layers. This clay layer occurs across most of the floodplain but is thinner to absent near basement margins. The clay is considered to form an aquitard.

The clay unit is underlain by a lower aquifer unit which has accumulated in the troughs between basement highs; hence, the aquifer is not believe to be continuous.

A key structural geology feature is the major northeast-trending fault which underlies the Fortescue River and Ethel Gorge. The geological sequence on the eastern side of the fault has been offset by about 2 km to the north. There are several east-west basement subcrops through the alluvium comprising Marra Mamba and Brockman Formations. OB37 and OB42 are positioned within one of these basement highs being about 1 km north of Ophthalmia Dam.

Figure 1 shows the geological long-sections through the Fortescue and Homestead Creek floodplains, showing the basement highs and troughs.

Section 1: Historical groundwater level and salinity changes continued

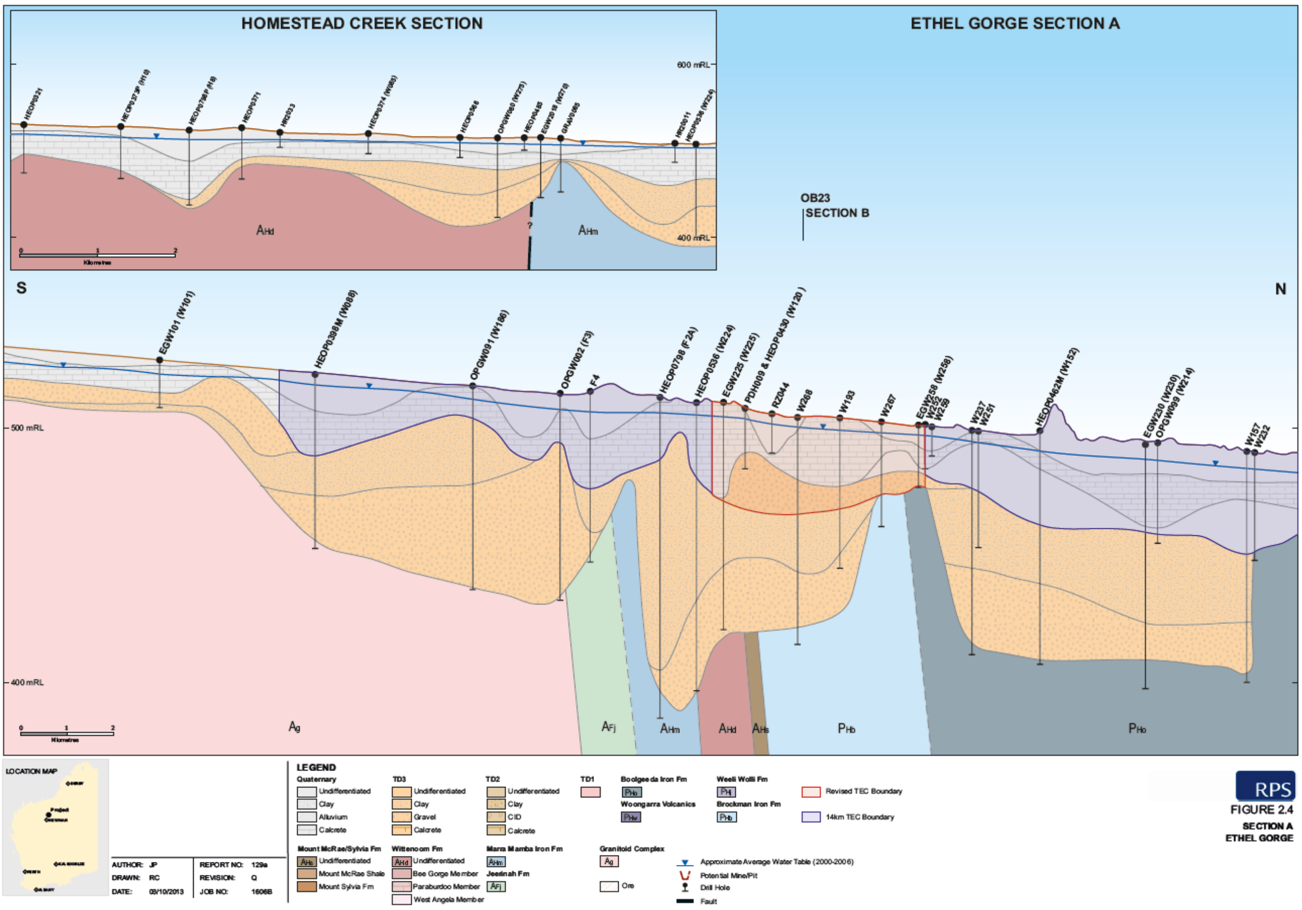

Figure 1: Geological long-section through the Fortescue River and Homestead Creeks

Aquifer thickness, groundwater fluctuations and rate of decline

There are long-term groundwater levels from 1971 to current for the Ethel Gorge and Ophthalmia alluvial aquifers. Groundwater levels appear to have been influenced by a number of anthropological and natural changes in the region and these are described in more detail below.

Figure 2 shows the locations of some of the monitoring bores which have been analysed and Figure 3 shows the hydrographs for these monitoring wells.

The groundwater response to mine dewatering has also been described in more detail in a separate BHPBIO memorandum “Summary of Ophthalmia Dam studies” dated 25 February 2014.

Section 1: Historical groundwater level and salinity changes continued

4.95cm

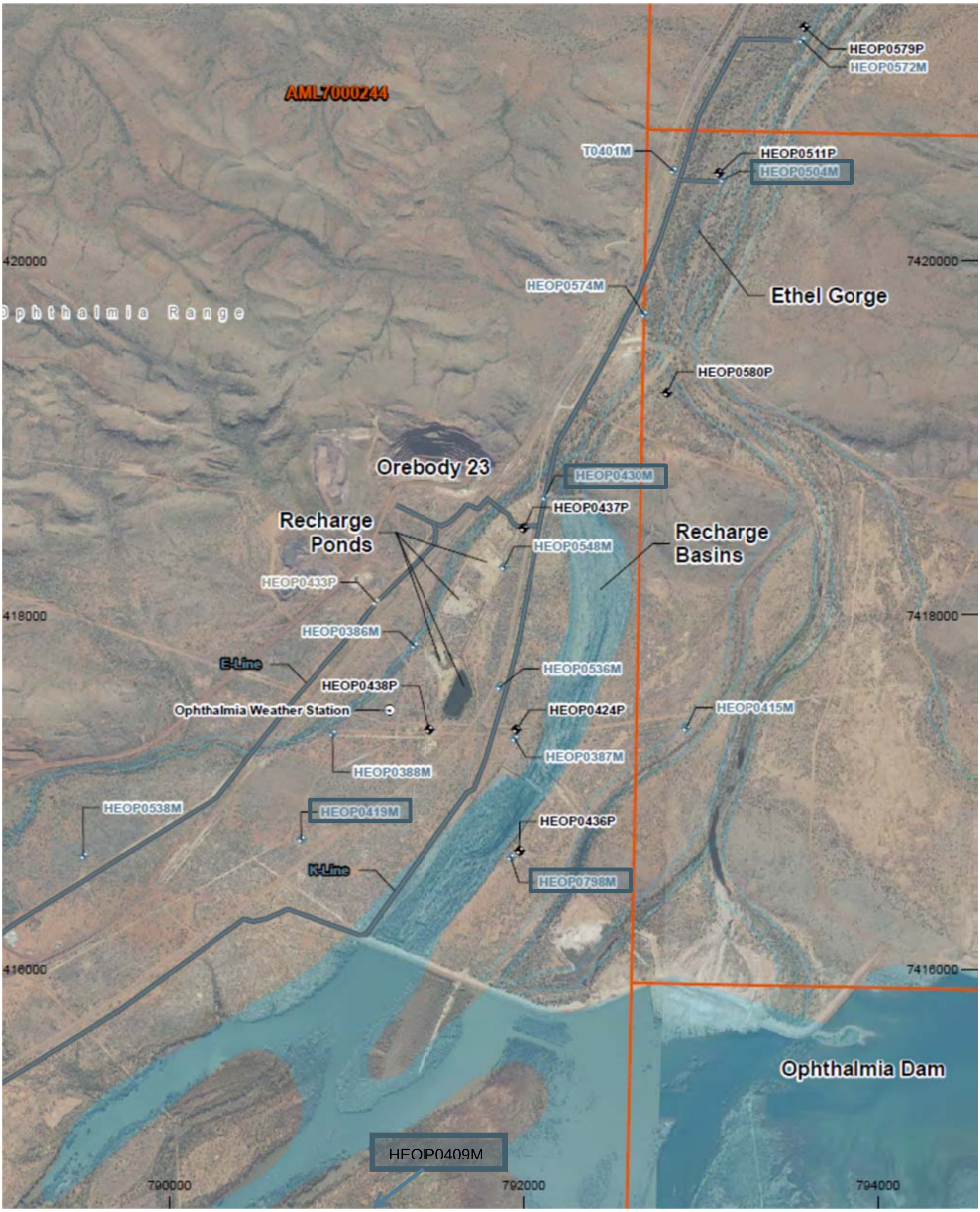

Figure 2: Locations of monitoring bores

Section 1: Historical groundwater level and salinity changes continued

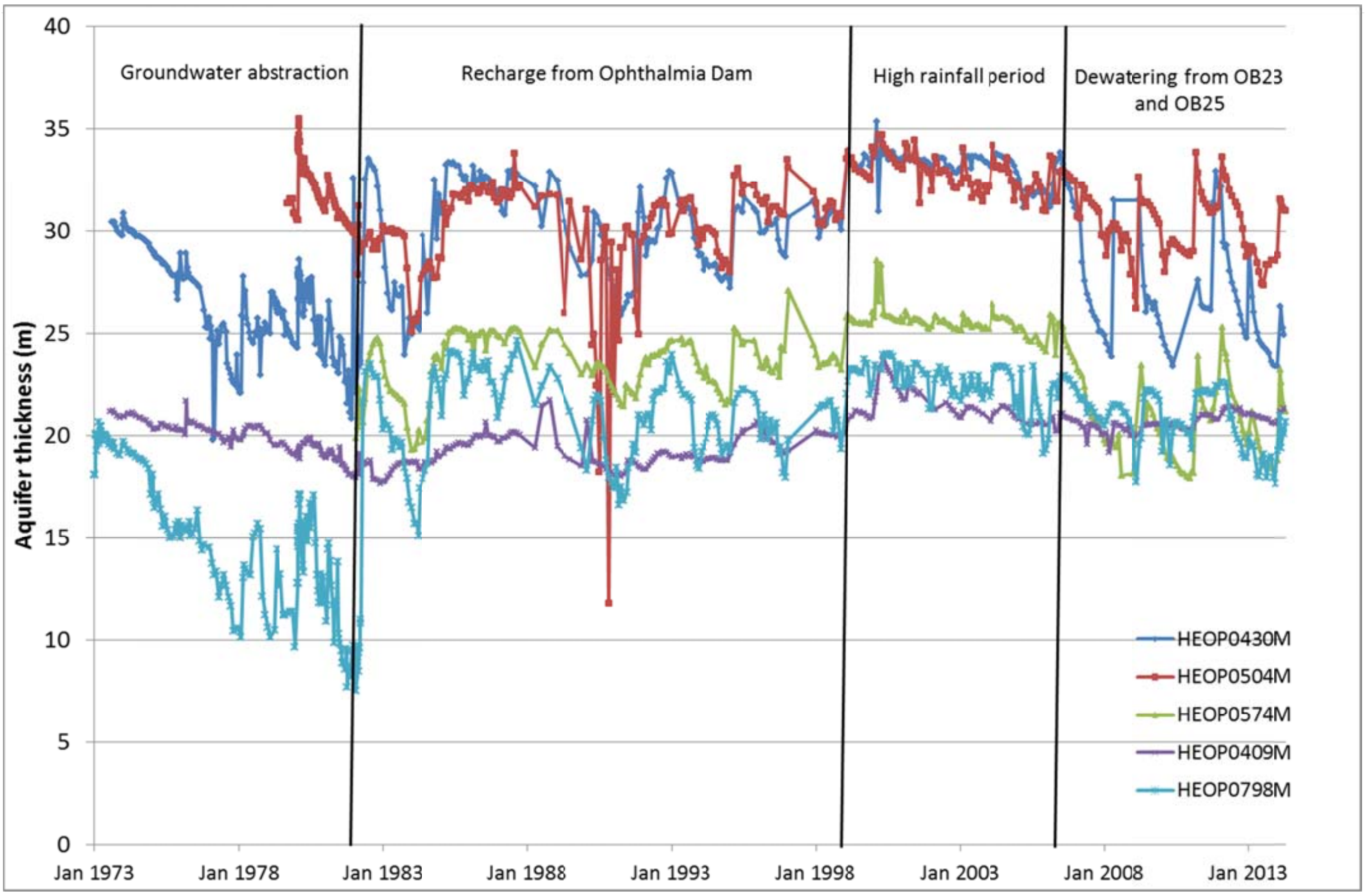

Figure 3: Hydrographs showing the changes in aquifer thickness

Phase 1: Groundwater abstraction

The Ophthalmia Borefield was established in the 1970s to provide water for the mining operations and the Newman township. Figure 3 shows a substantial decrease in groundwater levels over a period of about ten years between 1972 and 1982. Groundwater levels in the vicinity of Ethel Gorge decreased by 10 to 14 m. In contrast, very little groundwater drawdown was observed in the upstream portion of the alluvial aquifer.

Phase 2: Ophthalmia Dam Construction

Ophthalmia Dam was constructed in 1981 by the Mt Newman Mining Company to replenish groundwater levels in the Ophthalmia borefield. The Ophthalmia Dam recharged the groundwater resource in the alluvial aquifer resulting in , increased groundwater levels in the borefield. Figure 3 shows the recharge processes from Ophthalmia Dam during the initial years of the dam operations. In the central regions of the borefield (close to Ophthalmia Dam), groundwater levels increased by about 10 metres and water levels recovered to baseline groundwater levels. In the northern part of the borefield, close to Ethel Gorge, groundwater levels also increased but groundwater levels were about 3 m lower than baseline groundwater levels.

Phase 3: High groundwater levels and high rainfall period

Between 1999 and 2006, significant above-average rainfall occurred in the Ethel Gorge catchments resulting in substantial above average runoff from the Fortescue River and associated creeks into the Ophthalmia Dam. The high rainfall also coincided with lower groundwater abstraction from the Ophthalmia Borefield, as dewatering discharge was used in preference to Ophthalmia Borefield to meet mine water requirements.

The increased runoff from the catchment resulted in higher water levels in Ophthalmia Dam with the dam retaining water till the end of the dry season unlike other years. As such, the sustained leakage from Ophthalmia Dam produced increased groundwater levels across the borefield.

Figure 3 shows the groundwater hydrographs and increased groundwater levels from 1998 to 2000, after which levels remained relatively stable until 2006. Groundwater fluctuations are subdued compared with other periods.

Section 1: Historical groundwater level and salinity changes continued

4.95cm

Phase 4: Dewatering from OB23 and OB25

Mine dewatering related to OB23 and OB25commenced in 2006 resulting in the development of a groundwater drawdown cone around the open pits. The drawdown cone mainly occurred in the mineralised bedrock around the pit with a small portion of groundwater drawdown extending into the alluvial aquifer.

Figure 3 shows the groundwater hydrographs and shows a marked decrease for the period 2006 to 2013 in some monitoring bores indicating that a portion of the aquifer has been affected by mine dewatering activities. In addition to the effects of drawdown around OB23 and OB25, groundwater levels have tended to naturally recede following the very wet 1998 to 2000 period.

Groundwater fluctuations are much higher compared to other periods, partially owing to rainfall variability during the period (high rainfall years in between low rainfall years), variability in pumping rates from the abstraction bores, mine dewatering from OB23 and OB25, and discharge of surplus dewatering water into Ophthalmia Dam and recharge basins

Table 1 is a summary of the aquifer thickness, groundwater fluctuations and rate of groundwater decline for each of the four phases and the entire groundwater level record.

Table 1: Summary of aquifer thickness and fluctuations

Period	Description	Aquifer Thickness	Groundwater fluctuations	Rate of groundwater decline
1971-1981	Groundwater abstraction before Ophthalmia Dam	8 to 35 m	1 to 5 m	1 to 12 m over 10 years
1981-1999	Groundwater recovery after Ophthalmia Dam	18 to 34 m	1 to 5 m	0 to 5 m over 3 years
1999-2006	High rainfall and high groundwater levels	21 to 34 m	0 to 2 m	0 to 1 m over 6 years
2006-2014	Groundwater drawdown from OB23 and OB25	18 to 31 m	1 to 6 m	0 to 4 m over 2 years
1971-2014	Entire range	8 to 35 m	0 to 6 m	0 to 2.5 m per year[1]

[1]Represent long-term rate of groundwater decline. The short term rate of groundwater decline could be up to 6 m per year and depends on fluctuations of groundwater abstraction from the production bores.

Groundwater Quality

There is long-term groundwater quality data from 1978 to present for the Ethel Gorge and Ophthalmia alluvial aquifers. The change in water salinity has been used to represent groundwater quality changes associated with the infiltration of fresh surface water and evapoconcentration.

The groundwater salinity data comprised a mixture of laboratory TDS measurements, laboratory electrical conductivity (EC) measurements, field EC measurements and a combination of the aforementioned. The average TDS to EC ratio was calculated for readings where both TDS and EC data were available. The average TDS to EC ratio was consistent for all production bores at 0.61. For readings where only EC was available, TDS was calculated by multiplying the EC to the average TDS/EC ratio to create long-term calculated TDS values.

Figure 4 shows the location of monitoring bores from which groundwater quality data was used for the analysis. Figure 5 shows the calculated groundwater salinity for these production bores.

The groundwater quality at Ophthalmia Dam has also been described in a separate BHPBIO memorandum “Summary of Ophthalmia Dam studies” dated 25 February 2014.

Section 1: Historical groundwater level and salinity changes continued

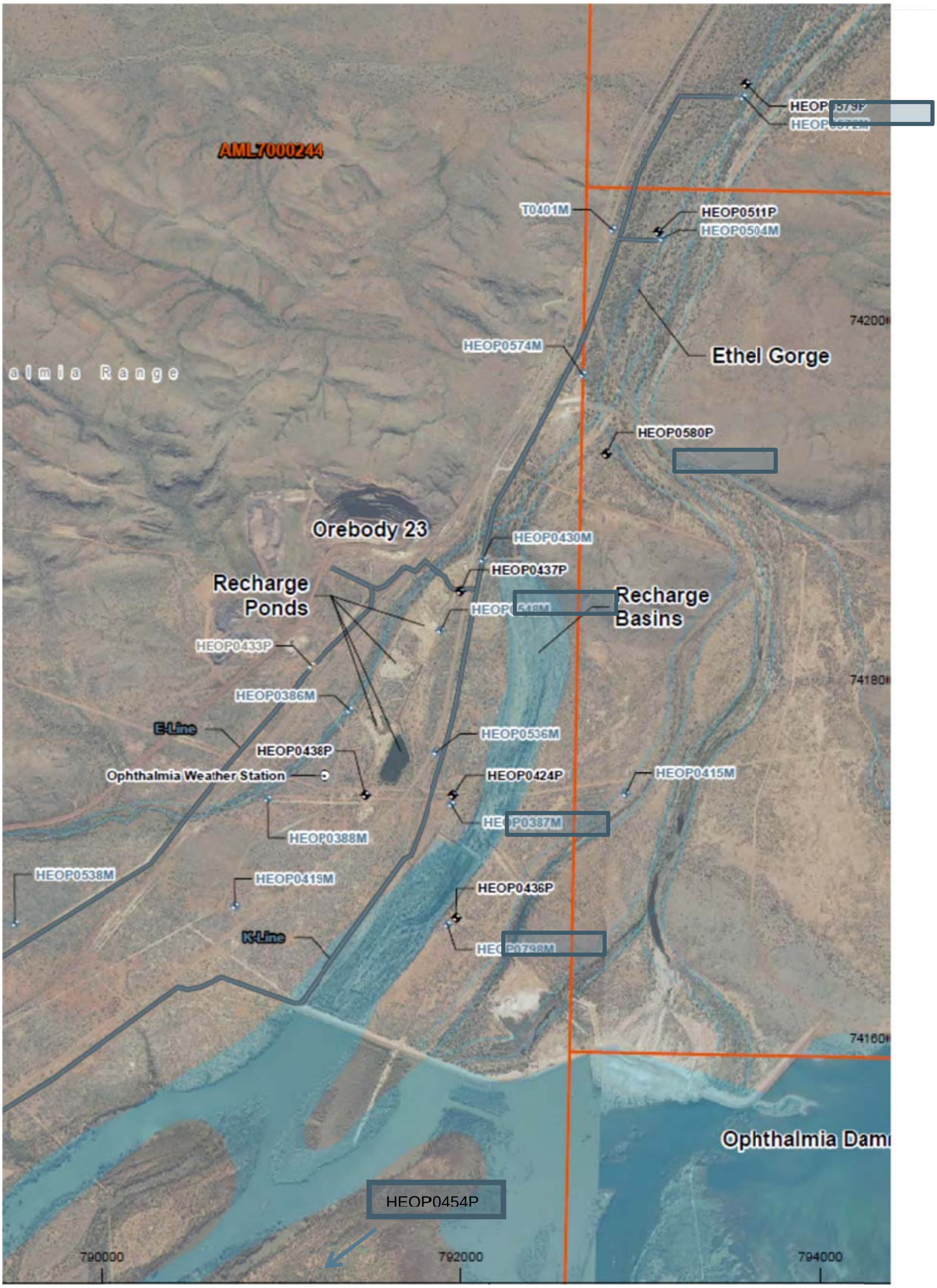

Figure 4: Locations of production bores

Section 1: Historical groundwater level and salinity changes continued

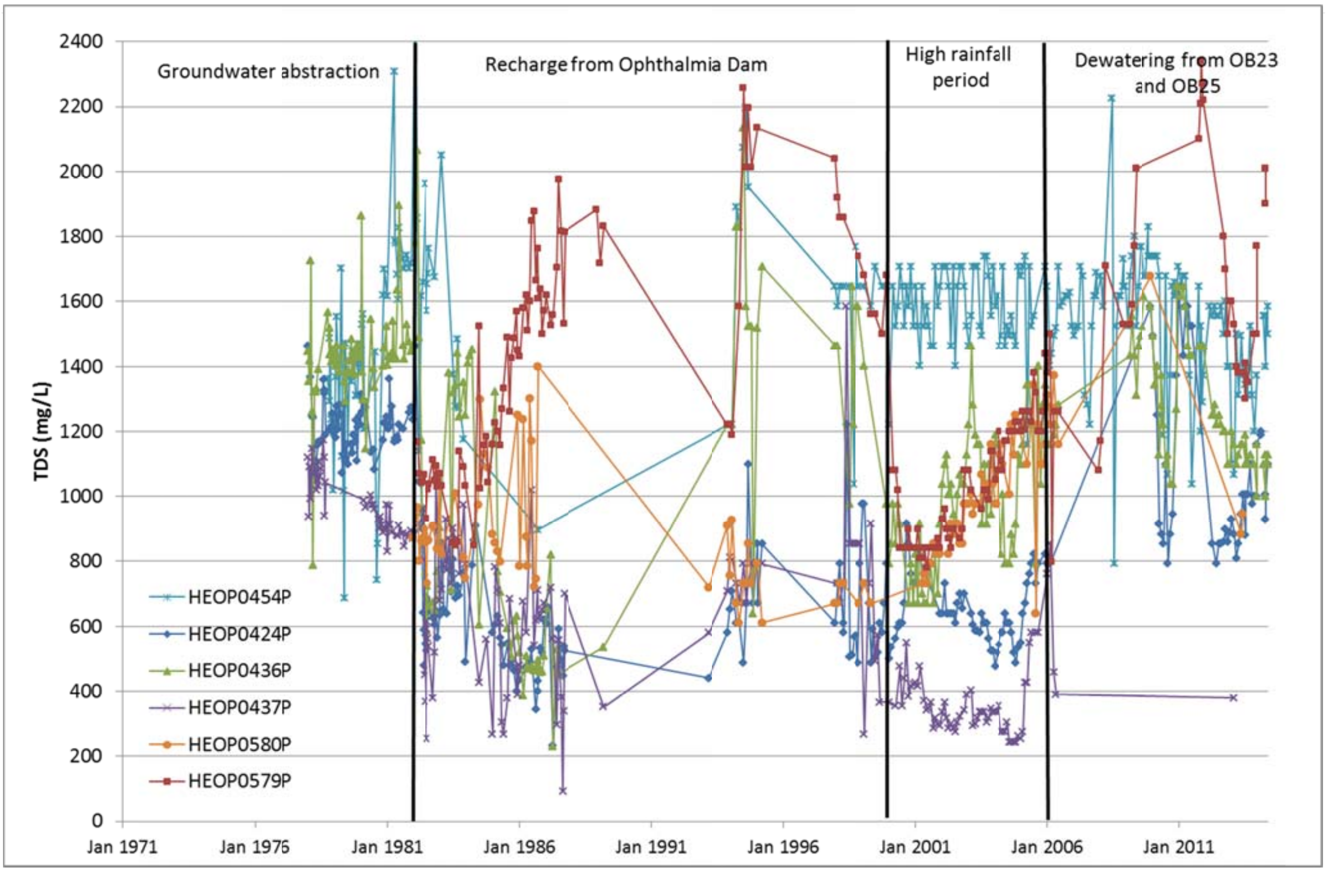

Figure 5: TDS records for the production bores

Groundwater quality has been influenced by a number of anthropological and natural changes in the region which were described earlier. The trends in groundwater salinity for the down-gradient bores (HEOP04579P and HEOP0580P), shown in Figure 5 as red and orange colours, are noticeably different to the central bores and these are discussed in more detail below.

