Subterranean Ecology

Scientific Environmental Services

STYGOFAUNA SURVEY
TROPICANA GOLD PROJECT
MINIGWAL WATER SUPPLY AREA

Prepared for Tropicana Joint Venture
AngloGold Ashanti Australia Ltd
Independence Group NL

January 2009

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MINIGWAL WATER SUPPLY AREA

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Project No. 60

Prepared for Tropicana Joint Venture

AngloGold Ashanti Australia Ltd
Independence Group NL

Prepared by: Subterranean Ecology

Date: January 2009

COVER: Drill cuttings showing the very fine grain size of sediments in the lower sandstone aquifer. Photo Copyright Subterranean Ecology.

LIMITATIONS: This survey was limited to the requirements specified by the client and the extent of information made available to the consultant at the time of undertaking the work. Determination of potential impact and reference sites was based on information provided by Tropicana Joint Venture. Information not made available to this study, or which subsequently becomes available may alter the conclusions made herein.

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EXECUTIVE SUMMARY

The Tropicana Joint Venture (TJV) is currently undertaking a pre-feasibility study on the viability of establishing the Tropicana Gold Project (TGP), which is centred on the Tropicana and Havana gold prospects. The proposed TGP is located approximately 330 km east north-east of Kalgoorlie in Western Australia.

Water requirements for the TGP in the order or 20,000m^3 per day will be obtained from a borefield proposed to be developed in the confined lower sandstone aquifer of the Minigwal Trough approximately 50 km north of the TGP operational area which lies to the south and west of Lake Rason and its palaeodrainage.

To determine whether stygofauna occur within the area of the proposed water supply borefield, AngloGold Ashanti Australia (AngloGold) commissioned Subterranean Ecology to conduct a study of stygofauna consistent with the EPA Guidelines No 54 and 54a.

The study comprised both a desktop review and field survey with the purpose of evaluating stygofauna in the confined lower sandstone aquifer of the Minigwal Trough. Specifically, the study involved the following:

1. A desktop review of information (world literature and Western Australia) addressing the environmental conditions and limits that control the occurrence of stygofauna;
2. A pilot study of bores in the proposed Minigwal Trough water supply borefield to determine the presence or absence of stygofauna in accordance with EPA Guidance No 54 and 54a;
3. Pilot study sampling of groundwater physico-chemistry (temperature, pH, TDS, conductivity, redox, dissolved oxygen) to characterise the environmental conditions available for groundwater fauna in the study area;
4. Evaluate the field survey results with reference to existing knowledge to determine the likelihood of stygofauna occurring in the aquifer proposed for the water supply borefield.

The desktop review concluded that the lower sandstone aquifer of the Minigwal Trough has a very low likelihood of supporting habitat suitable for stygofauna because:

1. The aquifer geohydrology is deep, confined and fully saturated. Most stygofauna are known from shallow depths in unconfined and unsaturated aquifers. Stygofauna is less likely to occur in deep, confined and fully saturated aquifers, and to my knowledge, no stygofauna have been recorded from this type of aquifer in Western Australia.
2. The aquifer typology is compact with very fine grain size (0.1 mm), so there is lack of interstitial living space which will exclude most stygofauna groups except possibly burrowing forms.

3. The compact sediment texture implies reduced hydrologic conductivity for exchange of nutrients and oxygen;
4. The aquifer is deep and isolated from overlying superficial aquifer by an aquitard, so vertical inputs of energy and oxygen from surface are prevented;
5. Recharge and through flow rates are likely to be extremely low, so nutrients and oxygen inputs are likely to be limited, and gradually depleted along the confined flow path;
6. The high salinities probably exclude many species which occur in fresher groundwaters. Some measured salinities lie near the upper limits or exceed the tolerance limits recorded for stygofauna;
7. Lake Rason is located near the southern boundary of the Yilgarn stygoregion coinciding with the absence of major calcrete aquifers that elsewhere harbour rich stygofauna communities in the northern Yilgarn.
8. The Eocene marine transgression may have eliminated freshwater lineages from Lake Rason area.

A pilot field survey was conducted to validate the conclusions of the desktop review. Ten accessible bores were sampled by net hauling or pumping methods, and water physico-chemistry parameters (temperature, pH, salinity, conductivity, redox, dissolved oxygen) were measured to characterise and evaluate water quality conditions for stygofauna. The pilot field survey detected no stygofauna in the sampled bores, consistent with the conclusions of the desktop review.