Phase 1: Groundwater abstraction

Before the Ophthalmia Dam was in place, groundwater salinity increased gradually in response to groundwater abstraction. This increase in salinity probably reflects groundwater inflows and contribution from the adjacent bedrock aquifers, which have a higher salinity when compared to the alluvium aquifers.

Groundwater salinity ranged between 1000 to 1400 mg/L before increasing to 1800 mg/L in 1981.

Phase 2: Ophthalmia Dam

Groundwater salinity decreased rapidly after the Ophthalmia Dam was constructed beiong associated with the infiltration of fresh surface water. The central bores shows a continued decreasing salinity trend to about 400 mg/L in response to continued infiltration of surface water.

In contrast, the down-gradient production bores show a substantial increase in salinity. This may be associated with substantial transpiration from the woodland that occur down-gradient of the dam and along Ethel Gorge, as well as evapoconcentration processes.

After the dam was constructed, flows from the Fortescue River were contained in the dam and there were very few instances that the dam overflowed. As a result, there have been few instances where fresh surface water may infiltrate the down-gradient portion of the creek and reduce groundwater salinity.

Phase 3: High rainfall period

The 1999/2000 high rainfall period resulted in significant inflows into the Ophthalmia Dam, which overflowed into the down-gradient creek. A large portion of this overflow water infiltrated the alluvium aquifer resulting in a significant reduction in groundwater salinity. Groundwater salinity in all production bores, except the up-gradient production bore (HEOP0454P), decreased to less than 900 mg/L.

Section 1: Historical groundwater level and salinity changes continued

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After the 1999/2000 event, groundwater quality showed a similar trend to the initial years of Phase 2 with down-gradient production bores increasing in groundwater salinity, while central bores decreased gradually to about 300 to 500 mg/L.

Phase 4: dewatering from OB23 and OB25

Groundwater salinity trends between 2006 and 2014 showed substantial variability reflecting the variability of overflows from the Ophthalmia Dam and discharge of higher salinity surplus dewatering water into Ophthalmia Dam. The groundwater salinity has generally increased between 2006 and 2010 before decreasing between 2010 and 2014.

The range in groundwater salinity between 2006 and 2014 was more or less similar to the period 1978 to 1981, except for the down-gradient production bore HEOP0579P with an increase to about 2300 mg/L before decreasing to 1400 mg/L.

Table 2 presents the ranges in groundwater salinity, fluctuations and the rate of salinity increases for the respective phases. There is a considerable range in groundwater salinities during this period. Importantly, stygofauna sampling does not show any significant changes in species abundance or diversity suggesting that the stygobiont community appears to be resilient to groundwater salinity changes.

Table 2: Summary of groundwater salinity

Period	Description	Salinity range (mg/L)	Salinity fluctuations (mg/L)	Rate of salinity concentration increase
1971-1981	Groundwater abstraction before Ophthalmia Dam	800 – 1800	100 – 400	400 mg/l over 3 years
1981-1999	Groundwater recovery after Ophthalmia Dam	200 – 2200	100 – 800	800 mg/l over 3 years
1999-2006	High rainfall and high groundwater levels	200 – 1700	100 – 300	600 mg/l over 4 years
2006-2014	Groundwater drawdown from OB23 and OB25	800 – 2300	100 – 400	700 mg/l over 3 years
1971-2014	Entire range	200 – 2300	100 – 800	130 to 270 mg/l per year

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Section 2: Existing Knowledge

Overview

Scientific studies of stygobiont communities in the Pilbara are relatively new. These studies commenced after the discovery of stygobiont communities in the 1980s and 1990s, and since then a number of scientific papers have been published to date. Bennelongia Environmental Consultants (Bennelongia) completed a review of regional subterranean fauna to support BHP Billiton Iron Ore's Strategic Environmental Assessment.

The Pilbara is a globally important region for subterranean fauna. The region has very high species richness, some important relictual species and some outstandingly diverse species radiations, such as those recorded for stygofaunal ostracods and troglofaunal schizomids.

It is conservatively estimated that the Pilbara supports 500 to 550 species of stygofauna (Eberhard *et al*. 2009; Halse *et al*. 2014). The results of a regional survey conducted by the Department of Parks and Wildlife suggested that areas containing rich stygofauna communities occur across most of the Pilbara (Halse *et al*, 2014). Using these data and other sampling results, Bennelongia identified 29 focal sites with especially high richness of stygofauna were identified, seven of which is located in or adjacent to the SEA area (Bennelongia, 2014). These were near Paraburdoo, south-west of Tom Price, Ethel Gorge, Upper Weeli Wolli and Coondewanna Creeks, Weelumurra Creek, northern and eastern Fortescue Marsh and Mulga Downs. In addition to being a focal site, Ethel Gorge supports a stygofaunal Threatened Ecological Community (TEC) and Weeli Wolli Spring within the Upper Weeli Wolli Catchment is listed as a Priority Ecological Community (PEC), partly because of stygofaunal values.

Stygofauna richness is highest in aquifers within Quaternary and Tertiary detrital deposits in palaeovalleys and modern river channels, which underlie large parts of the Pilbara. These detrital deposits are understood to have a number of aquifer units present associated with calcrete, gravels and sands that provide numerous voids and spaces for prospective stygofauna habitat, as well as mostly having a shallow watertable.

The results of the Pilbara Biodiversity Survey (PBS) suggest that low numbers of stygofauna occur where depth to groundwater is greater than 30 m. Accordingly, the depth to groundwater across the eastern and central parts of the SEA area was determined based on existing information to identify areas that are prospective for stygofauna (depth to groundwater less than30 m) and those where few stygofauna will occur, irrespective of geology, because the watertable is too far below the surface.

Some areas with depth to groundwater less than 30 m, usually in palaeovalleys, occur within or close to BHP Billiton Iron Ore mining hubs in the SEA area. Current understanding of the distributions of stygofauna species suggests that approximately half of the species present at these hubs may have ranges restricted to the local groundwater system. Some species will have ranges restricted to smaller areas of habitat, such as associated with a headwater tributary.

There is variation among groups of stygofauna in the proportion of species with small ranges. Ostracods, syncarids, isopods and, probably, amphipods have mostly small ranges. Many species in other groups will also have small ranges. There is little quantitative information on the ranges of stygofauna species but it has been suggested that half the species considered to be 'locally' restricted will have ranges less than 700 km^2.

In addition to being recognised as a focal site from the PBS data, Ethel Gorge is listed as a TEC as a result of surveys conducted in the late 1990s (e.g. Eberhard and Humphreys 1999). Further impact assessments and compliance monitoring have since provided considerable additional knowledge. The stygofauna community is largely associated with the Ethel Gorge palaeochannel, which contains alluvial aquifers and a calcrete aquifer at depth. The highest species richness and greatest proportion of localised species in the Newman area are found at Ethel Gorge and upstream to about 1.5 km below the Ophthalmia Dam wall. Altogether, 78 stygofauna species have been collected in the vicinity, with 37 (47%) of the species thought to be restricted to the Newman area (Bennelongia 2013a).

Occurrence and abundance

The occurrence and abundance of stygofauna seems to be controlled by and correlated to a number of inter-related hydrogeological factors (Halse *et al*, 2014) and these are:

Section 2: Existing Knowledge continued

- Degree of surface water and groundwater interaction
- Depth to groundwater and
- Porosity and pore void size.

Stygofauna abundance is low where the watertable is deeper than 30 m, irrespective of geology (Halse et al. 2014; Bennelongia, 2014). Stygofauna occurrence appears to be controlled by the degree of connection with surface water. The abundance of stygofauna is higher in areas where associated with infiltration along drainage channels into the underlying aquifers. In these areas, groundwater levels are generally shallow (Halse et al. 2014, Bennelongia, 2014.).

In addition, stygofauna abundance is also controlled by local factors. For example, there are many locations with low abundance of stygofauna even though the depth to groundwater is shallow and the sampling site is located close to drainage channels. At some other sites which are high in the landscape, there may be high stygofauna abundance associated with localised shallow groundwater systems. In these areas, recharge may not necessarily occur along drainage lines, but be associated with direct rainfall recharge.

Stygofauna has adapted to survive in an environment where food is scarce, and they often have a low metabolism (Barr, 1967). It is hypothesised that in active recharging areas, such as drainage lines, food sources are transported into the underlying aquifers through percolating creek recharge, and these sustain richer stygofauna communities. These food sources may then be transported through the deeper regional aquifer systems, which may sustain stygofauna communities even though they are distant from the drainage lines.

Stygofauna abundance appears to be greater in aquifers with high porosity and relatively large pore size spaces. The pore space controls the available stygofauna habitat (Eberhard et al. 2005, Halse et al. 2014 and Hahn & Fuchs 2009). Calcrete and coarse-grained sediments is believed to provide the main habitats for stygofauna in the Pilbara.

The groundwater salinity may determine the type of stygofauna species present in the aquifer. The type of species in freshwater aquifers will be different to the type of stygofauna in brackish water with the stygofauna in the brackish water being more tolerant to salinity. Other chemical factors may also control the type of species in aquifers, but these are still poorly documented (Halse et al. 2014, Reeves et al. 2007, Pinder et al. 2005).

Diversity and endemism

Although stygofauna occurs throughout the Pilbara, there are 29 identified focal sites with distinctly high species richness (Bennelongia, 2014). One of these focal points is Ethel Gorge, and relatively high species richness also occurs near the Weeli Wolli Spring, Marillana Creek, Coondewanna and the Northern Fortescue Marsh.

The other stygofauna focal points occur in the Ashburton River Basin (10 sites), Robe River Basin (6 sites), Fortescue River Basin (6 sites other than Ethel Gorge), Port Headland Coast Basin (2 sites) and De Grey River Basin (3 sites) (Bennelongia, 2014).

Stygofauna resilience and factors affecting stygofauna persistence

Loss of habitat

The loss of habitat through groundwater drawdown presents the most significant risk to stygofauna persistence. Groundwater drawdown decreases the saturated thickness of the aquifer, and hence the available habitat for the stygofauna (Halse *et al*, 2014).

Groundwater drawdown may not only impact on the vertical component of stygofauna habitat. Extensive groundwater drawdown in the aquifer may result in the fringes of the aquifer (where saturated thickness is smaller) becoming completely desaturated and inhabitable for stygofauna (BHP Billiton Iron Ore, 2014c).

Species distributions in the aquifer also depend on the type of stygofauna habitat, with some species preferring the larger pore sizes in calcrete aquifers and others preferring the alluvium habitat. Species persistence may be threatened if different types of habitat are affected by groundwater drawdown, where calcrete overlies alluvium there may be species in the calcrete aquifer at risk if the calcrete aquifer becomes dewatered (Halse et al., 2014)

Section 2: Existing Knowledge continued

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Stygofauna may be able to migrate downward into the deeper portions of the aquifer during mine dewatering events and up to the shallower portions of the aquifer during water recovery. This may suggest that stygofauna are less sensitive to the *rate* of groundwater change (BHP Billiton Iron Ore, 2014a, BHP Billiton Iron Ore, 2014c).

Salinity

As mentioned earlier, different types of stygofauna communities may occur in groundwater of different salinities, with salinity tolerant species occurring in brackish groundwater systems.

Many freshwater stygofauna species are likely to have limited tolerance of increases in salinity concentrations but those species collected in marginally brackish groundwater may tolerate a range in groundwater salinity (see Pinder *et al*, 2005)

Halse (2014) suggests that stygofauna could potentially tolerate a three times increase in groundwater salinities over relatively short time periods. This opinion is based on the work by Pinder et al (2005). Halse (2014) suggests that in almost all parts of the Pilbara species richness and abundances may be impacted, if groundwater salinities increase to more than 5000 mg/L TDS. In parts of the Pilbara where groundwater salinities are, at most, a few hundred milligrams per litre changes to species richness and abundances are likely if salinities increase much above 1000 mg/L.

At Ethel Gorge, some monitoring data shows distinct decreases in groundwater salinity from about 2000 mg/L to 200 mg/L over a couple of months related to the seepage of freshwater from the Ophthalmia Dam into the underlying aquifers. This was followed by distinct salinity increases from 800 mg/L to more than 1800 mg/L over about 5 years. There we no noticeable change in stygofauna abundance or richness during this monitoring period.

Tolerance Ranges

Based on the scientific studies to date, the potential tolerance ranges are shown in Table 1. The studies to date indicate that stygofauna communities

Table 1: Tolerance ranges

Criteria	Threshold Ranges	References
Saturated Thickness	30% to 50% of baseline saturated thickness (end of dry season), assuming a uniform stratigraphy through the aquifer.	Halse, 2014 BHP Billiton Iron Ore, 2014a
Depth to groundwater	< 30 m below ground level	Halse, 2014
Groundwater fluctuations	Baseline fluctuations (about 2 m/year to 6 m/year)	BHP Billiton Iron Ore, 2014a
Long-term rate of groundwater level change	<2.5 m per year (excluding groundwater fluctuations range)	BHP Billiton Iron Ore, 2014a
Salinity (freshwater)	3x baseline salinity levels, but not exceeding 5000 mg/L TDS, possibly higher	Halse, 2014
Rate of salinity change	200 mg/L TDS per year, as long it remains in salinity tolerance range	BHP Billiton Iron Ore, 2014a

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Section 3: Groundwater modelling summary

1 Introduction

1.1 Background

Ethel Gorge is located on the Fortescue River some 15 km north-east of Newman (Figure 1). The Gorge is downstream (north) of the confluence of Homestead, Shovelanna and Warrawanda Creek within the Fortescue River catchment. It is formed where the Fortescue River flows through the Ophthalmia Range in a northerly direction. Surface and groundwater flows from the entire upstream catchment area are focused into Ethel Gorge resulting in relatively shallow groundwater levels, typically less than 10 m below ground level (mbgl). The area hosts the Ethel Gorge Stygobiont Threatened Ecological Community (TEC).

1.2 Objectives

As part of the Ethel Gorge Case Study, a regional numerical groundwater flow model was developed with the following objectives:

- Allow for predictions of the change in water level regionally and within the TEC area in response to mining related water management within the catchment
- Allow for predictions of the behaviour of the groundwater system under mine closure conditions (i.e. the recovery characteristics with the presence of open or backfilled mine voids in the catchment)

The model was to be calibrated against the available data and be used to demonstrate the ability of the tool to predict system response to the water management requirements of the Strategic Environmental Assessment (SEA) suite of mines.

The numerical groundwater model was updated following completion of the detailed dewatering estimates for the proposed OB31 mine. The OB31 dewatering estimates are provided by BHP Billiton Iron Ore (2014) and the updated Ethel Gorge numerical groundwater model is provided in RPS (2015)

1.3 Previous work

The Ethel Gorge area has been the focus of numerous previous studies involving drilling, testing, ongoing monitoring and groundwater modelling dating back to 1970. The availability and synthesis of this data gives a high degree of confidence in the understanding of the local hydrological system and most recently this data was used to complete a detailed hydrogeological conceptualisation for the Ethel Gorge area and surrounding catchments (RPS 2014a).

2 Conceptual model

The conceptual hydrogeology of Ethel Gorge and the wider catchment is described in detail in the Eastern Pilbara Region (EPR) Ecohydrological Conceptualisation Report (RPS, 2014a). A summary of the salient features is provided below.

The Ethel Gorge groundwater system occurs in detrital sediments bound by low-permeability basement rocks. It consists of a highly permeable alluvial aquifer comprising an upper unit of sandy-alluvium and calcrete (upper alluvial aquifer) and a lower unit of gravelly-alluvium (deep aquifer). The two aquifers are separated by a low permeability clay sequence.

Groundwater flows from south to north aligned with the Fortescue River valley. Groundwater levels decrease from ~510 mAHD at the Dam to ~500 mAHD in the Gorge.

The hydraulic behaviour of the Ethel Gorge groundwater system has been dominated by Ophthalmia Dam (the Dam), since it's commissioning in 1981. The Dam acts as a Managed Aquifer Recharge (MAR) scheme which impounds and retards flood waters in the Fortescue River to allow larger volumes of infiltration into the underlying aquifers. Groundwater levels in the alluvial aquifers have been sustained at much higher levels since the Dam was constructed than would otherwise have been the case.

Section 3: Groundwater modelling summary continued

Groundwater levels in the upper alluvial aquifer range between 0 and 10 mbgl. This provides a substantial saturated thickness in the upper alluvium and calcrete, which constitutes the main stygofauna habitat.

The lower aquifer is confined by the overlying clay and water level changes are thought to be a result of hydrostatic loading from the Dam rather than the physical movement of water into this aquifer. Bore data indicates that the lower aquifer has piezometric heads which commonly equal or exceed water levels in the upper alluvial aquifer, particularly in the area immediately downstream of the Dam.

The upper alluvial aquifer is unconfined and receives most of the water seeping from the Dam as well as recharge from direct infiltration associated with river flow events. Recharge also occurs along Homestead Creek and Shovelanna Creek. There is also likely to be a small component of throughflow into Ethel Gorge from the upstream catchments.

Percolation into the lower aquifer is restricted by the low permeability clay and the minimal (or reversed) vertical hydraulic gradients (i.e. high potentiometric levels in the deep aquifer as a result of hydraulic loading).

Prior to mining related water management activities, groundwater discharge would have occurred as throughflow along the Gorge and evapotranspiration from riparian vegetation communities. In recent times groundwater abstraction for potable water supply has provided an additional discharge from the system.

Groundwater levels in the alluvial aquifer that hosts the TEC have fluctuated over time, mostly related to climatic cycles of wetter and drier periods and more recently due to dewatering at OB23.

Beyond the area of Ethel Gorge, the broader catchment comprises the headwaters of the Fortescue River and Warrawanda, Shovelanna and Homestead Creeks. The regional groundwater flow system is hosted in aquifers associated with Tertiary detritals and underlying Paraburdoo Member dolomite which are generally surrounded by low-permeability lithologies. The regional aquifer is present beneath most of the present day strike oriented valleys between ridges of Brockman and Marra Mamba Iron Formations and where major drainages have eroded valleys across strike and there are deep sequences of Tertiary detritals.

There are also zones of high-permeability material associated with orebodies in the Brockman and Marra Mamba Formations that form local aquifers within the low-permeability surrounds (orebody aquifers). The extent to which the orebody aquifers are in hydraulic connection with the broader regional groundwater system varies with site-specific geology. The conceptualisation of the orebodies closest to Ethel Gorge is provided below:

- OB25 (Pit 3) and OB23 are hosted in Brockman Iron Formation to the north of Homestead Creek. The orebody aquifer is bound on three-sides by basement aquitards, isolating the pits to the north, east and west. To the south, the pits extend into the Homestead Creek channel and a substantial thickness of saturated Tertiary detritals is exposed in the pits footwalls. The detritals are permeable and result in hydraulic connection with the Homestead Creek regional aquifer.
- OB37 is hosted in Marra Mamba on the southern side of Homestead Creek. The orebody dips to the north under Homestead Creek and the pit will intersect alluvium/detritals in the north-wall. The orebody will form a significant aquifer, although bound to the south east and west by basement aquitards. To the north, the hanging wall sequence at OB37 will include the Tertiary sequence providing direct connection between the orebody aquifer and regional groundwater system.

3 Numerical model

3.1 Model set-up

3.1.1 Introduction

The Ethel Gorge regional groundwater flow model uses the Modflow Surfact groundwater modelling code (Hydrogeologic, 1996) operating under the Groundwater Vistas graphical user interface (Version 6.63 Environmental solutions Inc., 1996 to 2001).

Four model variants were produced to achieve the study objectives. They were:

Section 3: Groundwater modelling summary continued

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- A pre-mine (steady state) model. Used to provide appropriate initial conditions for the time variant calibration model.
- A time variant calibration model replicating the period from January 1970 to October 2012.
- A time variant predictive model simulating a period of active mining from November 2012 to June 2033.
- A time variant predictive model simulating a period post mine closure, from June 2033 to June 2073.

For the model update (incorporating the updated dewatering estimates from OB31), the following model variants were produced

- Time variant predictive models simulating a period of active mining from November 2012 to June 2033 and comprising:
    - o Five discharge scenarios to Ophthalmia Dam MAR (0 ML/d, 15 ML/d, 30 ML/d, 60 ML/d and 120 ML/d)
    - o Two evapotranspiration scenarios (600 mm/a and 900mm/a)

3.1.2 Domain and layering

The model domain is shown in Figure 2. The model extends 23 km upstream and 15 km downstream of Ethel Gorge. The model domain also extends 30 km east of Ethel Gorge to include the OB17, OB18, OB31, OB34 and OB39 mining areas and 30 km to the west to include the OB23, OB24, OB25, OB32 and OB37 mining areas. The model uses a minimum cell size of 50 m close to Ethel Gorge and the TEC area and in the vicinity of orebody aquifers.

The model uses six layers. The Ethel Gorge palaeovalley aquifer is simulated by four model layers (upper alluvium, calcrete, clay aquitard and an underlying alluvial aquifer). The extents and thicknesses of the palaeovalley aquifer have been based on extensive data. Where available the extent of low grade mineralisation (supplied by BHPBIO) has been used to define the extent of orebody aquifers.

3.1.3 Regional throughflow

Specified head and specified flow boundaries have been applied to provide inflow from catchments outside the modelled area and also outflow from the model to downstream catchments. These boundaries, and the assigned heads and flows, are shown in Figure 2. No flow boundaries have been set consistent with groundwater catchment divides.

3.1.4 Rainfall recharge

Direct rainfall recharge is applied to areas of surficial alluvium and outcropping orebody aquifers and bedrock at rates equivalent to 0.5% and 0.001% average annual rainfall respectively.

3.1.5 Evapotranspiration

The vegetation along surface drainages and flood plains within the modelled catchment rely on groundwater as a source of water. Red Gums and Coolibahs, with root depths of up to 20 m, are facultative phreatophytes and vadophytes and will contribute to an evapotranspiration loss from the water table both directly (where roots penetrate the water table) and indirectly (where the water table is below the roots but matric suction induced by the roots causes a capillary rise of groundwater into the unsaturated zone). This evapotranspiration (ET) is represented in the model using the Evapotranspiration Package.

Evapotranspiration losses are included along the major surface drainages (Figure 3). Evapotranspiration is specified at a maximum rate of 900 mm per year. The depth at which ET rates start to decline is set 5 m below the topographic surface to represent tree water use at maximum rates when predicted water levels are within 5 m of ground surface. This represents direct water use by shallow rooting vegetation. An extinction depth of 15 m below the ET surface (i.e. 20 m total depth) is specified. This represents progressively declining tree-water use as the depth to groundwater increases and fewer trees have the rooting-depth and matric potential to access the resource.

3.1.6 Groundwater / surface water interaction

Recharge from surface water flows in major creek and river systems is simulated using the Streamflow Routing Package. This approach simulates leakage from the specified stream cells based on a specified total flow along a modelled stream. This feature also allows for the discharge of groundwater to surface in the event that groundwater levels reach or exceed the specified stream bed elevation.

Gauged flows for the Fortescue River, measured upstream of Ophthalmia Dam were used to calculate stream flows for ungauged creeks within the model domain (Homestead Creek, Warrawanda Creek and Whaleback Creek). The extents of modelled creeks and rivers are shown in Figure 3.

Section 3: Groundwater modelling summary continued

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Infiltration from the recharge ponds located to the south of OB23 is simulated using the Recharge Package. The infiltration rates for each pond are assumed to be 50% of the historic or predicted discharge to the ponds.

3.1.7 Ophthalmia Dam

The modelled extent of Ophthalmia Dam is shown in Figure 3. MAR associated with Ophthalmia Dam was simulated using the MODFLOW Lake Package. This allows for leakage to the underlying aquifer system based on the difference between the elevation of surface water (held in the reservoir) and the underlying groundwater level. This model feature also allows for the wetted area to vary with elevation of water behind the Dam.

For the calibration period, measured Dam water levels are used as model inputs. For all model predictions (i.e. future simulations), Dam water levels are predicted using an analytical water balance model for Ophthalmia Dam (AQ2/RPS 2014a and b). The water balance model incorporates predicted upstream stream flow and projected dewatering surplus volumes.

Historical and predicted future overflows from Ophthalmia Dam are included as surface water inputs to the Fortescue River just downstream of the Dam.

3.1.8 Mine dewatering and water supply

Aquifers in and around Ethel Gorge have been used for town and mine water supplies for Newman since the Ophthalmia Borefield was developed in 1969. The OB18 water supply borefield has been operated since 2002. Since 2006 orebody aquifers at OB23 and OB25 have been dewatered.

All historical groundwater abstraction for water supply and dewatering is included in the Ethel Gorge model. For the calibration period, this has generally been modelled using the Fracture Well Package using measured rates as inputs. The only exception to this is at OB25 Pit 1, where dewatering over the calibration period was simulated using the Drain Package, which removes groundwater to a specified level.

For all model predictions, future dewatering of each mining area was simulated using the Drain Package. The model inputs are set using the projected lowest yearly mining level described in the mine plan. Future water supply pumping from the Ophthalmia and Homestead borefields is simulated using the Evapotranspiration Package such that pumping is constrained by a minimum water level at pumping locations.

The locations of these borefields are shown in Figure 3.

3.1.9 Mine closure

Once mining and dewatering is complete, the drain cells are removed and groundwater levels are allowed to recover.

Simulation of backfill or open void was based on committed or planned closure approaches where they exist (OB25, OB23). Where the approach to pit closure is yet to be determined it was assumed open voids would remain, as this represents the worst case for drawdown in Ethel Gorge.

For mine voids that are infilled, it was assumed that the infill material has similar parameters (storage and hydraulic conductivity) as the original orebody aquifer material. It is also assumed that the final infilled surface is engineered such that there is no change to the recharge conditions in the rehabilitated mine area.

Mine voids that are not backfilled are simulated by changing the hydraulic conductivity and specific yield within the void to very high values. Evaporation was then applied within the void footprint at a constant rate of 50% of Pan Evaporation (1.7 m per year) consistent with Department of Agriculture estimates of evaporation from agricultural dams (Department of Agriculture, 1987). Recharge was applied to the footprint assuming 20% of incident rainfall runs off from the pit catchment along with 100% of incident rainfall to the pit lake surface

3.2 Model calibration

The groundwater model has been calibrated to measured water levels over the period January 1970 to October 2012. The data is predominantly located within the vicinity of Ethel Gorge. The calibration data show responses to a fairly wide range of hydrological conditions, including:

- Groundwater drawdown from the early 1970's due to abstraction from the Ophthalmia borefield.
- The recovery of groundwater levels from the early 1980's resulting from the operation of Ophthalmia Dam.
- Changes in groundwater levels from dewatering at OB23 and OB25 since 2006.
- A range of natural hydrological conditions, including a period of higher than average rainfall from 1997 to 2001.

The time variant model calibration data set includes data from nearly 150 calibration bores. The locations of selected monitoring bores included in the model calibration data set in the Gorge and TEC areas are shown in Figure 4, along with their simulated and observed groundwater levels. In general the model calibration performance within Ethel Gorge is

Section 3: Groundwater modelling summary continued

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good, with water level magnitudes and trends well simulated by the model over the calibration period. In particular the measured water level trends associated with the operation of Ophthalmia borefield, MAR from Ophthalmia Dam and dewatering at OB23 and OB25 are well replicated by the model.

Model aquifer parameters are summarised in Table 2.1. The assigned aquifer parameters are consistent with typical values for similar hydrogeological units for the Pilbara and consistent with, and draw from work completed for, other modelling studies completed in the catchment for example those completed for OB23 and OB25 (RPS Aquaterra 2013) and OB31 (RPS 2014c).

Section 3: Groundwater modelling summary continued

Table 3.1: Model Aquifer Parameters

Model Layers	Hydrogeological Unit	Horizontal Hydraulic Conductivity Kh (m/d)	Vertical Hydraulic Conductivity Kv (m/d)	Specific Storage Ss (1/m)	Specific Yield Sy (%)
1 to 2	Calcrete	4.0×10^{2}	4.0×10^{2}	2.0×10^{-6}	3.0×10^{-2}
3	Clay	1.0×10^{-1}	5.0×10^{-4}	2.0×10^{-6}	3.0×10^{-1}
4	Gravel	5.0×10^{0}	5.0×10^{-1}	2.0×10^{-6}	7.0×10^{-2}
1 to 6	Basement (Hamersley Group and unmineralised Brockman Iron Formation)	1.0×10^{-3}	1.0×10^{-3}	1.0×10^{-6}	1.0×10^{-3}
	Brockman Orebody	5.0×10^{-0} to 1.0×10^{1}	5.0×10^{-1} to 1.0×10^{0}	4.7×10^{-7} to 2.0×10^{-6}	5.0×10^{-2}
	Mt McRae Shale and Mt Sylvia Formations	1.0×10^{-2}	1.0×10^{-2}	1.0×10^{-6}	1.0×10^{-3}
	Wittenoom Formation (undifferentiated)	1.0×10^{-0} to 1.0×10^{1}	1.0×10^{-1} to 1.0×10^{0}	4.7×10^{-7} to 1.0×10^{-6}	1.0×10^{-4} to 1.0×10^{-3}
	Marra Mamba Orebody	5.0×10^{-0}	5.0×10^{-1}	2.0×10^{-6}	5.0×10^{-2}
	Basement (unmineralised Marra Mamba Iron Formation, Fortescue Basement and Metagranite/Granitoid)	1.0×10^{-3}	1.0×10^{-3}	1.0×10^{-6}	1.0×10^{-3}
	Faults	1.0×10^{-4}	1.0×10^{-4}	1.0×10^{-6}	1.0×10^{-6}

3.3 Model predictive uncertainty

3.3.1 Uncertainty assessment

The majority of calibration data is in the vicinity of Ethel Gorge. The model replicates the majority of these observations accurately. This data shows how the system responds to various climatic conditions, enhanced recharge after construction of the Dam, mine dewatering and abstraction for water supply. In this area then, the model will be able to predict the groundwater response to similar future conditions with a high degree of confidence.

There are however areas away from Ethel Gorge that have only limited monitoring data and hydrostratigraphic controls. There is greater uncertainty in these areas in terms of the response to mining related activities and the migration of drawdown from here towards Ethel Gorge and the TEC. The most significant of these are immediately west of Ethel Gorge (specifically around OB37) and the area to the east that includes the Shovelanna mining area. Based on the data available, the following assumptions have been made in these areas:

- West of Ethel Gorge it is assumed that:
    - there is minimal hydraulic connection between Homestead Creek and the bedrock aquifer exploited by the Homestead borefield
    - there is good lateral hydraulic connection between the OB37 area and Homestead Creek
- East of Ethel Gorge it is assumed that:
    - there is some hydraulic connection between the OB31, OB34, and OB39 areas and the regional aquifer system
    - there is limited hydraulic connection between the OB17 and OB18 mining areas and the regional aquifer, but both of these areas are assumed to be in direct hydraulic connection with OB31
    - east of the Shovelanna mining area (and east of OB31), there is no hydraulic connection to the east across the Wheelarra Fault (which is defined as a no flow boundary in that area)

The closure simulations involve closing all active mines in the model domain (and outside) at the same time. There is no precedent for this in the area and therefore no observed data with which to calibrate the model to this. Combined with the fact that the closure predictions are undertaken up to 60 years into the future, this means that the confidence in these predictions is lower than the operational predictions.

The predictive capability of the model is therefore between the Class 2 and 3 model confidence level classification described in the Australian Groundwater Modelling Guidelines (Barnett et al, 2012), depending on whether operational or closure conditions are being simulated. The operational confidence is also variable depending on the proximity of the mines to the Dam, where most of the historical data is located.

Section 3: Groundwater modelling summary continued

4.95cm

3.3.2 Climate change

Two model runs were undertaken with climate sensitive parameters updated to reflect the conditions under the latest dry and wet climate predictions for the Pilbara. The runs were used to assess whether climate change may influence model predictions.

A CSIRO model provided simulated rainfall and evaporation for several climate change scenarios. This data essentially provides an answer to the question “What would the historical record have looked like under different climatic conditions?” The data was used to estimate the change in historical streamflow. This process resulted in an overall addition of the number of stream flow events in the wettest scenario and an overall removal of stream flow events in the driest scenario. This data was then used to adjust model settings including Dam water level, creek flows and rainfall recharge.

4 Change assessment

4.1 Approach

To investigate the influence on the groundwater system of the SEA mines separate from any other influences (long term climate trends, seasonality, etc.) the predictive model was run twice. The first run (the “baseline” scenario) included no mines or mining related water management activities in the catchment. The second run (the “SEA” scenario) included mining at OB17, OB18, OB23, OB24, OB25, OB31, OB33, OB34, OB37 and OB39 (shown in Figure 5). Dewatering of these mines was simulated as per the SEA mining schedule (Table 4.1).

The difference in predicted groundwater levels from these two runs would therefore be attributable to the influence of the mines only, rather than any other variables, such as climate variability.

To ensure that this was the case, the models were identical in all other ways. For example, both models shared the following settings:

- Rainfall recharge (using the 1980 to 1996 climatic sequence (repeated into the future))
- Stream flows (using the 1980 to 1996 climatic sequence (repeated into the future))
- Evapotranspiration rates and spatial extents

In both models the Ophthalmia and Homestead borefields were active until 2033. Abstraction from the Ophthalmia borefield was maintained at a constant 12 ML/d whereas the Homestead borefield reduced with reducing saturated thickness of the aquifer.

For both model variants Dam levels were calculated using the analytical water balance model (AQ2/RPS, 2014a and b). As inputs this used the 1980 to 1996 stream inflows (repeated into the future) and the predicted surplus mine dewatering volumes (including South Jimblebar) (Figure 6).

From 2012 to September 2016, the recharge ponds are assumed to receive the full mine surplus discharge. For the purposes of the scenarios, it is assumed that after this time they are not used and the mine discharge reports directly to the Dam.

Model update (OB31 dewatering)

The predictive model comprised five discharge scenarios and it was assumed that a constant discharge to the Ophthalmia Dam MAR scheme applies for the duration of the OB31 mining. It was assumed that 75% surplus dewatering water from OB31 will be discharged to Ophthalmia Dam and the remainder will be discharged to the recharge ponds. he scenarios included

- Zero discharge to the Ophthalmia Dam and recharge ponds total (baseline conditions)
- 15 ML/d discharge to the Ophthalmia Dam and recharge ponds total (considered the most likely scenario)
- 30 ML/d discharge to the Ophthalmia Dam and recharge ponds total (assuming a partial hydraulic connection between OB31 and the regional aquifer)
- 60 ML/d discharge to the Ophthalmia Dam and recharge ponds total (assuming a full hydraulic connection between OB31 and the regional aquifer)
- 120 ML/d discharge to the Ophthalmia Dam and recharge ponds total (assuming a worst case hydraulic connection between OB31 and the regional aquifer)

Each of the predictive models was also carried out for two evapotranspiration scenarios

- 900 mm/a: assumed to be the upper limit for evapotranspiration potential and generally have a better calibration fit
- 600 mm/yr assumed to be a more reasonable evapotranspiration potential but generally have a poorer calibration fit

Section 3: Groundwater modelling summary continued

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Table 4.1 Simulated mining schedule

Year Ending June	OB23	OB25 Pit 1	OB25 Pit 3	OB24	OB17	OB18	OB31	OB34	OB39	OB37	OB32
2013	X	X	X								
2014	X	X	X		X	X					
2015	X	X	X	X	X	X					
2016	Empty Void	X	X	X	X	X					
2017		X	X	X	X	X					
2018		X	X	X	X	X	X				
2019		X	X	X	X	X	X			X	
2020		Infilled Void	Infilled Void	X	X	X	X			X	
2021				X	Empty Void	Empty Void	X			X	
2022				X			X			X	
2023				X			X			X	X
2024				X			X	X	X	X	X
2025				X			X	X	X	X	X
2026				Empty Void			X	X	X	X	X
2027							X	X	X	X	X
2028							X	X	X	X	X
2029							X	X	X	X	X
2030							X	X	X	X	X
2031							X	X	X	X	X
2032							X	X	X	X	X
2033							X	X	X	X	X
2034 to 2073							Empty Void	Empty Void	Empty Void	Empty Void	Empty Void

X Denotes mining below the water table

The content of the table is conceptual only, of a general nature and does not purport to contain all information relevant to future project development associated with the Project. This table has been prepared solely for the purposes of informing environmental impact assessment pursuant to the Environmental Protection Act 1986 (WA) and Environment Protection and Biodiversity Conservation Act 1999 and is not intended for use for any other purpose. No representation or warranty is given that project development will actually proceed. As project development is dependent upon future events, the outcome of which is uncertain and cannot be assured, actual development may vary materially from the contents of the table.

4.2 Results

4.2.1 Introduction

The model predictions were analysed by determining the difference between the two scenarios over the whole model domain at specific times (thereby producing water level difference contours) and by reporting the predicted water levels through time at several key locations.

4.2.2 Operational

The predicted difference in groundwater level between the SEA and baseline model runs are shown in Figures 7 and 8 at the end of the operational period. These show that by 2033:

- Groundwater levels are predicted to have been significantly reduced due to the SEA mining activities around the OB31, OB37 and OB39 mines. Drawdown in these locations is in the order of 100 m.
- Drawdown from OB37 is predicted to migrate preferentially to the north, rather than the south.

Section 3: Groundwater modelling summary continued

4.95cm

- Groundwater levels are generally predicted to be between 1 and 5 m lower within the western and northern portions of the TEC (and up to 10 m just south of OB37), but no more than 1 m lower in the central and eastern portions.

Figures 9 and 10 show the predicted groundwater levels from both scenarios at several key locations within the model domain from 2012 to 2033. These show that:

- The area directly north of the Dam (within the TEC) is predicted to experience a pulse of drawdown between 2012 and 2016 which is most likely associated with dewatering the OB23 pit lake. This is followed by an immediate recovery in levels of 5 to 10 m and then a continuous but gradual decline in the order of metres until 2033.
- The operation of the Ophthalmia Borefield at the simulated rate (12 ML/d) is higher than the average historical abstraction and results in a gradual decline in water levels between 2012 and 2033 immediately north of the Dam and in the Gorge.
- North of OB37 the groundwater levels are predicted to continue to fall due to dewatering at OB25, then recover considerably, before being reduced again (although to a much lesser magnitude) by dewatering of OB37.

Figures 11 and 12 show the groundwater level change attributable to mining related activities only. These show that north of the Dam within the TEC water levels are predicted to be effected primarily by the activities at OB23 (i.e. dewatering historically (for mining) and in the future (for backfilling)), rather than the SEA mines. On completion of backfilling (and therefore cessation of dewatering) the levels quickly recover to within about 2 m of the background level, where they remain until 2033.

4.2.3 Updated OB31 model

The section presents the results for the scenario where there is a 15 ML/d discharge to the Ophthalmia Dam and recharge ponds total and assuming 900 mm/s evapotranspiration, which are considered the most likely scenario. The predicted groundwater hydrographs are shown in Figure 13 while Figure 14 shows the depth to groundwater attributable to the higher discharge rate to the Ophthalmia Dam. The model indicates that the system reaches a pseudo-equilibrium with the discharge inflows within a period of about 10 years. The results shows

- At discharge rates from Zero to 30 ML/d, seasonal climactic conditions are maintained into the future and there are minimal changes to the depth to groundwater level.
- At discharge rates of 60 to 120ML/d the seasonal responses are reduced and the groundwater system appears to approach capacity with a larger area having less than 2 m depth to groundwater.
- At the highest rates of discharge, the system appears to near capacity within a few years and large areas have depths to water less than 2m depth.
- The less than 2m zone extends further south of the Dam (upstream) and is more widespread in the 600mm/yr EVT scenarios compared to the 900mm/yr EVT scenarios.

4.2.4 Closure

Dewatering to support all active mines within the model domain is terminated in 2033 and the mine voids are managed as per the schedule shown in Table 4.1. All mine related discharge to the Dam is also terminated at this time.

Pit lakes are predicted to form in the open voids at OB31, OB34, OB39, OB18, OB23, OB24, OB37 and OB32.

The hydrographs (Figures 9 to 12) show that recovery to a new equilibrium level within the TEC occurs rapidly (within 10 years). Within the TEC this equilibrium is generally between 1 and 2 m lower than the level that is predicted without the mines.

The difference contours (Figures 15 and 16) show that by 2073 drawdown from OB31 and OB39 has migrated further to the west and, in the northern part of the TEC has combined with the drawdown originating from west of Ethel Gorge. Drawdown in this area is between 1 and 2 m at this time.

4.2.5 Climate change

The results of the two climate change scenarios show that:

- The most significant changes to model predictions occurs in the area of the Dam and in the area of the creeks (particularly Homestead)
- The maximum variation compared to the predictions from the base case climate sequence was an increase / decrease in the predicted water levels by 2 and 1 m respectively. This occurs just north of OB37.
- In areas of the TEC the difference is no greater than 1 m higher or lower than the base case.

4.95cm

5 Conclusions and recommendations

5.1 Conclusions

A regional scale, 3D numerical groundwater flow model has been constructed and used to predict the effect of mining related activities on the groundwater levels in the Ethel Gorge catchment. The model includes the natural flow systems and is able to account for removal of water via dewatering and the input of water via discharge to Ophthalmia Dam. The model considers the system under both operational and closure conditions.

The model has been calibrated and predicts that once backfilling of the OB23 mine void is complete, groundwater levels within the Ethel Gorge Stygobiont Threatened Ecological Community (TEC) will not be reduced more than 1 or 2 m as a result of further mining activities in the area.

For the case that dewatering rates from OB31 are higher than anticipated, depths to groundwater levels are still maintained up to 30 ML/d discharge to Ophthalmia Dam (Note that the most likely scenario is 15 ML/d). If discharge rates are higher than 30 ML/d, depths to groundwater decreases and a larger area is subjected to groundwater depths of less than 2m. At very high discharge rates (120 ML/d) large areas downstream of the dam will have depths to groundwater less than 2m, which could result in waterlogging conditions.

The model also predicts that water levels within the TEC will recover rapidly once the mines are closed and to within a couple of metres of the levels predicted without the mines.

5.2 Uncertainty and limitations

The model has been calibrated to a temporally extensive groundwater level monitoring dataset. The monitoring locations are clustered around the Gorge area. This means that the confidence in predictions of the groundwater system response to stresses within or close to the Gorge is higher than the predictions of the response to stresses away from the Gorge. This applies particularly to mines to the west (OB37 specifically) and in the Shovellana mining area. As there has also been little in the way of mine closure in the catchment to calibrate the recovery of water levels to, this aspect of the modelling is also more uncertain.

The model provides a good calibration to the observed data. However, as with all models, there are settings in the model that are uncertain. These uncertainties include:

- Evapotranspiration settings (maximum rate and profile with depth)
- Seepage from the Dam
- Discharge to the Dam (representing the uncertainty in predicted dewatering and process requirements)
- Creek flow and interaction with groundwater
- Future climate (although the predictions have been shown to be relatively insensitive to these inputs)
- The exact water management strategy that will be used (as it is adaptive)

The significance of these uncertainties has not yet been tested, but the intention is to continue improving the model in accordance to the adaptive management approach, which will focus on the range of possible outcomes given the uncertainty in the system.

6 References

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RPS, 2015. Regional numerical modelling of orebody 31 summary report. Report to BHP Billiton. February 2015