To evaluate, in an Australia-wide context, the suitability of the lower sandstone aquifer of the Minigwal Trough to support stygofauna, the geohydrology, aquifer typology and physico-chemical attributes were compared with data from other studies where stygofauna have been recorded. This evaluation revealed major geohydrological, aquifer typological and some groundwater quality differences between the lower sandstone aquifer in the Minigwal Trough and other sampled aquifers which contain stygofauna.

In conclusion, the lower sandstone aquifer of the Minigwal Trough is not considered to be highly prospective for stygofauna, and additional field sampling is not considered necessary for further validation of the assessment made herein.

1. INTRODUCTION

1.1 BACKGROUND

The Tropicana Joint Venture (TJV) is currently undertaking a pre-feasibility study on the viability of establishing the Tropicana Gold Project (TGP), which is centred on the Tropicana and Havana gold prospects. The proposed TGP is located approximately 330 km east north-east of Kalgoorlie, and 15km west of the Plumridge Lakes Nature Reserve, on the western edge of the Great Victoria Desert (GVD) biogeographic region of Western Australia (Figure 1). The project is a joint venture between AngloGold Ashanti Australia Limited (70% stakeholder and Manager) and the Independence Group NL (30% stakeholder).

The TGP consists of three main components (Figure 1):

- Operational Area - This area contains the mine, processing plant, aerodrome, village and other associated infrastructure;
- Water Supply Area - Two basins have been investigated, the Minigwal Trough and Officer Basin; and
- Infrastructure Corridor - Two options are under consideration (Tropicana-Transline and Pinjin Road options).

The TJV envisage that the project will be in full production by the end of 2012. The TGP may demand up to 20,000 m^3/day of processed water (based on an assumed plant size of 7Mtpa), ideally with salinity fresher than sea water (Pennington Scott 2007). Exploration activity to date has focused on Neo Proterozoic sandstone aquifers in the Minigwal Trough in an area approximately 40 to 100 km north of Tropicana which lies to the south and west of Lake Rason and its palaeodrainage.

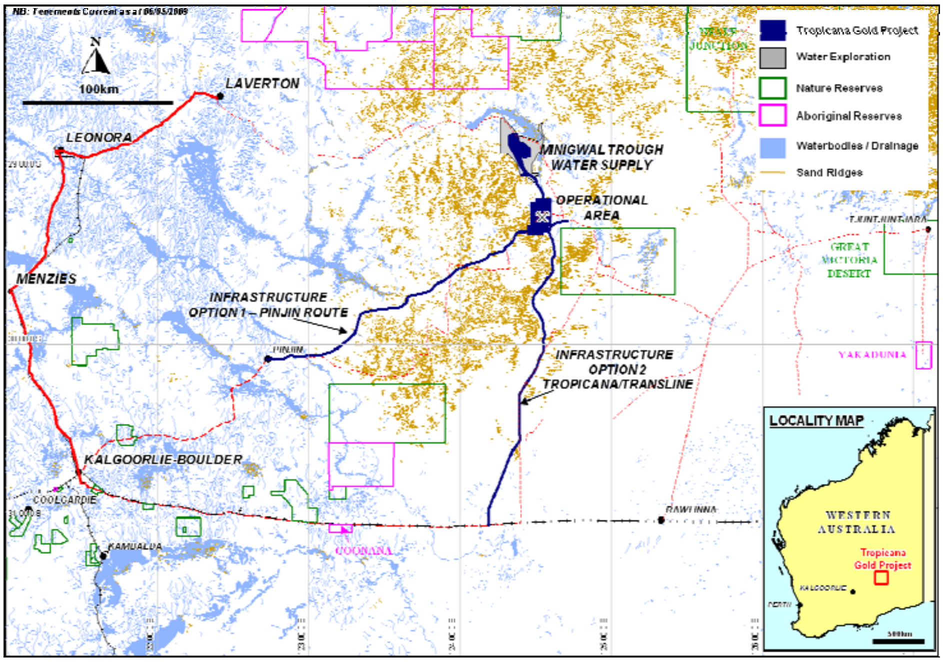

Figure 1 Tropicana Gold Project Location

1.2 PURPOSE AND SCOPE OF THIS REPORT

This report presents the results following a desktop review and pilot field survey for stygofauna at the proposed Minigwal Trough water supply area for the proposed Tropicana Gold Project in the Great Victoria Desert Region of Western Australia. The objectives of the field survey were to:

1. Prepare a desktop review of information (world literature and Western Australia) addressing the environmental conditions and limits that control the occurrence of stygofauna;
2. Undertake a pilot study of bores in the proposed water supply borefield to establish the presence or absence of stygofauna;
3. Measure groundwater physico-chemistry (temperature, pH, total dissolved solids (TDS), conductivity, redox, dissolved oxygen) to characterise the environmental conditions for groundwater fauna in the study area; and
4. Evaluate the field survey results with reference to existing knowledge to evaluate the likelihood that stygofauna occur in the aquifer proposed for the water supply borefield.