Figure 1. Location map

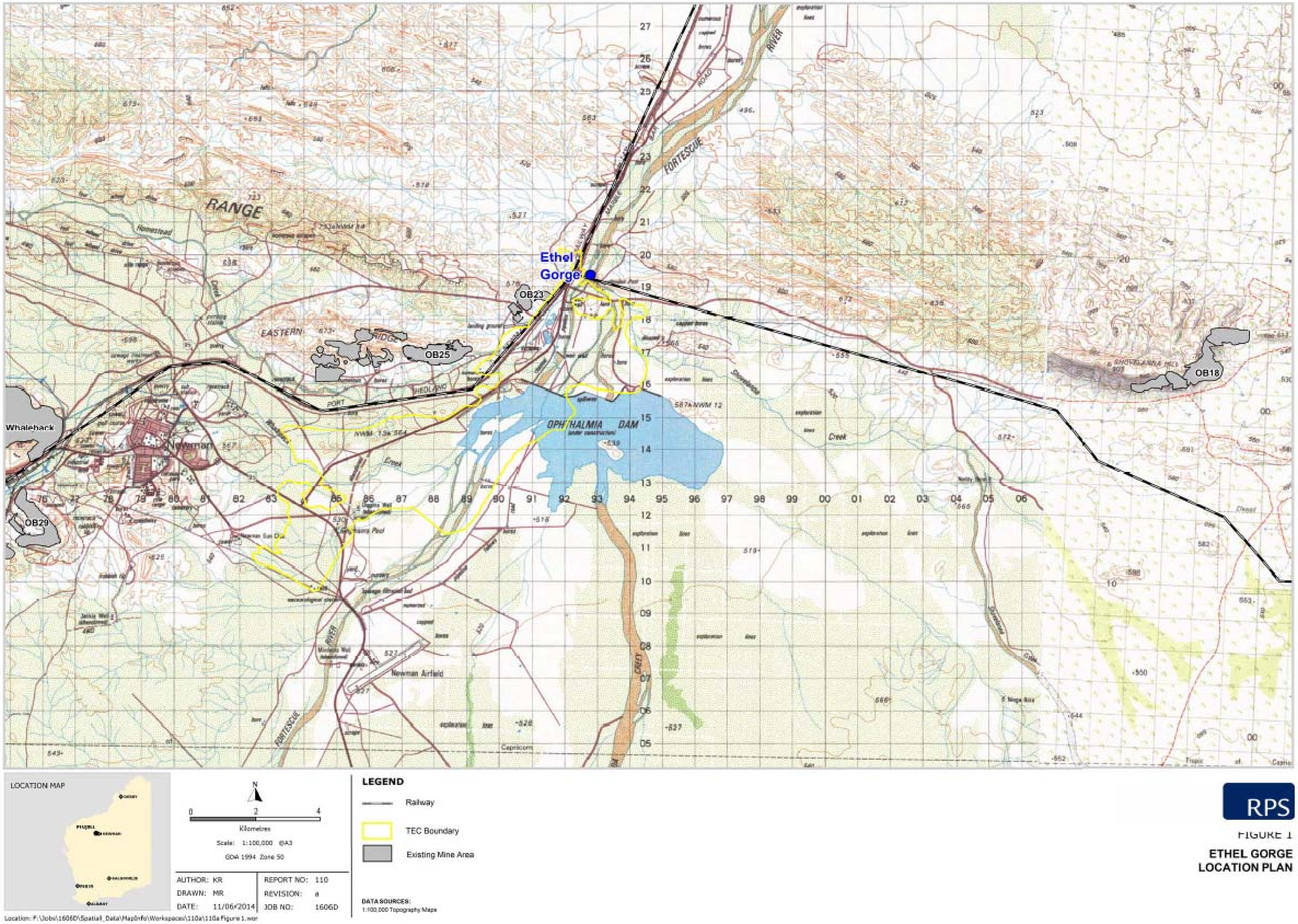


Figure 2. Model domain and boundaries

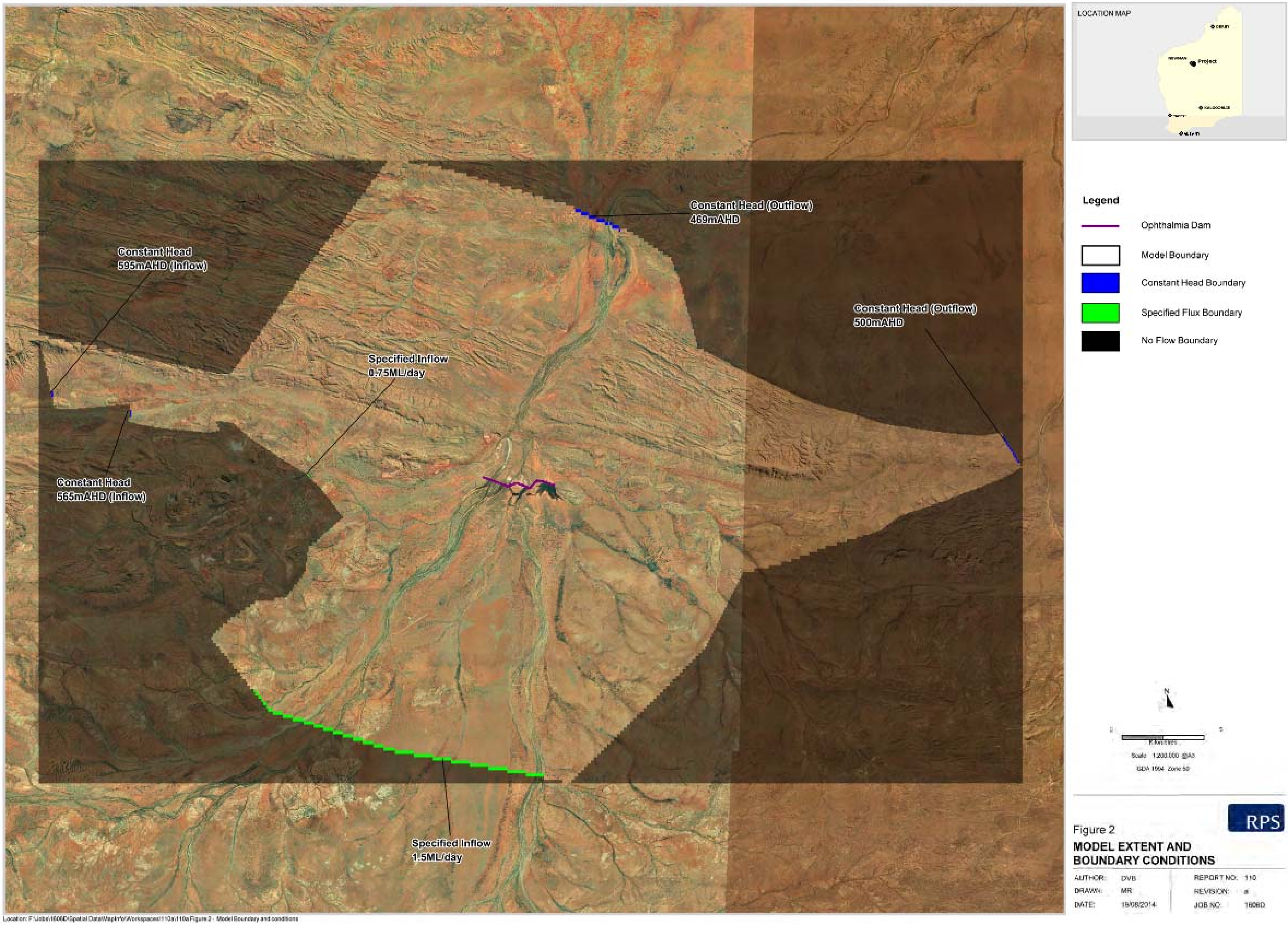


Figure 3. Model evapotranspiration, Dam and abstraction settings

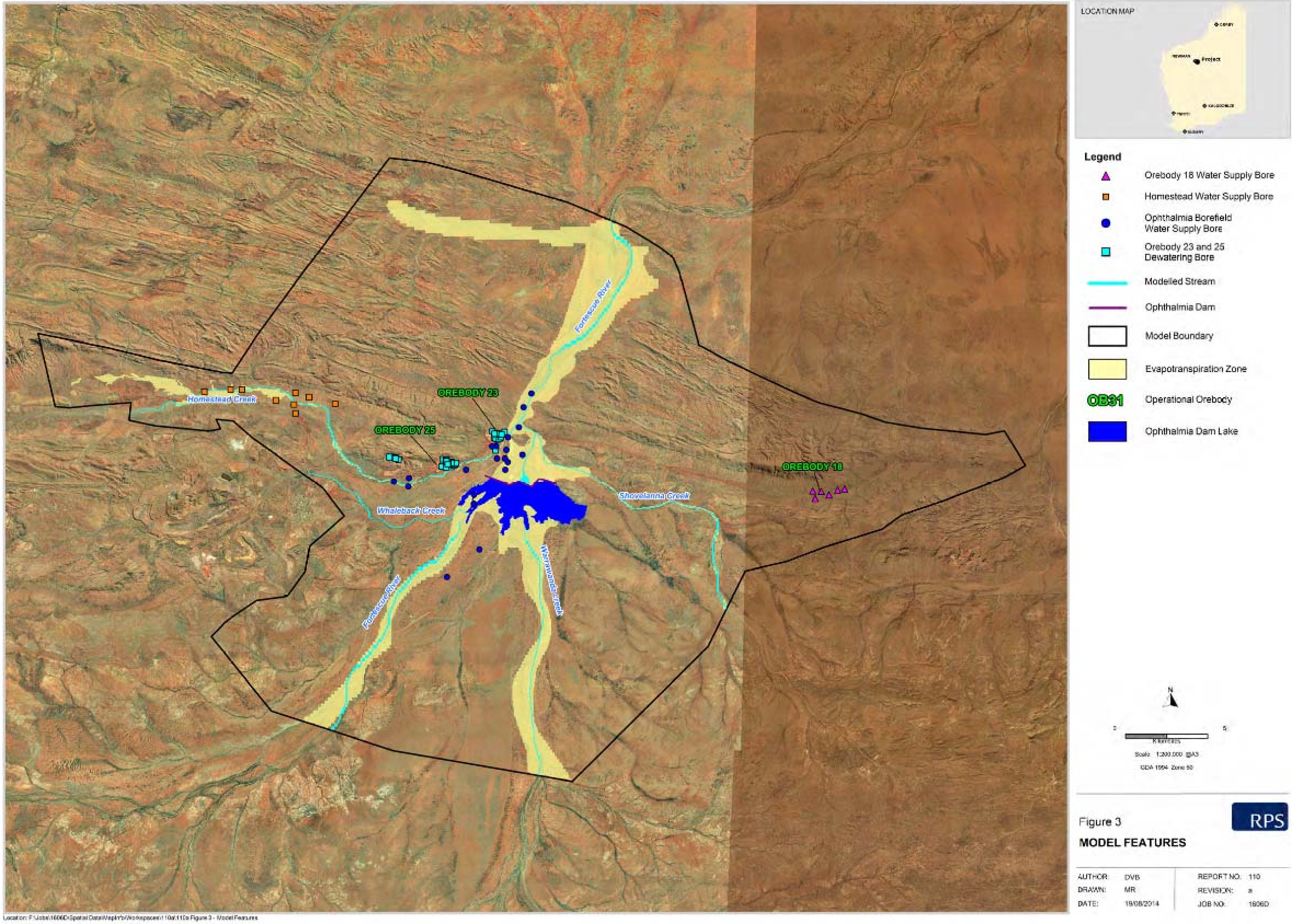


Figure 4. Example calibration hydrographs

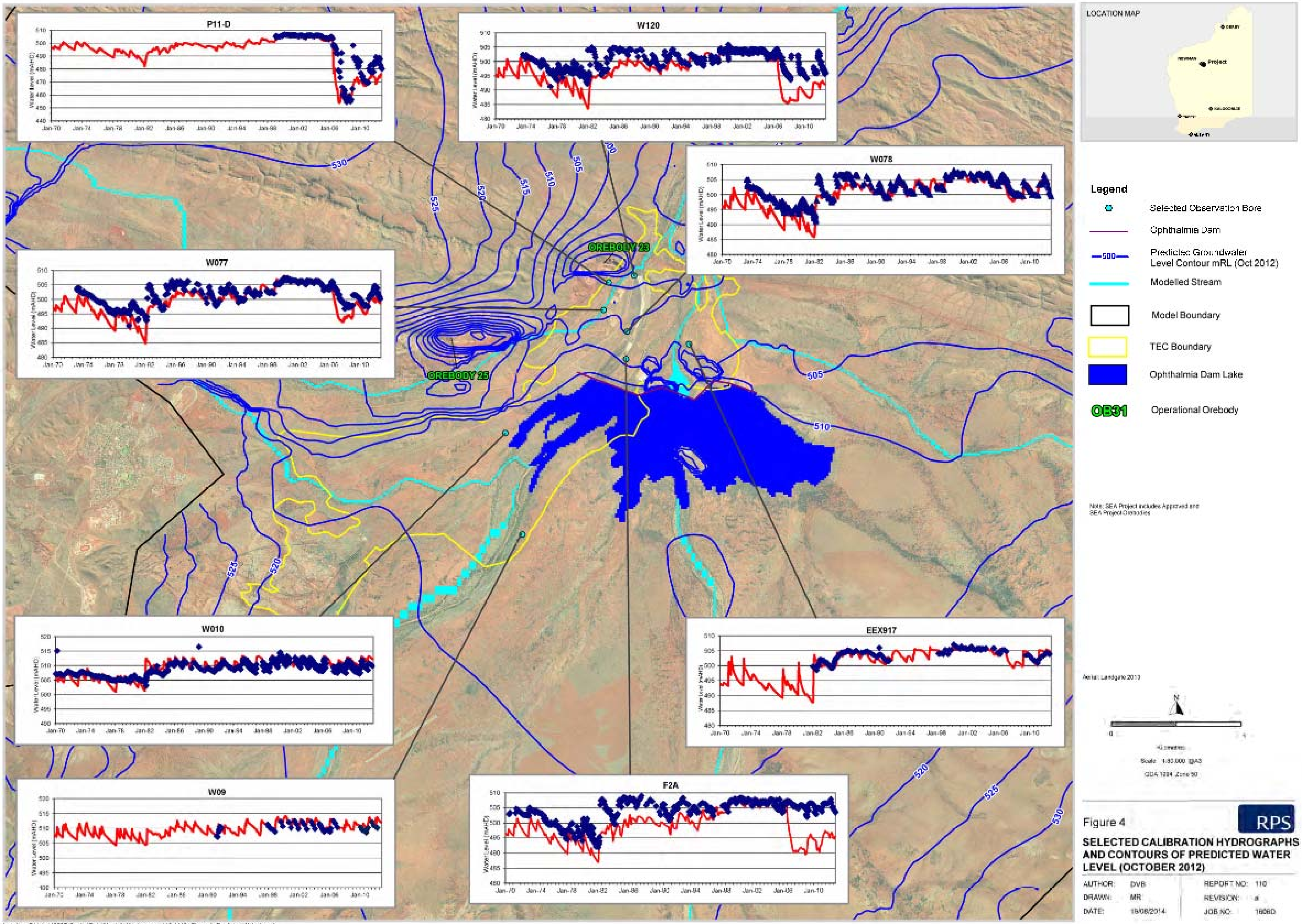


Figure 5. Simulated mine and borefields (2012 to 2033)

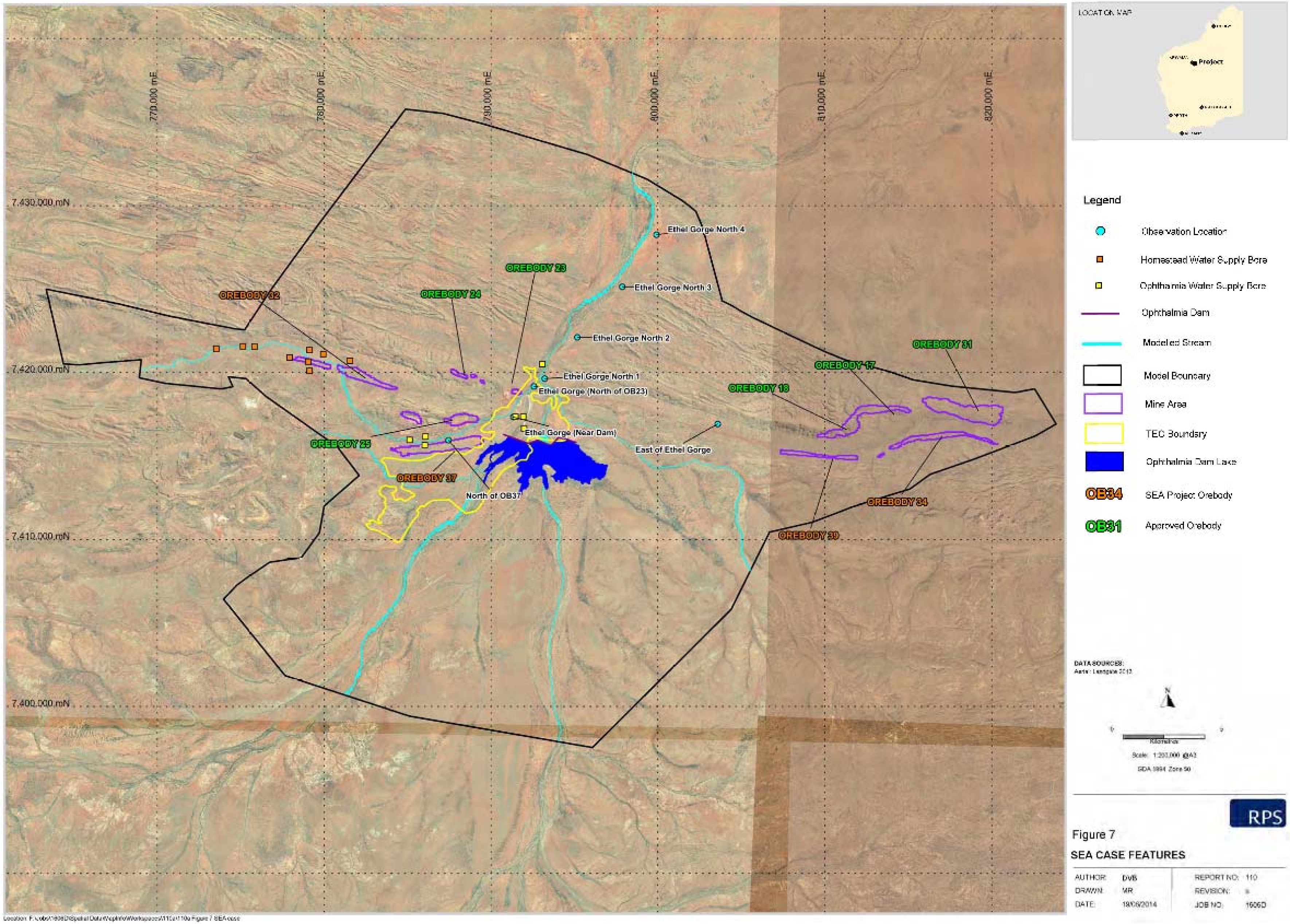


Figure 6. Predicted discharge to recharge ponds and Dam (2012 – 2033)

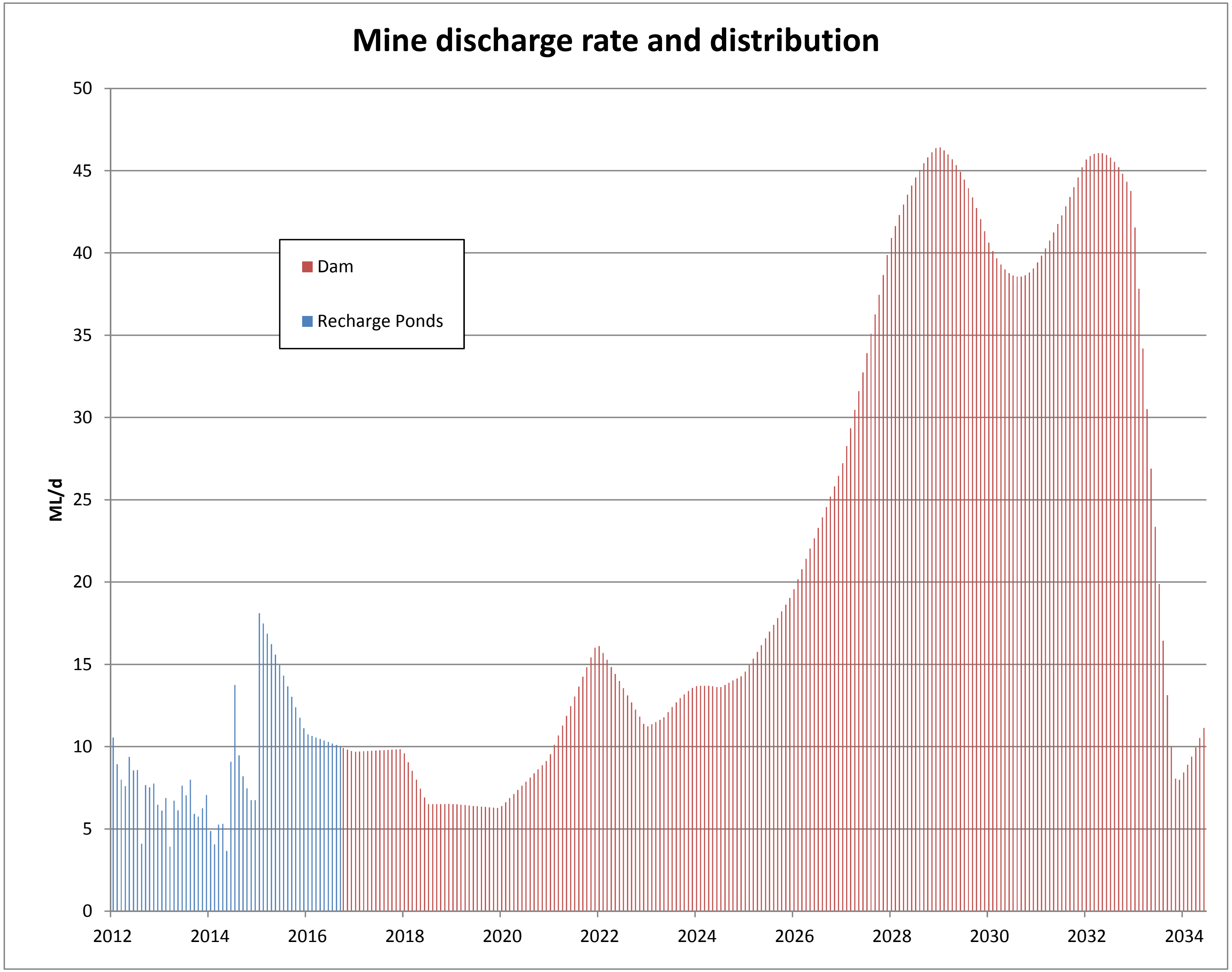


Figure 7. Regional groundwater level change due to mining activities (2033)

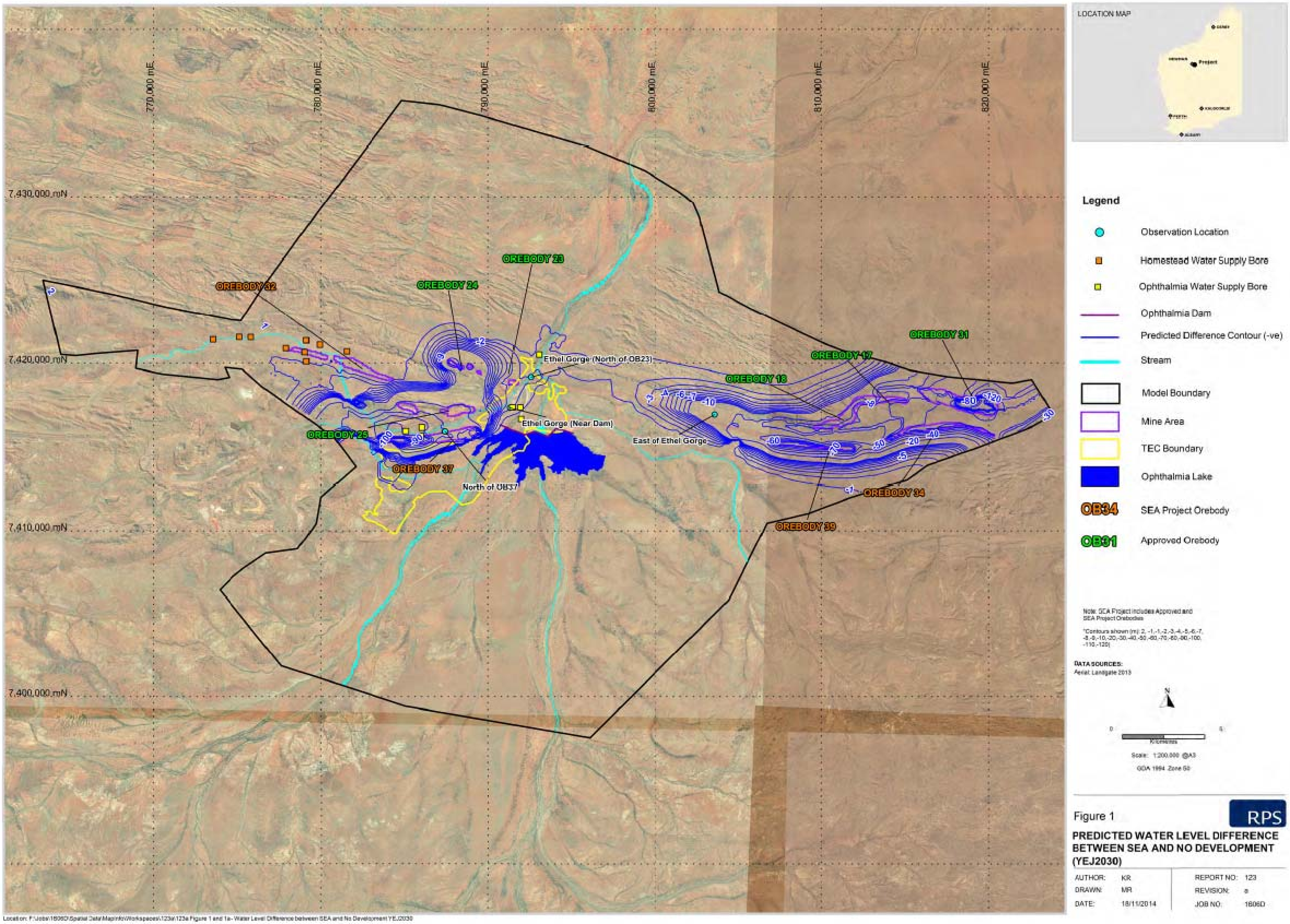


Figure 8. Groundwater level change due to mining activities within the TEC (2033)

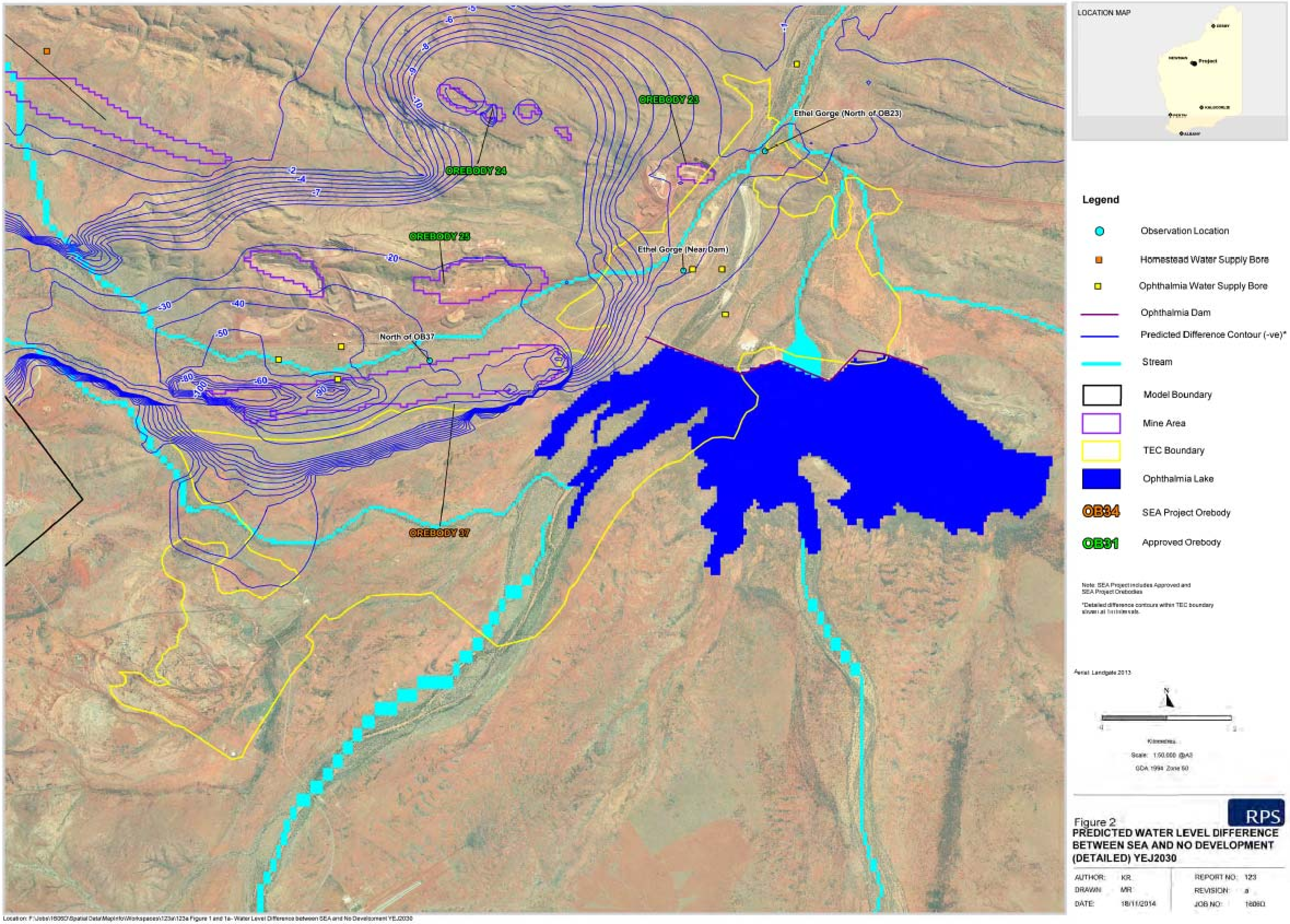
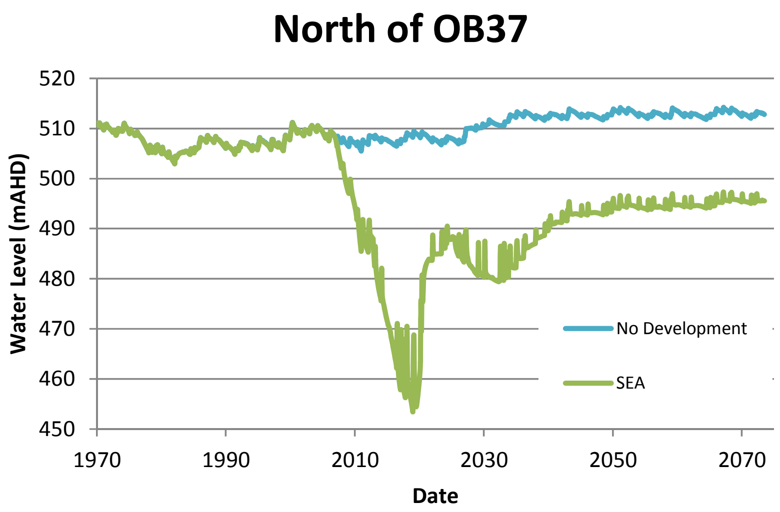
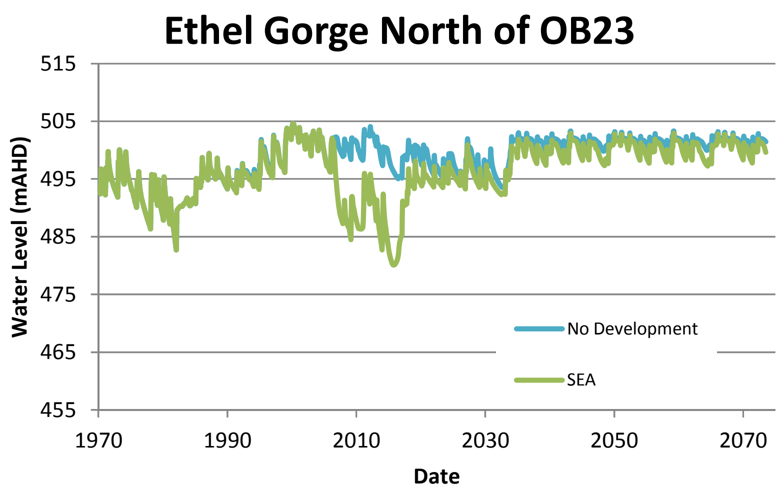
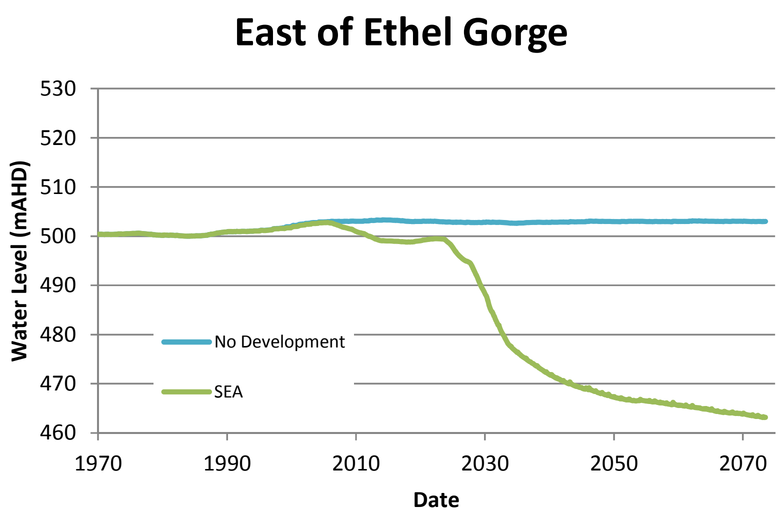


Figure 9. Predicted groundwater levels at key locations (1)

Add “TEC” to these?







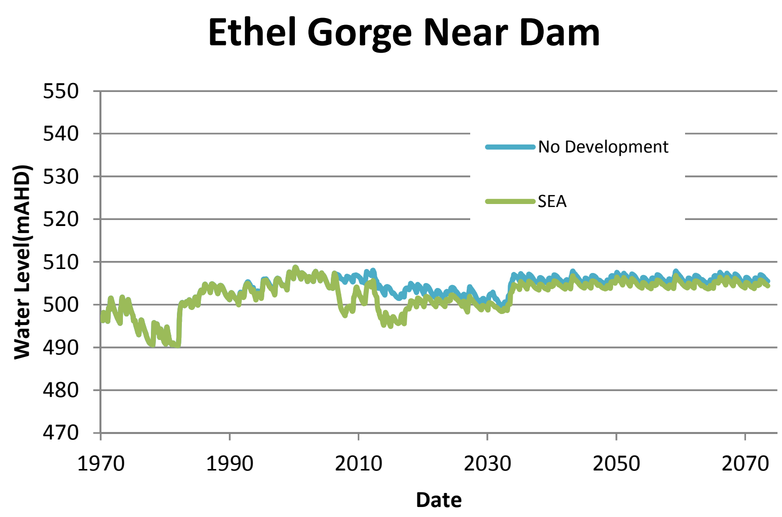


Figure 10. Predicted groundwater levels at key locations (2)

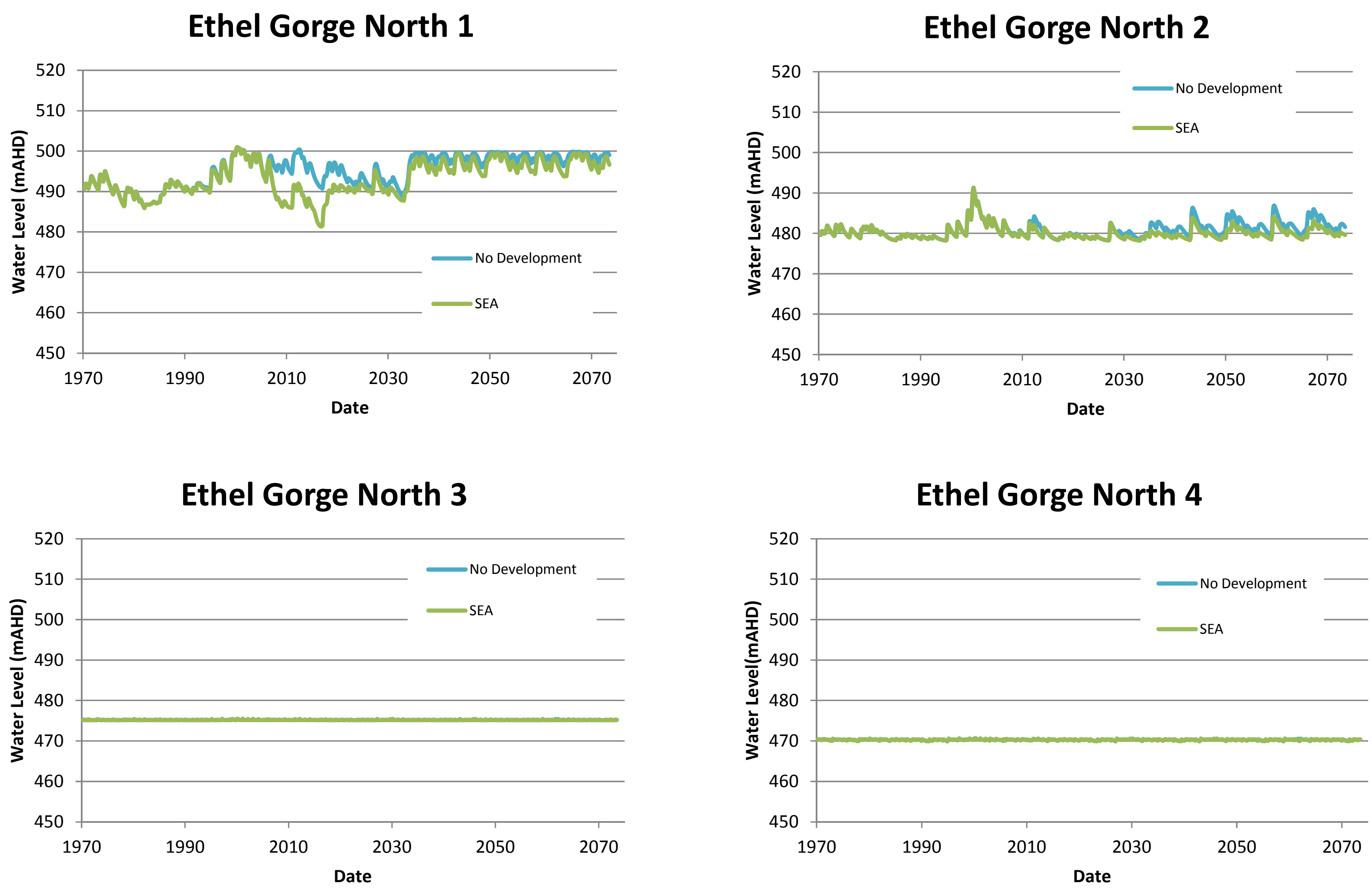


Figure 11. Predicted change in groundwater levels due to mining activities at key locations (1)

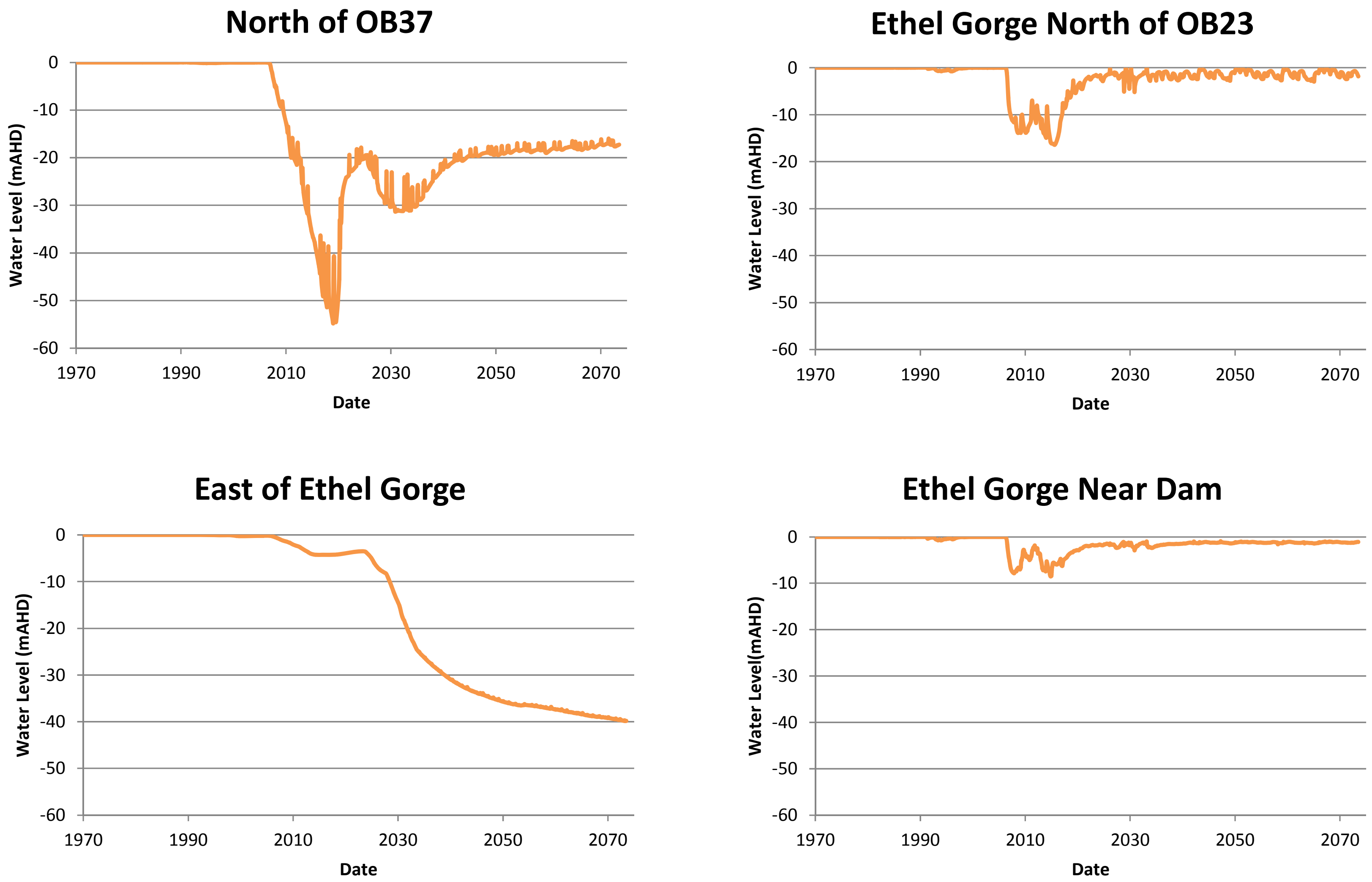
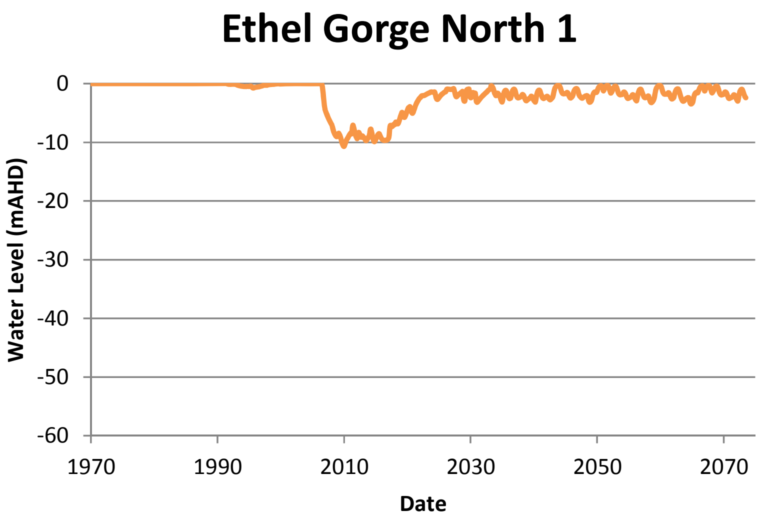
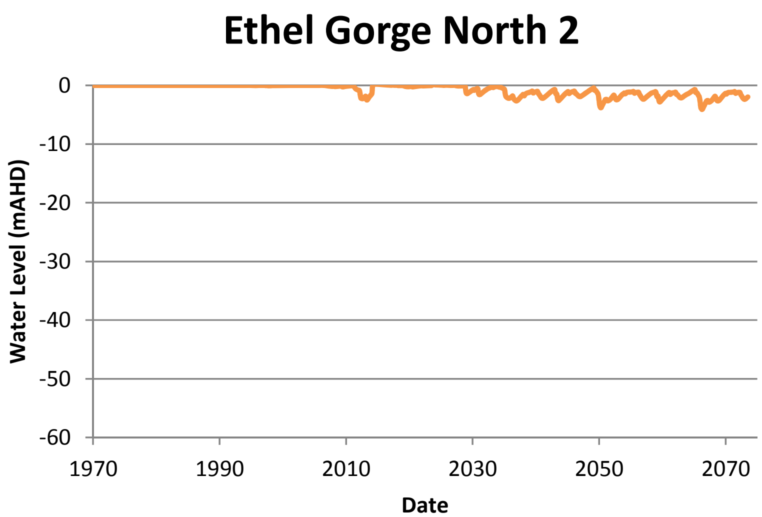
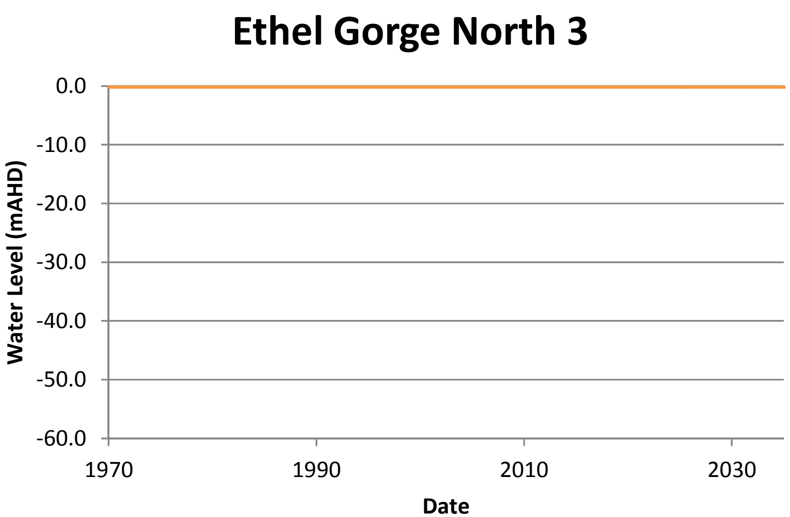


Figure 12. Predicted change in groundwater levels due to mining activities at key locations (2)







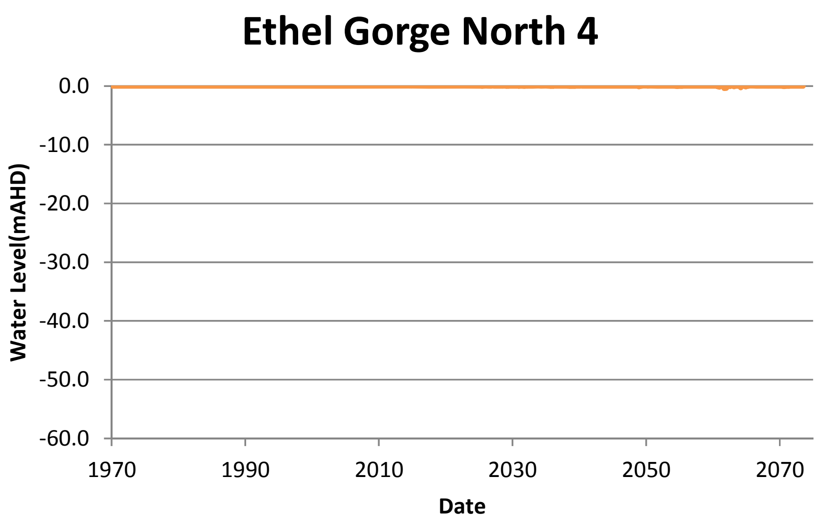
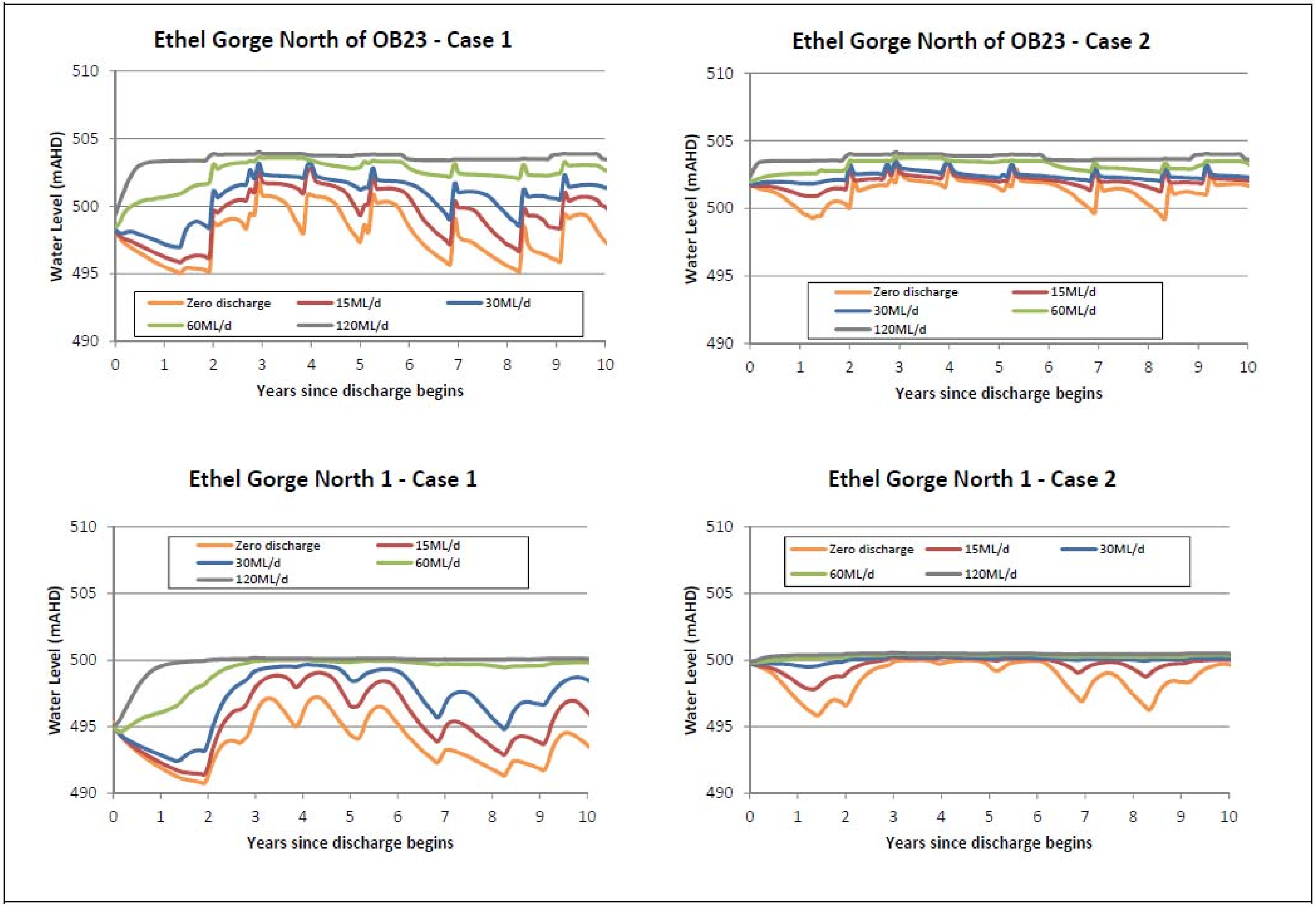


Figure 13. Predicted change in groundwater levels due to discharge of OB31 dewatering at key locations



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PREDICTED WATER LEVELS, CASES 1 AND 2. FIGURE 13

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Figure 14. Predicted depth to groundwater due to discharge of OB31 dewatering

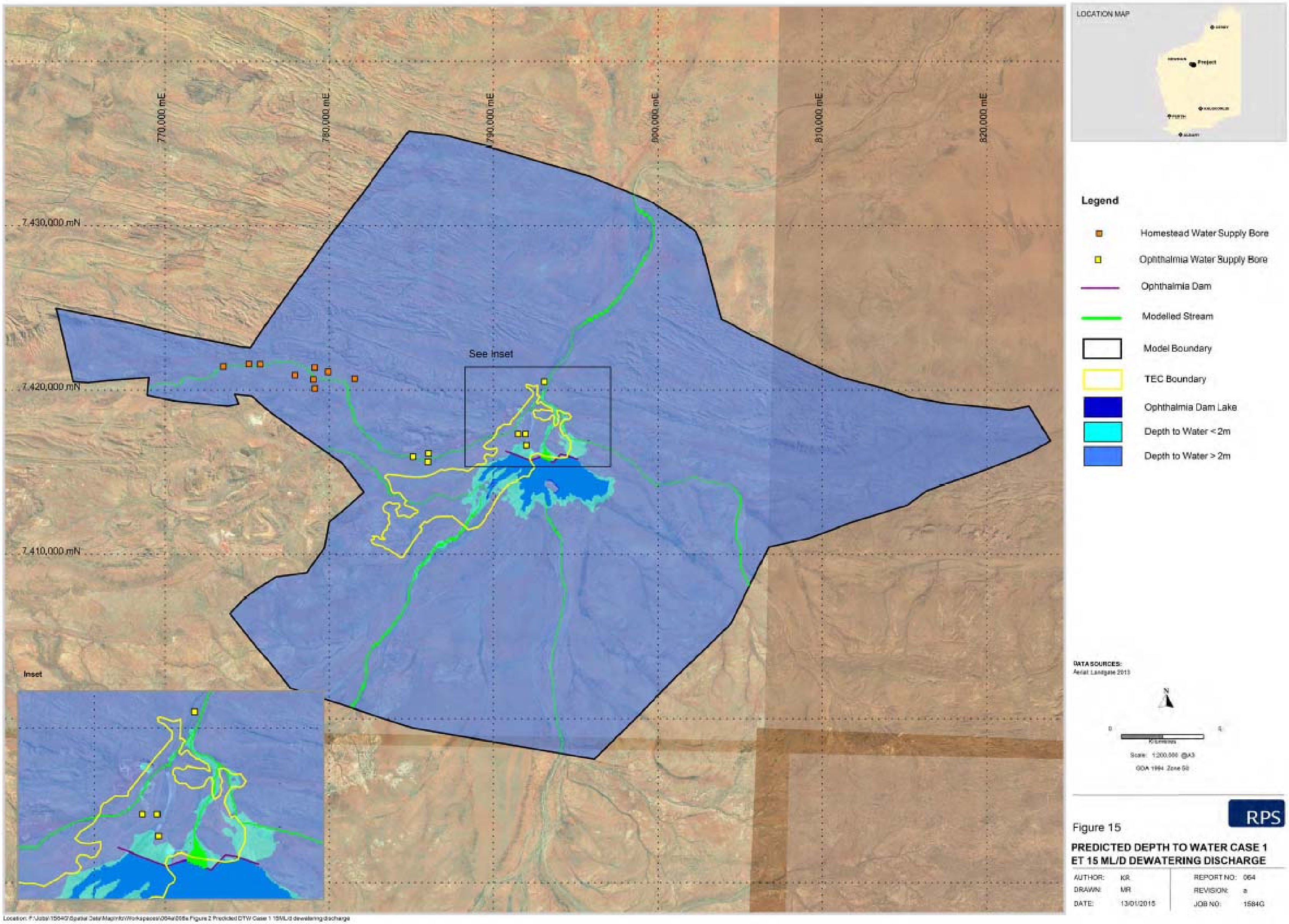


Figure 15. Regional groundwater level change at closure (2073)

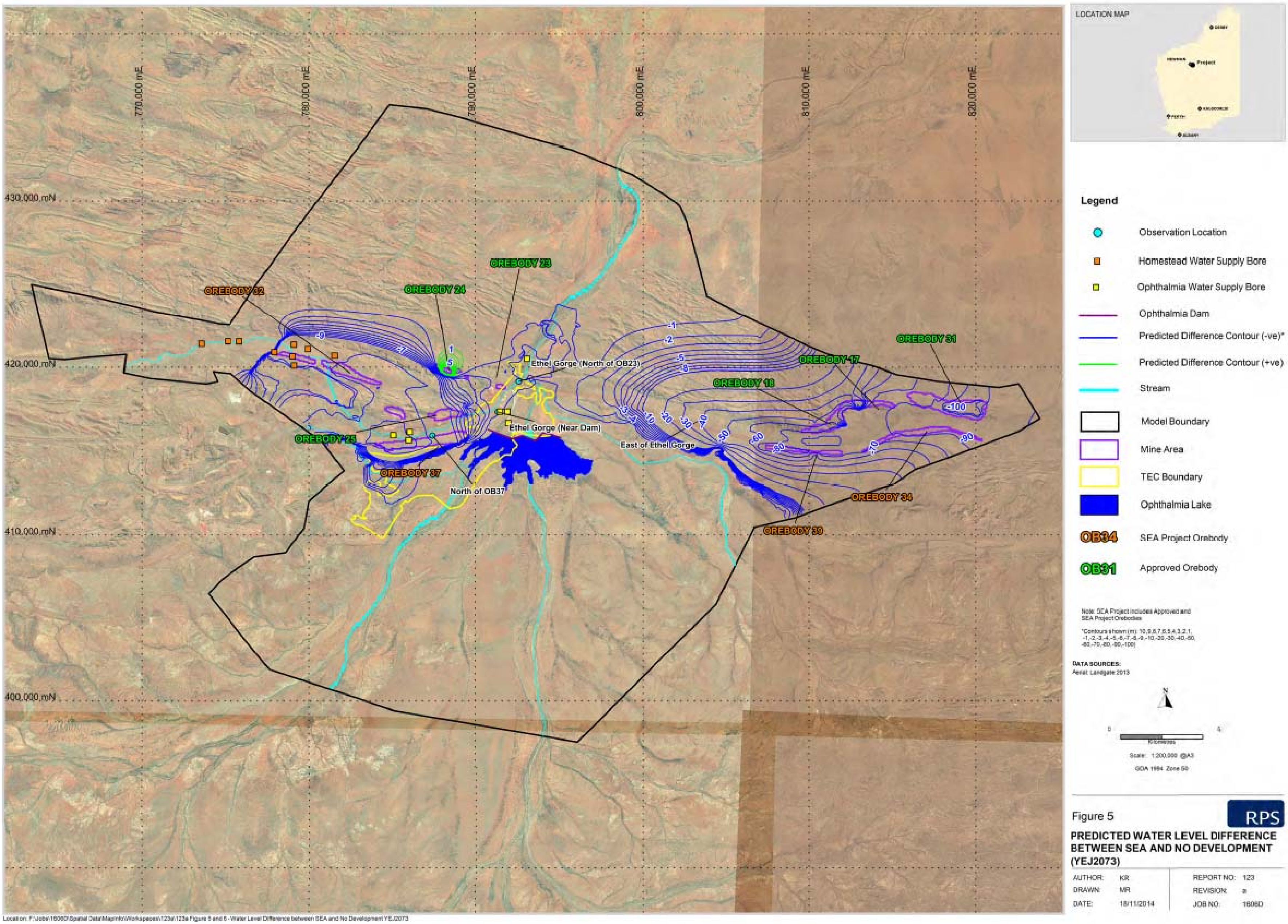
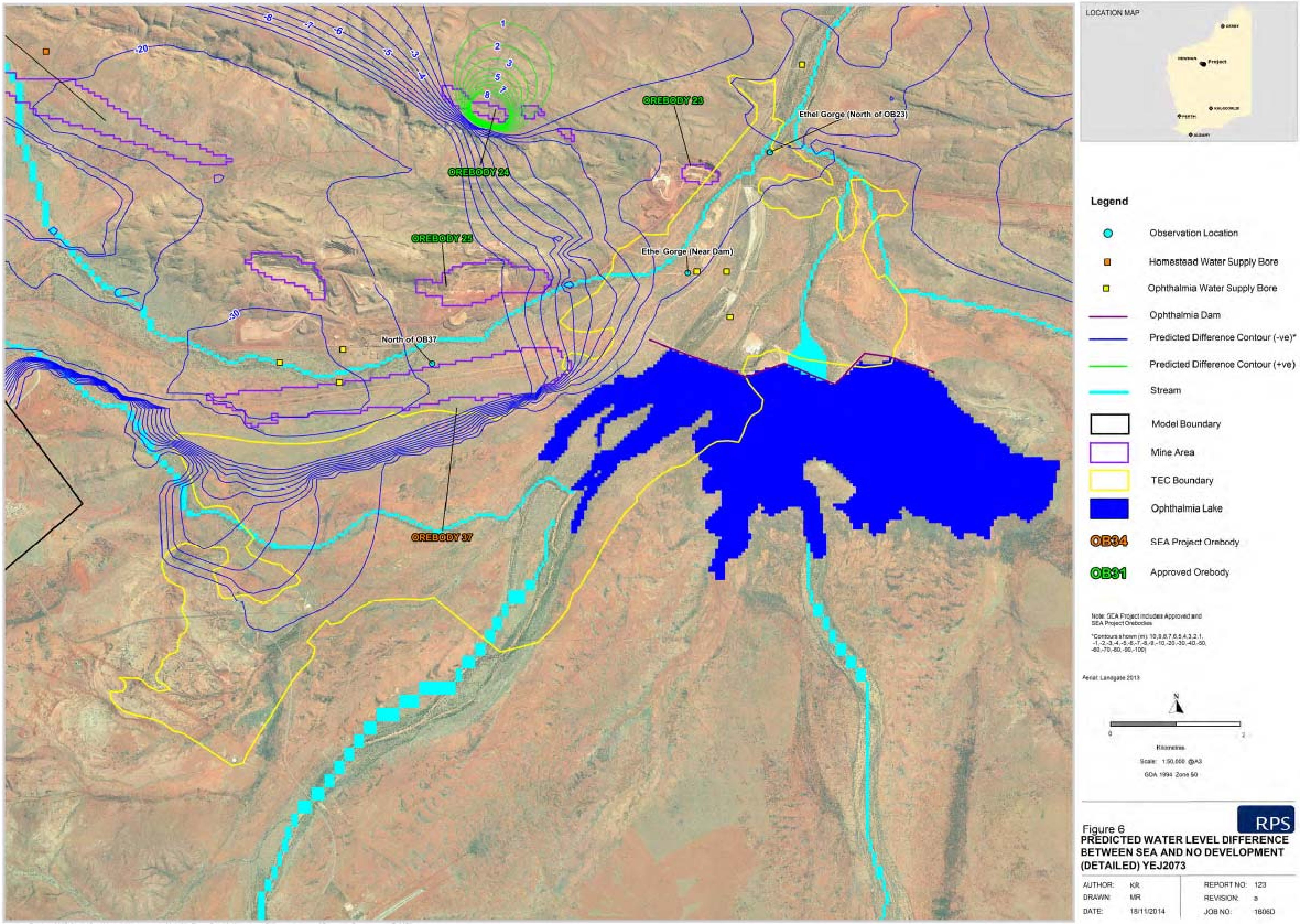


Figure 16. Groundwater level change within the TEC at closure (2073)



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Section 4: Water and salinity balance modelling

Introduction

Ophthalmia Dam is located about 3km upstream from Ethel Gorge at the confluence of the Upper Fortescue River, Warrawanda and Whaleback Creeks. It was constructed in 1981 as a Managed Aquifer Recharge (MAR) scheme, capturing surface water runoff which then infiltrate and recharge the underlying aquifers. The Ophthalmia Dam MAR scheme comprises the Ophthalmia Dam, infiltration basins and recharge ponds (Figure 1). Water from the dam can be released into the infiltration ponds or pumped to the recharge ponds to increase infiltration into the underlying aquifers.

The area hosts the Ethel Gorge Stygobiont Threatened Ecological Community (TEC) which occurs mainly in the upper Ophthalmia aquifer comprising alluvium and calcrete units. Additionally, dense riparian vegetation occurs along the downstream creek channels and is of local conservation significance.

Since 2006, the Ophthalmia Dam received surplus dewatering water from the OB23 and OB25 operations. Approvals are in place for the dam to receive surplus dewatering water from the OB29, OB30, OB35 and Jimblebar mining operations. BHP Billiton Iron Ore is also planning to discharge surplus dewatering water from the SEA mining schedule to Ophthalmia Dam. For the SEA mining schedule, Ophthalmia Dam will receive surplus dewatering water from OB24, OB17, OB18, OB31, OB32, OB34, OB 37 and OB39 in addition to the surplus dewatering water from the approved operations.

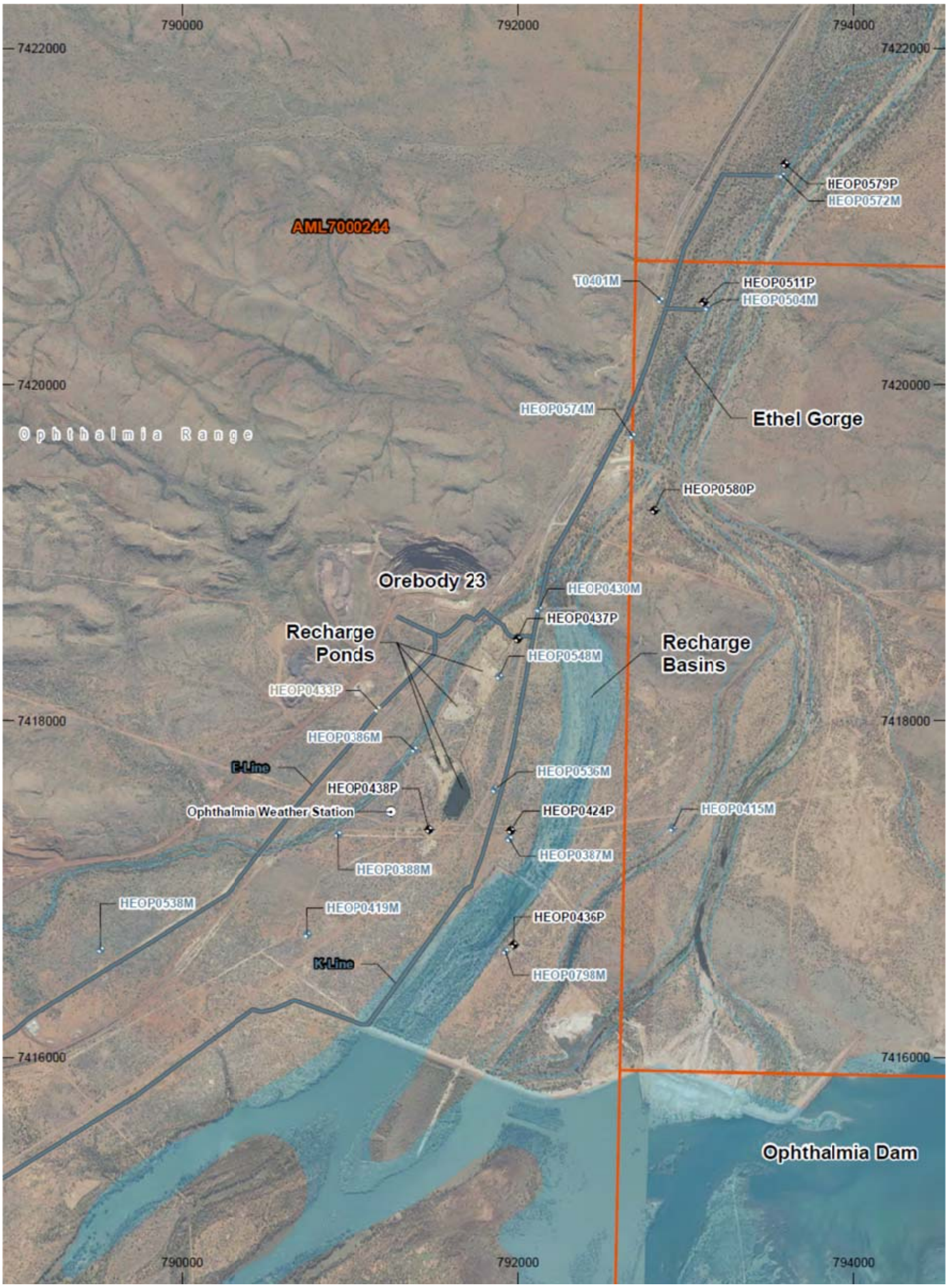
The salinity of surplus dewatering water is higher than the water that is captured from surface runoff. Additional discharge of surplus dewatering water will increase the leakage rate and salinity loading to the Ophthalmia aquifer.

BHP Billiton Iron Ore commissioned RPS to carry out studies to assess the potential salinity impacts to the downstream ecological receptors, in particular the Ethel Gorge stygobiont TEC and the downstream riparian vegetation. In 2014, BHP Billiton Iron Ore requested RPS to update the salinity modelling to take in consideration higher than anticipated discharge to Ophthalmia Dam as a result of higher dewatering rates from OB31.

This report is a summary of the technical reports and memorandums prepared by RPS to BHP Billiton Iron Ore (RPS, 2014a, RPS, 2014b, RPS, 2014c, RPS, 2014d).

Section 4: Water and salinity balance modelling continued

Figure 1: Location of the Ophthalmia Dam and related MAR components and production and monitoring bores



Section 4: Water and salinity balance modelling continued

Approach

The water and salt water balance model comprises two components

1. A water and salt balance model of the Ophthalmia Dam
2. A water and salt balance model for the Ophthalmia aquifer for the area between Ophthalmia Dam and Ethel Gorge

The two components are linked: The Ophthalmia Dam water and salt balance is used to determine the leakage rate and salinity concentration of Ophthalmia Dam leakage, which are inputs to the Ophthalmia aquifer water and salt balance model.

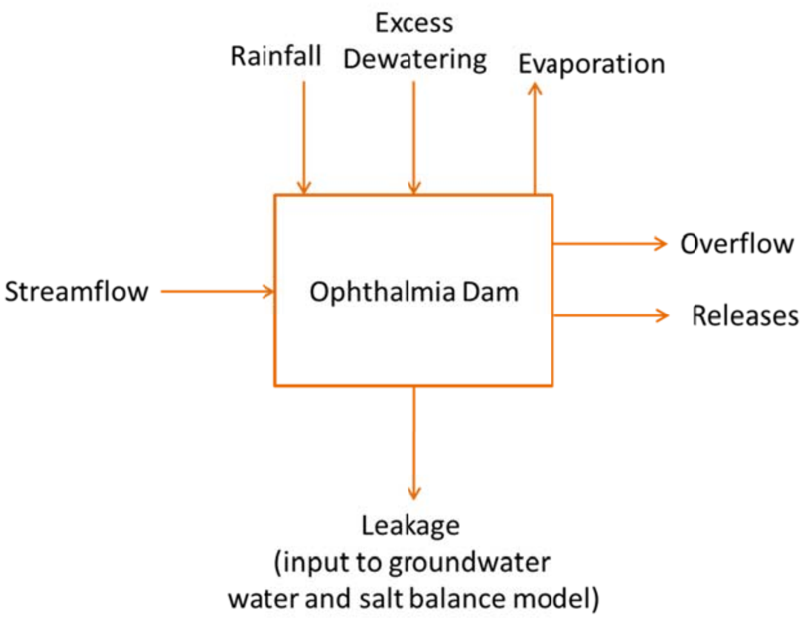
The water and salt balance models are based on the same conceptualisation and assumptions of the Ethel Gorge numerical groundwater model.

Ophthalmia Dam

RPS developed an analytical water and salt balance model for the Ophthalmia Dam. The model was originally developed to assess the potential increases in salinity concentrations caused by the discharge surplus dewatering water from the Jimblebar mining operations into the Ophthalmia Dam (Aquaterra, 2010). The water and salt balance model was then modified to also assess the increases in salinity concentrations caused by the discharge of surplus dewatering water from approved operations as well as the operations of the SEA mining schedule.

The conceptual model is shown in Figure 2. The model comprises the Ophthalmia Dam storage facility and its major inflows and outflow components which are described in more detail below.

Figure 2: Conceptual water and salt balance process flow diagram for the Ophthalmia Dam



A summary of the model characteristics are described below

- The dam has a storage of 31 GL and a surface area of 16 km^2 when full. The spillway crest level is at RL513.5 m and the storage is considered empty at RL509.0 m.
- Leakage was assumed to vary linearly with no seepage at RL 509.0 m to 100 ML/d at RL513.5 m, based on the numerical groundwater model
- Total streamflow into the dam was assumed to be 1.46 times the Fortescue River streamflow, taking into account inflow from the ungauged Warrawanda catchment. The streamflow salinity was assumed to be 40 mg/L based on measured streamflow salinity data.
- Direct rainfall was based on the Newman weather station and the average rainfall salinity was assumed to be 20 mg/L.
- Pan evaporation was assumed to be 0.5, derived through calibration of the numerical groundwater model.
- At low water levels, salt mass in the dam becomes concentrated resulting in increased salinity concentrations. When the storage is empty, residual salt mass is retained and are remobilised with the next inflow event.

Section 4: Water and salinity balance modelling continued

Modelling Scenarios

The modelling scenarios comprised

- No surplus dewatering discharge, which is the base case scenario.
- Approved case dewatering schedule which comprises the existing operations (OB25) and OB29, OB30, OB35 and Jimblebar mining operations
- SEA case dewatering schedule which include the approved case mining operations as well as OB17, OB18, OB31, OB32, OB34, OB37 and OB39.

The surplus dewatering rates were estimated from the numerical groundwater model for each of the orebodies and considered the mining schedule, the degree of hydraulic connection with the regional aquifer and the extent of below water table (BWT) mining. Dewatering salinity concentrations were assumed to be as follows:

- Jimblebar mining operations: 1000 mg/L TDS
- Other orebodies: 900 mg/L TDS

RPS used the historical climate and stream flow data sets for the period 1980 to 1996 for the water balance model, which avoids the abnormally high 1997 to 2001 rainfall period.

RPS also considered the following conditions for the model runs:

- Dry and Wet climate scenarios
- Different dam operating strategies namely:
    - No outlet structure discharge
    - Outlet structure discharge equivalent to 50% of the surplus dewatering rates

There were 10 modelling scenarios in total namely

- Two models for the baseline scenario (wet and dry climates)
- Four models for the approved case schedules (wet and dry plus no outlet discharge and 50% outlet discharge)
- Four models for the SEA case schedules (wet and dry plus no outlet discharge and 50% outlet discharge)

Additional Modelling Scenarios

Additional modelling scenarios were considered assuming the discharge of higher than anticipated dewatering discharge from OB31

- Approved case dewatering schedule which comprises the existing operations (OB25) and OB29, OB30, OB35 and Jimblebar mining operations plus the dewatering schedule from OB31
- Different dam operating strategies namely:
    - No outlet structure discharge
    - Outlet structure discharge equivalent to 50% of the surplus dewatering rates

Ophthalmia aquifer water and salt balance

RPS developed a water and salt balance model for the Ophthalmia aquifer to predict the degree of salinity concentration increases in the aquifer, caused by the discharge of surplus dewatering water into Ophthalmia Dam. The study focussed on the aquifer area between Ophthalmia Dam and Ethel Gorge.

The analytical model was designed to identify and scale the key processes that influence groundwater quality for broad sections of the aquifer. The aim was to replicate broad trends of groundwater levels and quality rather than simulate actual observed responses to a specific location.

The conceptual model of the model is shown in Figure 3. The groundwater inflow components comprise:

- Leakage from the Ophthalmia Dam
- Infiltration of water that overflows the spillway during periods when the dam is full
- Infiltration of water that is released from the dam outflow structures as per defined operating strategy
- Groundwater through-flow

The main groundwater outflow components comprise:

- Evapotranspiration from the riparian vegetation along the downstream drainage channels
- Groundwater through-flow through Ethel Gorge.

The numerical groundwater model showed that evapotranspiration represents a significant outflow of water from the system. Since salinity loads are not removed through evapotranspiration, salinity concentrations in the aquifer are typically higher compared to the Ophthalmia Dam.

Section 4: Water and salinity balance modelling continued

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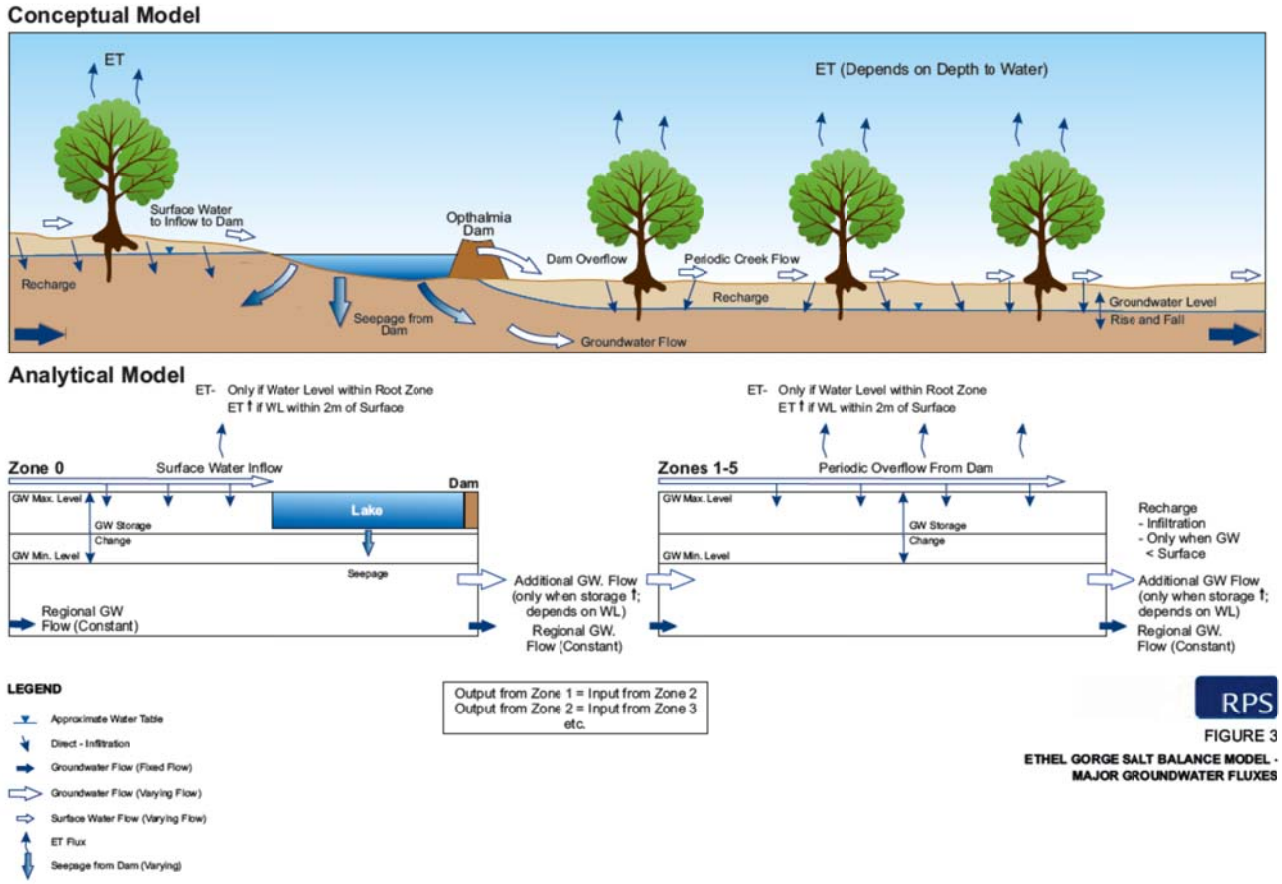
Figure 3: Conceptual water and salt balance model for the Ophthalmia aquifer.



The key characteristics of the analytical model are as follows:

- The study area was divided into six zines (Zone 0 to Zone 5) with Zone 0 representing the groundwater directly underneath Ophthalmia Dam and Zone 5 representing the groundwater underneath Ethel Gorge (Figure 4). Water levels and salinity concentrations were estimated for each zone.
- Only the upper Ophthalmia aquifer was considered in the study.
- The modelling was carried using a monthly time-step
- The main water and salinity input in Zone 0 is leakage from the Ophthalmia Dam, which is based on the Ophthalmia Dam water and salt balance model.
- Other water inputs to Zone 0 are groundwater recharge along the Fortescue River in the area upstream of the dam and groundwater inflow from up-gradient aquifers.
- Inputs for the remaining zones (Zones 1 to 5) are groundwater inflow from the zone up-gradient, infiltration of water that overflows the Ophthalmia Dam and infiltration of water that is released from the Ophthalmia Dam outlet structures. The Ophthalmia Dam overflows and releases were derived from the Ophthalmia Dam water and salt balance model.
- The main water outflow is evapotranspiration which is a depth-dependent function with an average rate of 600 mm/yr. The evapotranspiration rate is based on the calibrated numerical groundwater model.
- Changes in groundwater storage for each of the zones are calculated as the net inflows less evapotranspiration losses. The change in groundwater storage was then used to determine the change of groundwater levels in the zone (assuming a specific yield of 7% to 10%).
- The regional groundwater through-flow rate was assumed to be 1500 kL/d, which were based on the numerical groundwater model. Where there are a difference of groundwater levels between two adjacent groundwater zones (e.g. during infiltration following an overflow event), additional groundwater flow occurs to the down-gradient zones.
- Infiltration is constrained if water levels are at the ground surface at any particular zone (i.e. the aquifer has no infiltration capacity if the water levels are at ground surface).
- The main salinity inflows are

Section 4: Water and salinity balance modelling continued

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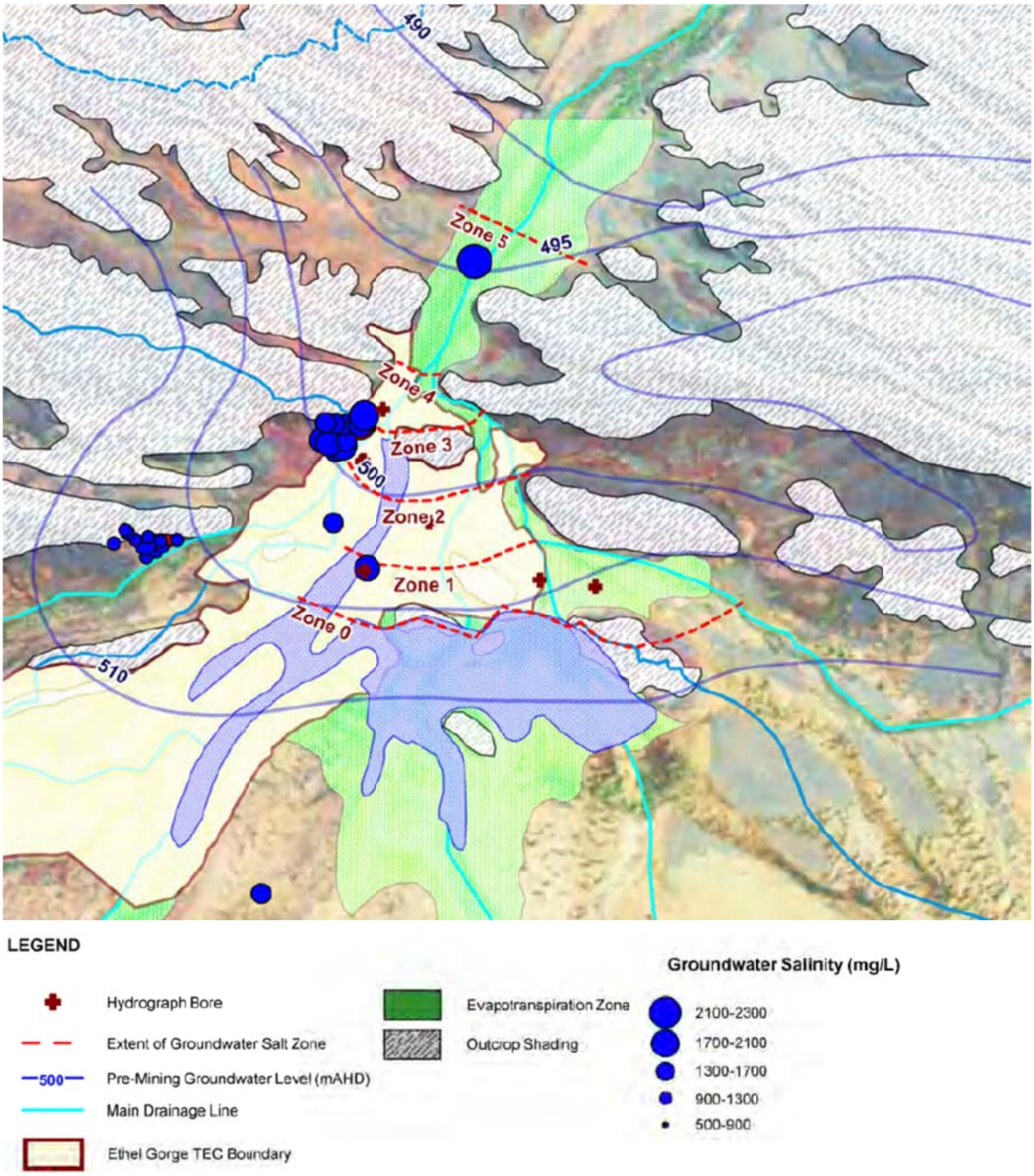
- o Leakage from the Ophthalmia Dam
- o Infiltration of water that overflows the Ophthalmia Dam
- o Infiltration of water that are released from the Ophthalmia Dam outlet structures
- o Groundwater through-flow

The main salinity outflow is groundwater through flow from Zone 5.

- The salinity concentration for each zone is calculated by the total TDS load divided by the water volume for each of the zones.

Figure 4: Groundwater salinity zones on the Ophthalmia aquifer



Section 4: Water and salinity balance modelling continued

Modelling Scenarios

The modelling scenarios were consistent with the Ophthalmia Dam water and salt balance model and comprised

- No surplus dewatering discharge, which is the base case scenario.
- Approved case dewatering schedule which comprises the existing operations (OB25, Whaleback) and OB29, OB30, OB35 and Jimblebar mining operations
- SEA case dewatering schedule which include the approved case mining operations as well as OB17, OB18, OB31, OB32, OB34, OB37 and OB39.

RPS also considered the following conditions for the model runs:

- Dry and wet climate scenarios
- Different dam operating strategies namely:
    - No outlet structure discharge – water overflows the spillway when the dam is full
    - Outlet structure discharge equivalent to 50% of the surplus dewatering rates

There were 10 modelling scenarios in total namely

- Two models for the baseline scenario (wet and dry climates)
- Four models for the approved case schedules (wet and dry plus no outlet discharge and 50% outlet discharge)
- Four models for the SEA case schedules (wet and dry plus no outlet discharge and 50% outlet discharge)

Additional Modelling Scenarios

Additional modelling scenarios were considered assuming the discharge of higher than anticipated dewatering discharge from OB31

- Approved case dewatering schedule which comprises the existing operations (OB25) and OB29, OB30, OB35 and Jimblebar mining operations plus the dewatering schedule from OB31
- Different dam operating strategies namely:
    - No outlet structure discharge
    - Outlet structure discharge equivalent to 50% of the surplus dewatering rates

The outputs of the Ophthalmia Dam water and salt balance model, which include the leakage rates, overflow rates and release flow rates, as well as the TDS concentrations for each of the flow rates, were used as input to the Ophthalmia aquifer water and salt balance model.

Model results

Ophthalmia Dam water and salt balance

A summary of the Ophthalmia Dam water and salt balance modelling results are shown in Table 1. The water level and salinity graphs for the baseline and SEA cases (dry climate only) are shown on Figures 5 to 7.

For the baseline scenarios, where it was assumed that there will be no discharge of surplus dewatering water to Ophthalmia Dam, the modelling results shows that the average water levels in the dam will be at 510.6 m and the average salinity will be 55 mg/L TDS for the dry climate scenario. For the wet climate scenario, water levels are about 0.2 m higher and predicted salinities are essentially the same.

For the approved case mining schedule, water levels are predicted to be only slightly higher compared to the baseline scenarios. Salinity concentrations are predicted to be about 2.3 times higher compared to the baseline scenarios. If 50% of the dewatering water is released through the outlet structures of the dam, salinity concentrations are predicted to be only slightly lower compared to the case where no water is released from the dam.

For the SEA case mining schedule, water levels are predicted to be 0.5 m higher compared to the baseline scenarios. Average salinity concentrations are predicted to be about 5 times higher compared to the baseline scenarios. If 50% of the dewatering water is released through the outlet structures of the dam, salinity concentrations are predicted to be 4 times higher compared to baseline conditions.

Where surplus dewatering water is discharged to the Ophthalmia Dam, the dam is less likely to completely empty, and the model predicts that a small volume of water will mostly remain in the dam during the end of the dry seasons. The salinity concentrations at the end of the dry seasons are predicted to be high – 5 to 10 times higher than the peak salinity concentrations for the baseline conditions.

Section 4: Water and salinity balance modelling continued

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Ophthalmia Dam water and salt balance: Approved plus OB31 dewatering

A summary of the Ophthalmia Dam water and salt balance modelling results for the approved case plus OB31 dewatering discharge is shown in Table 2. The water level and salinity graphs for the approved and OB31 cases are shown on Figures 6 to 11.

For the approved case mining schedule plus OB31 dewatering, average water levels are predicted to be between 0.6 and 0.9 m higher than the baseline conditions. Salinity concentrations are predicted to be between 7 and 9 times higher compared to the baseline scenarios. If 50% of the dewatering water is released through the outlet structures of the dam, salinity concentrations are predicted to be between 5 and 6 times higher compared to the baseline scenarios

Section 4: Water and salinity balance modelling continued

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Table 1: Results of the Ophthalmia Dam water and salt balance modelling

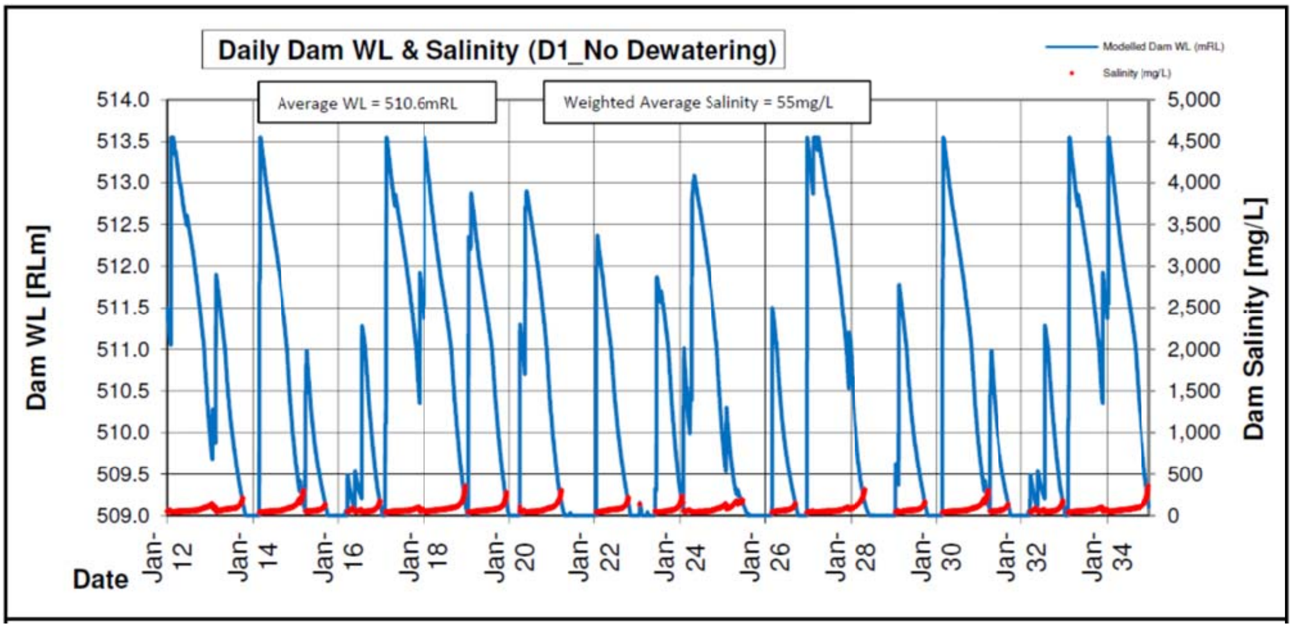
Mining Schedule	Outlet Discharge	Climate Scenario	Storage Water Level (RL m)	Average TDS (mg/L)	Average Max TDS (mg/L)	Seepage Rates (ML/d)	Average overflows (GL/yr)
Baseline	None	Dry	510.6	55	250	35	11.2
		Wet	510.8	55	250	39	13.0
Approved Case	None	Dry	510.7	127	2500	38	11.4
		Wet	510.9	124	2000	42	13.3
	50%	Dry	510.6	109	1500	36	11.2
		Wet	510.8	110	1500	41	13.1
SEA Case	None	Dry	511.1	298	3000	46	11.9
		Wet	511.3	279	2500	50	13.7
	50%	Dry	510.8	217	1800	40	11.5
		Wet	511.0	211	2000	45	13.3

Table 2: Results of the Ophthalmia Dam water and salt balance modelling: higher OB31 discharge

Mining Schedule	Outlet Discharge	Dewatering case*	Storage Water Level (RL m)	Average TDS (mg/L)	Seepage Rates (ML/d)	Average overflows (GL/yr)
Baseline	None	N/A	510.6	55	35	9.4
Approved Case and OB31	None	Low	511.2	375	49	10.1
		High	511.5	480	55	10.6
	50%	Low	510.9	255	42	9.7
		High	511.1	320	45	9.9

*Shovelanna and Jimblebar profiles

Figure 5: No surplus dewatering (baseline)



Section 4: Water and salinity balance modelling continued

Figure 6: Surplus dewatering discharge from SEA schedule – no release, except spillway overflow

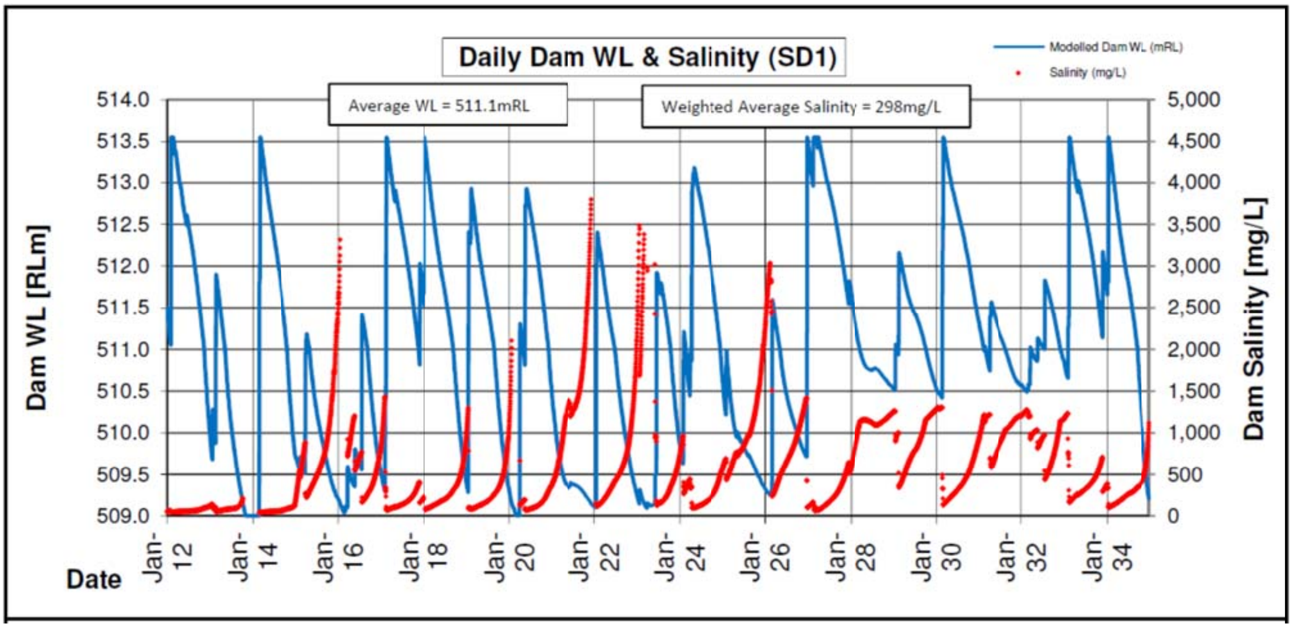
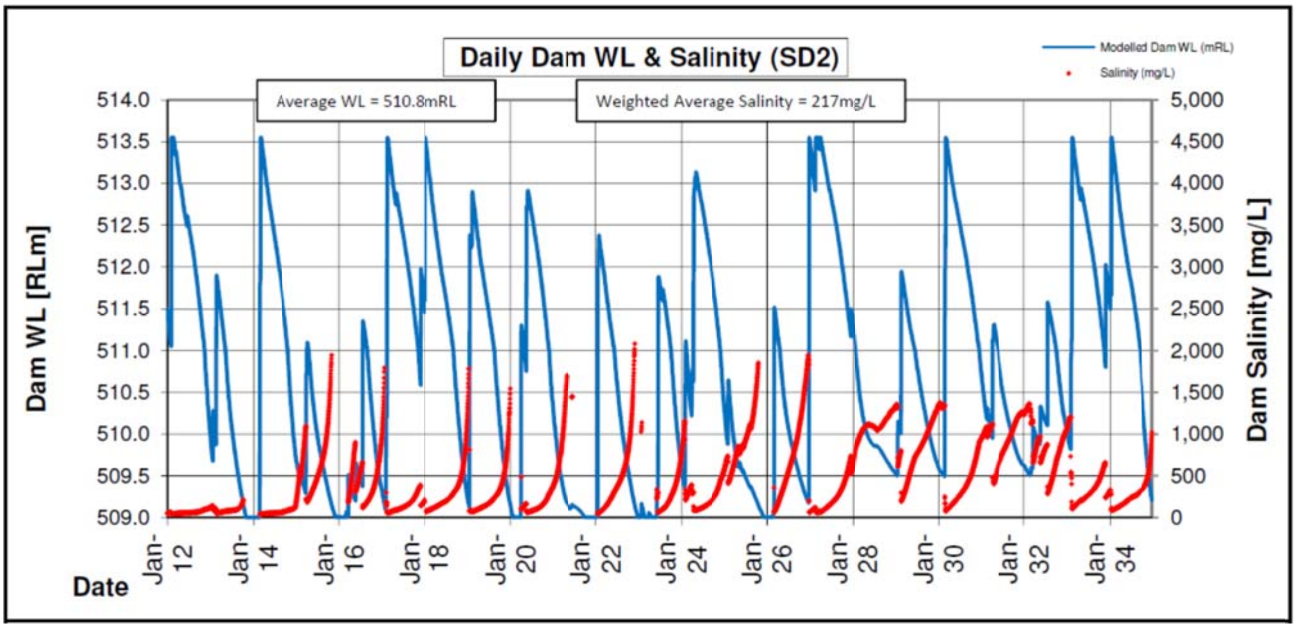


Figure 7: Surplus dewatering discharge from SEA schedule – 50% dewatering release from outlet structures



Section 4: Water and salinity balance modelling continued

Figure 8: Surplus dewatering discharge from Approved plus OB31 schedule – Low case and no dewatering release from outlet structures

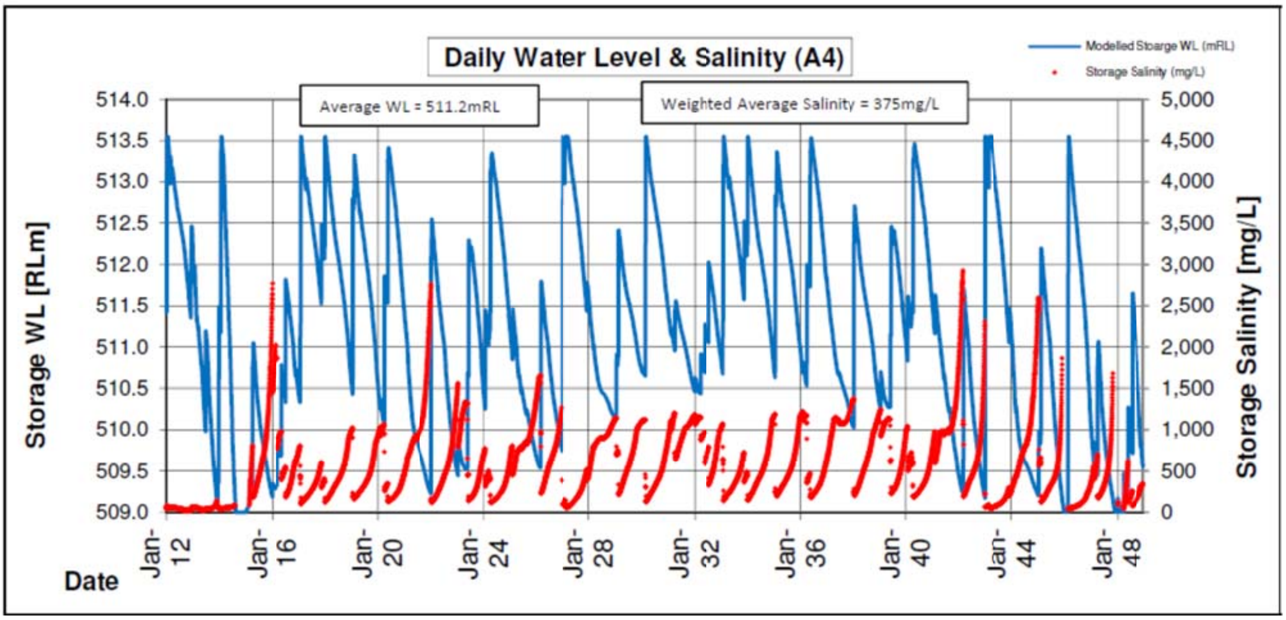
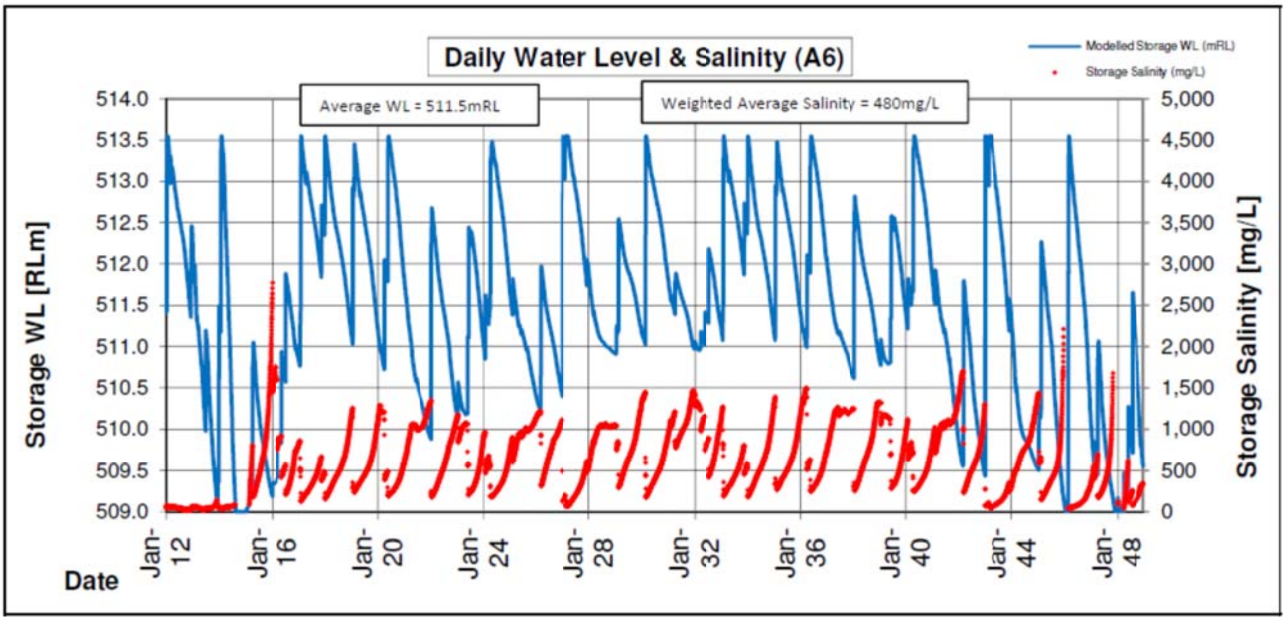


Figure 9: Surplus dewatering discharge from Approved plus OB31 schedule – High case and no dewatering release from outlet structures



Section 4: Water and salinity balance modelling continued

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Figure 10: Surplus dewatering discharge from Approved plus OB31 schedule – Low case and 50% dewatering release from outlet structures

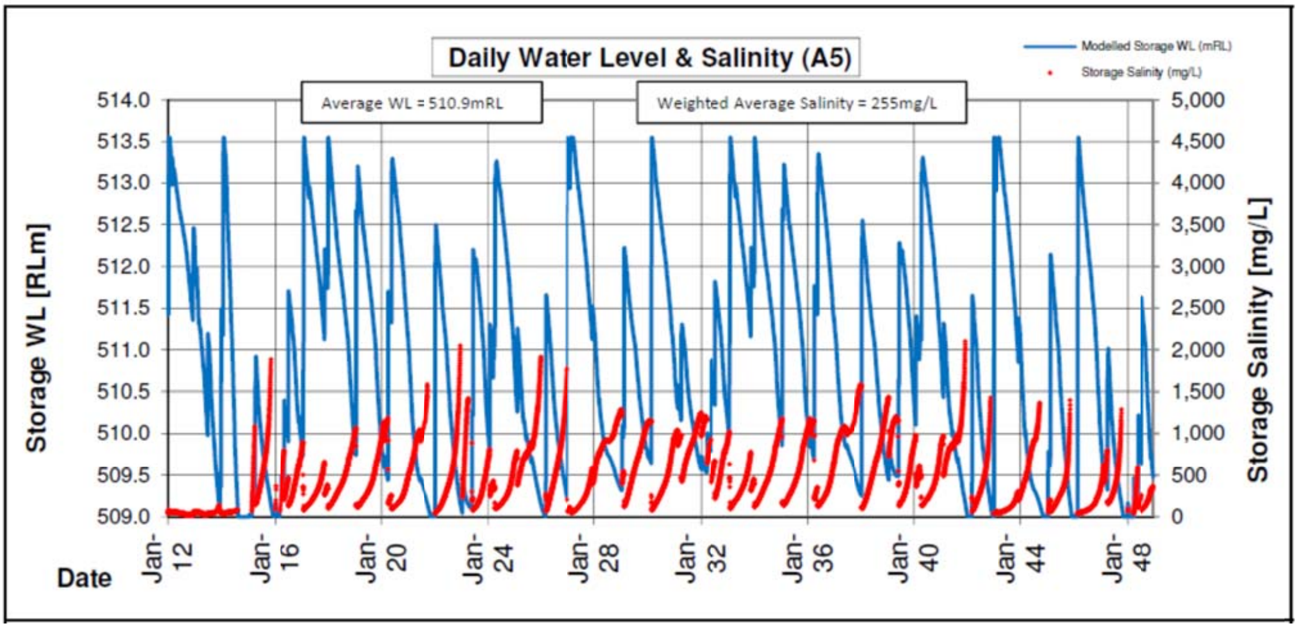
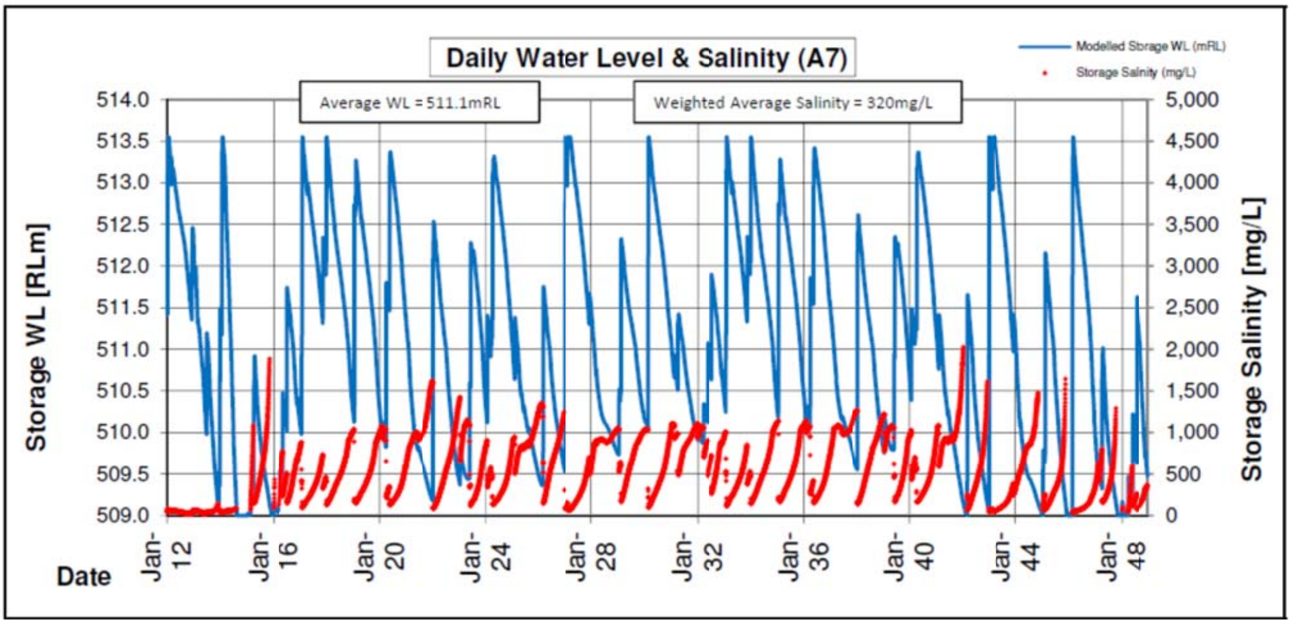


Figure 11: Surplus dewatering discharge from Approved plus OB31 schedule – High case and 50% dewatering release from outlet structures



Ophthalmia aquifer water and salt balance

A summary of the Ophthalmia aquifer water and salt balance modelling results are shown in Table 3. The predicted salinity concentrations for the wet and dry climate scenarios are very similar and as such, only the dry climate results are shown in Table 3. The salinity graphs for the baseline and SEA cases are shown on Figures 12 to 14.

The salinity concentrations in the Ophthalmia aquifer prior to the dam were about 1100 mg/L TDS. Since the dam construction, salinity concentration increased to about 1700 mg/L TDS. In some areas of the aquifer, maximum TDS concentrations are 2200 mg/L TDS. The higher salinity concentrations are probably the result of the establishment of a dense riparian vegetation that has become established downstream of the dam, taking advantage of the shallower groundwater conditions around the dam. The increased evapotranspiration along the area downstream of the dam removed more water from the aquifer, but left the salinity in the aquifer, resulting in increased salinity concentrations.

Section 4: Water and salinity balance modelling continued

The modelling results for the baseline conditions, i.e., assuming no further discharge of surplus water into the dam, shows a marginal increase in TDS concentrations in the aquifer. TDS concentrations are essentially stable and remain within historical ranges.

For both the approved case and the SEA mining schedule, there is a small increase in TDS concentrations in some zones of the aquifer, but TDS concentrations remain within historical ranges. Higher salinity water is retained in the dam and when the dam overflows, the overflow water is substantially diluted and does not significantly increase the salinity concentrations in the aquifer.

If water volumes equivalent to 50% of the surplus dewatering water is released through the Ophthalmia Dam outlet structures, the modelling shows an increase of salinity concentrations over most of the aquifer and TDS concentrations are above historical ranges. For this scenario, a portion of high salinity water in the dam is released and infiltrates the aquifer, resulting in increased salinity concentrations.

Table 3: Results of the Ophthalmia aquifer water and salt balance modelling

Mining Schedule	Outlet Discharge	Zone	Starting salinity (mg/L TDS)	Ending salinity (mg/L TDS)	Remarks
Historical	As per past operating strategy	Zone 0 Zone 1 Zone 2 Zone 3 Zone 4 Zone 5 ***Average***	900 975 1075 1175 1175 1175 ***1079***	681 1340 1984 2108 2076 1760 ***1658***	Substantial spatial variation of TDS concentrations occurs throughout aquifer, but average TDS concentrations are 1100 mg/L. Ophthalmia Dam resulted in the establishment of denser riparian vegetation and increased evapotranspiration resulting in an increase in TDS concentrations.
Baseline future (no discharge)	None	Zone 0 Zone 1 Zone 2 Zone 3 Zone 4 Zone 5 ***Average***	681 1340 1984 2108 2076 1760 ***1658***	635 1306 2137 2315 2253 2131 ***1796***	Marginal increase in TDS concentrations but essentially remaining stable. Salinity concentrations remain within historical ranges.
Approved Case	None	Zone 0 Zone 1 Zone 2 Zone 3 Zone 4 Zone 5 ***Average***	681 1340 1984 2108 2076 1760 ***1658***	713 1380 2285 2518 2440 2185 ***1920***	Small increase in TDS concentrations in some zones of the aquifer, but TDS concentrations remain within historical ranges.
	50%	Zone 0 Zone 1 Zone 2 Zone 3 Zone 4 Zone 5 ***Average***	681 1340 1984 2108 2076 1760 ***1658***	692 1691 2595 3264 2936 2613 ***2298***	Some changes over a number of zones and maximum TDS concentrations are above the historical ranges.
SEA Case	None	Zone 0 Zone 1 Zone 2 Zone 3 Zone 4 Zone 5 ***Average***	681 1340 1984 2108 2076 1760 ***1658***	873 1418 2046 2491 2547 2470 ***1974***	Small increase in TDS concentrations in some zones of the aquifer, but TDS concentrations remain within historical ranges.
	50%	Zone 0 Zone 1 Zone 2 Zone 3 Zone 4 Zone 5 ***Average***	681 1340 1984 2108 2076 1760 ***1658***	819 1884 2851 3574 3195 2804 ***2521***	Changes for most of the zones and maximum TDS concentrations are above the historical ranges

Section 4: Water and salinity balance modelling continued

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Ophthalmia aquifer water and salt balance: Approved case plus OB31 dewatering

A summary of the Ophthalmia aquifer water and salt balance modelling results for the approved case plus OB31 dewatering is shown in Table 4.

For both the low case and high case approved mining schedule plus OB31, there are increases in TDS concentrations in all zones of the aquifer and for zones 3 to 5 TDS concentrations are above historical ranges. Higher salinity water overflows and infiltrates the aquifer increasing the salinity concentrations in the aquifer.

For the low case, If water volumes equivalent to 50% of the surplus dewatering water is released through the Ophthalmia Dam outlet structures, the modelling shows a substantial increase of TDS concentrations over all the zones and TDS concentrations are significantly above historical ranges. However, for the high case, overflow water is diluted and TDS concentrations are comparable with the no water release scenarios.

Table 4: Results of the Ophthalmia aquifer water and salt balance modelling

Mining Schedule	Outlet Discharge	Zone	Starting salinity (mg/L TDS)	Ending salinity (mg/L TDS)	Remarks
Approved plus OB31: Low Case	None	Zone 0	681	1004	Increase in TDS concentrations in all zones of the aquifer and TDS concentrations are above historical ranges in zones 3 to 5
		Zone 1	1340	1524	
		Zone 2	1984	2335	
		Zone 3	2108	3062	
		Zone 4	2076	3289	
		Zone 5	1760	2839	
		Average	***1658***	**2342**	
	50%	Zone 0	681	966	Significant increases in TDS and maximum TDS concentrations are significantly above the historical ranges.
		Zone 1	1340	4824	
		Zone 2	1984	8400	
		Zone 3	2108	9498	
		Zone 4	2076	7098	
		Zone 5	1760	6006	
		Average	***1658***	**6132**	
Approved plus OB31: High Case	None	Zone 0	681	1081	Increase in TDS concentrations in all zones of the aquifer and TDS concentrations are above historical ranges in zones 3 to 5.
		Zone 1	1340	1601	
		Zone 2	1984	2434	
		Zone 3	2108	3061	
		Zone 4	2076	3185	
		Zone 5	1760	3361	
		Average	***1658***	**2454**	
	50%	Zone 0	681	1029	Increase in TDS concentrations in all zones of the aquifer and TDS concentrations are above historical ranges in zones 3 to 5
		Zone 1	1340	1927	
		Zone 2	1984	2629	
		Zone 3	2108	3062	
		Zone 4	2076	2592	
		Zone 5	1760	2510	
		Average	***1658***	**2292**	

Section 4: Water and salinity balance modelling continued

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Figure 12: No surplus dewatering

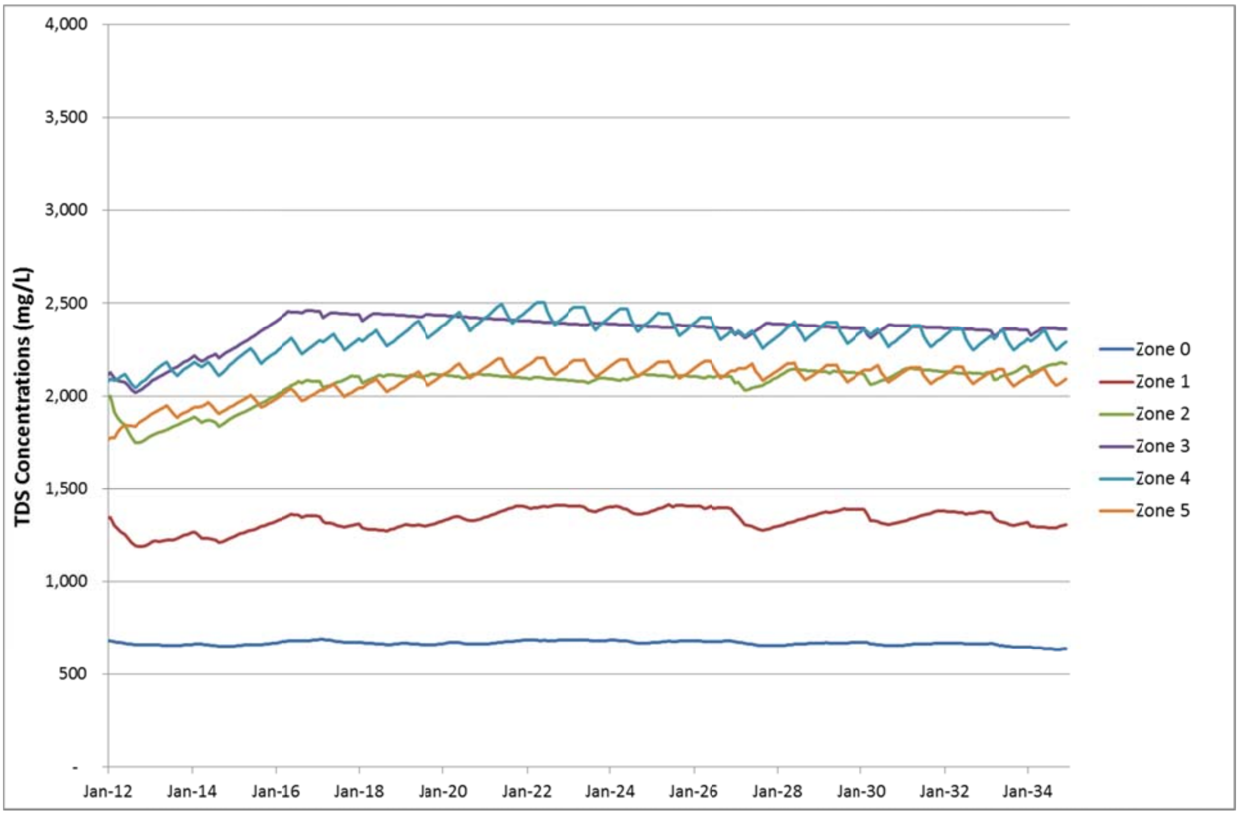
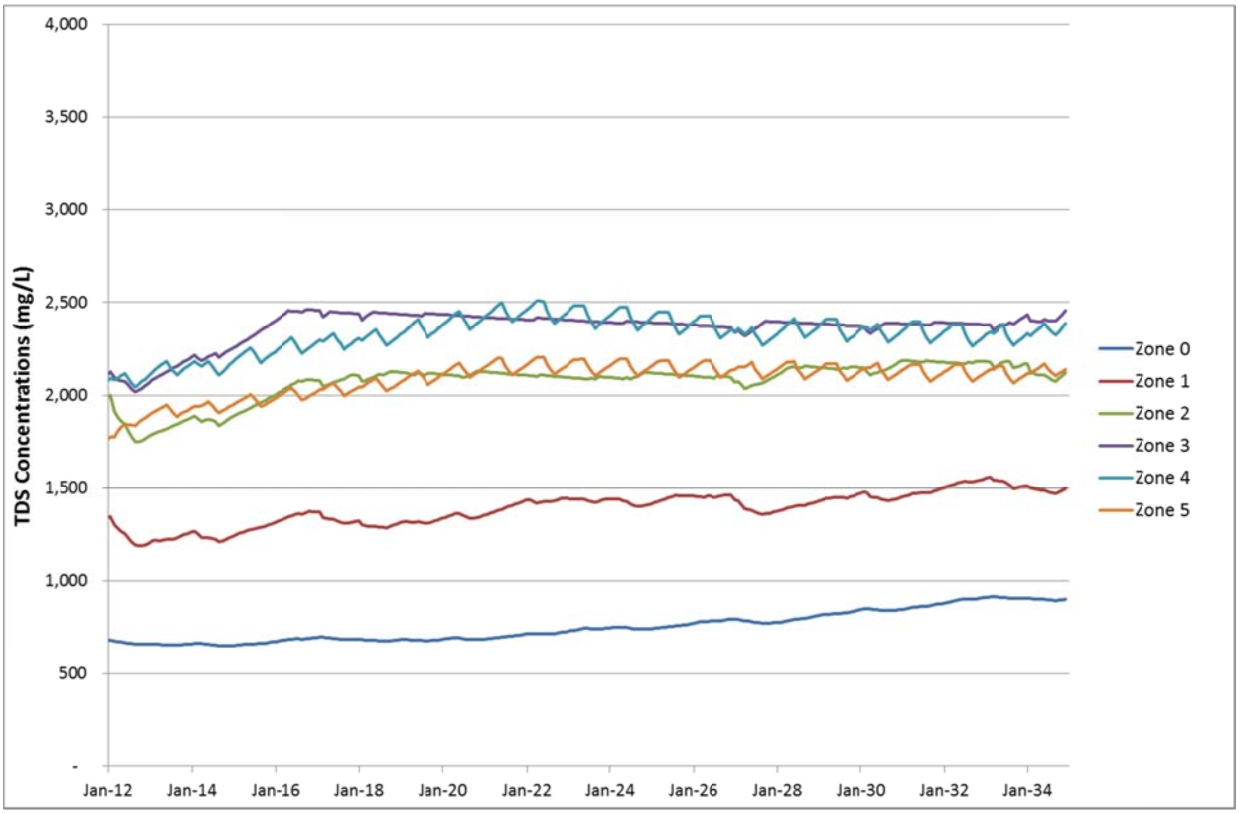


Figure 13: Surplus dewatering discharge from SEA schedule – no releases, except overflows



Section 4: Water and salinity balance modelling continued

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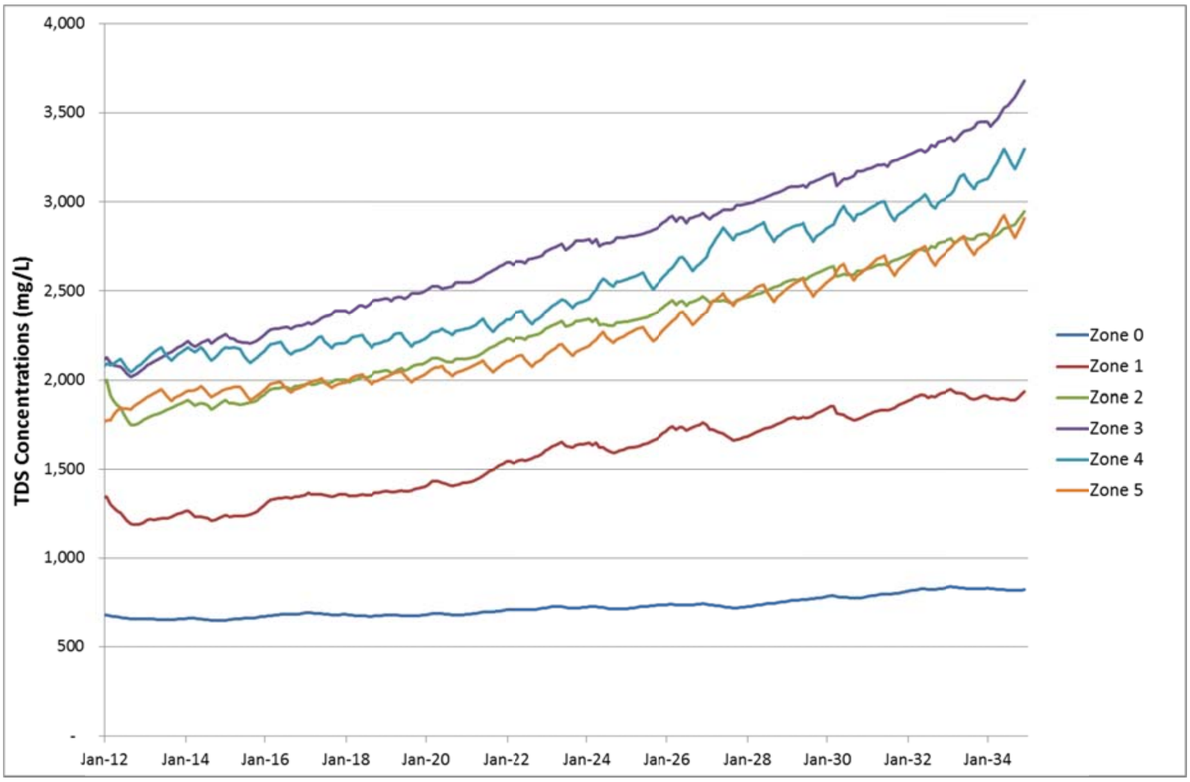
Figure 14: Surplus dewatering discharge from SEA schedule – 50% dewatering releases



Conclusions

There is a large variation of salinity concentrations within the Ophthalmia aquifer and the historical salinity concentrations ranged between 200 and 2200 mg/L. It is likely that the stygofauna communities within the TEC, as well as the riparian vegetation has adapted to this variability in salinity concentrations. Stygofauna remains abundant within the TEC and there has been no observed deterioration of riparian vegetation attributable to increased groundwater salinity concentrations.

If no surplus dewatering is discharged to the Ophthalmia Dam, the modelling results indicate that the salinity concentrations in the Ophthalmia Dam and the Ophthalmia aquifer will remain stable. In the Ophthalmia Dam, there will be seasonal fluctuations in salinity concentrations caused by the evapoconcentration effects during the dry season, but long-term salinity trends will remain stable.

Since 2006, BHP Billiton Iron Ore has discharged surplus dewatering water from OB23 and OB25 into the Ophthalmia Dam. During this period, groundwater salinity concentrations remained within the historical ranges and there have been no observable impacts on the stygofauna communities in the TEC or the riparian vegetation.

Approvals are in place to discharge surplus dewatering water from OB29, OB30, OB35 and Jimblebar mining operations. The modelling shows that TDS concentrations in Ophthalmia Dam will increase by a factor of about 2.3, but there will only be small increases on TDS concentrations in the Ophthalmia aquifer, and TDS concentrations will remain within the historical ranges.

For the SEA mining schedule, BHP Billiton Iron Ore is planning to discharge surplus dewatering water from the approved operations, as well as surplus dewatering water from OB24, OB17, OB18, OB31, OB32, OB34, OB 37 and OB39 into the Ophthalmia Dam. The modelling shows that TDS concentrations in Ophthalmia Dam will increase by a factor of about 5, but there will only be small increases on TDS concentrations in the Ophthalmia aquifer, and TDS concentrations will remain within the historical ranges.

If the dewatering from OB31 is higher than anticipated, TDS concentrations in the Ophthalmia Dam may increase by a factor of between 7 and 9. Subsequently, TDS concentrations in the Ophthalmia aquifer will also be higher and and TDS concentrations maybe above historical ranges.

The operating strategy of the Ophthalmia Dam is a key factor determining groundwater salinity in the Ophthalmia Dam. If 50% of the surplus dewatering water that is discharged into the Ophthalmia Dam is released through the outlet structures, salinity concentrations in the aquifer might be higher and exceed the historical salinity concentration ranges. However, if

Section 4: Water and salinity balance modelling continued

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water is released from the dam when the dam is full or nearly full, the salinity concentrations in the dam will be low and the subsequent infiltration of low salinity water from the dam will dilute the aquifer salinity.

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RPS (2014d) Ethel Gorge Assessment of the Impact of OB31 Dewatering Discharge into Ophthalmia Dam -Groundwater and Salt Balance Modelling

RPS (2014e) Eastern Pilbara Region Ecohydrological Conceptualisation, August 2014.

RPS (2015a) Regional numerical modelling of Orebody 31 summary report. February 2015.

RPS (in progress) Ethel Gorge Model Summary Report (in preparation)