The methods used in this survey complied with the EPA Guidance Statements No. 54 and 54A for the survey and assessment of subterranean fauna in Western Australia (EPA 2003, 2007). For this survey, one general limitation, and two site-specific limitations, were identified (listed below):

1. Probability of a false negative, viz. the sampling fails to detect the presence of stygofauna when in fact they are present.
2. Relatively few (11) bores available for sampling within the proposed water supply borefield area, and;
3. Construction of the bores only commenced in December 2007, so all bores were less than six months old at the time of sampling.

These limitations do not preclude or invalidate the desktop review and pilot field survey undertaken herein, as discussed later.

2. DESKTOP REVIEW: LIMITS TO BIOLOGICAL DISTRIBUTIONS IN GROUNDWATER

Just as in surface waters, there are limits to biological distributions in groundwater. Groundwater habitats are defined by biogeographic peculiarities, the geohydrological type of aquifer and by the hydrological exchange with surface water (Hahn in review). The distribution of groundwater biota is controlled by historical factors, physico-chemical variables, biological interactions, and interactions among these broad classes of elements (Strayer 1994).

2.1 Aquifer types

Stygofauna occupy groundwater across a diverse range of geologic / geomorphic settings, including karstic carbonate rocks, fractured rock aquifers, and porous unconsolidated sediments (eg. alluvium). They may be found in deep groundwater habitats tens to hundreds of metres below the surface, in addition to shallow groundwater habitats including springs and spring-brooks where groundwater discharges to the surface, also hyporheic and parafluvial setting (saturated sediments beneath and alongside surface water courses). Stygofauna are found in oxygenated groundwater ranging from fresh to brackish, but they may occur in salinities up to seawater (Humphreys 1999).

On the landscape mesoscale, the geohydrological type of aquifer provides a useful indication of the prospective habitat for stygofauna and the type of community that may be present. Hahn and Fuchs (2007 accepted) defined a typology comprising two main types of aquifer relevant for fauna:

1) ‘compact aquifers’ (aquitard), and;
2) ‘open aquifers’.

Compact aquifers have reduced pore spaces, and a very low or low hydraulic conductivity (kf < 10 -6 m sec^{-1}), so called aquitards such as clay, loess, and very fine sands, as well as compact rocks (Hahn 2007). Open aquifers comprise porous, fractured and karstic groundwater circulation systems. They are characterised by more or less well developed pore spaces and fractures, with at least moderate hydraulic conductivity (kf > 10^{-6} m sec^{-1}) (Hahn 2007). Hydraulic conductivity, surface water – groundwater exchanges, food and oxygen supply will be reduced in a compact aquifer. In Germany, Hahn (2007) sampled compact aquifers and found that they were often devoid of fauna, or taxonomic richness and abundance was depleted. It seemed likely that both lack of living space and reduced hydrologic exchange with surface water were contributory.

2.2 Sediment texture

The importance of sediment texture is probably chiefly related to its influence on hydraulic conductivity which in turn controls supply rates of dissolved substances such as oxygen, organic carbon and nitrate (Strayer 1994).

Sediment texture is also correlated with the sizes of pore spaces suitable for use by biota, and the suitability of the sediment for burrowing (Strayer 1994). Interstitial void space is known to influence community structure and the size of the animals living in it (Coineanu 2000). Larger pore spaces provide more living space, with higher animal abundances in coarse compared to fine sediments (see eg. Hahn 2006).

2.3 Hydraulic conductivity

On a local scale, hydrological exchange that controls food and oxygen supply is considered by many authors to be the key factor shaping groundwater communities (eg. Hahn 2006). In alluvial aquifers in Eastern Australia Hancock and Boulton found stygofauna richness was correlated with a number of factors including (lower) temperature, conductivity (most taxa occurring at conductivities < 1.5 mS cm^{-1}), proximity to the water table and the roots of phreatophytic vegetation, coarse sediments and higher hydraulic conductivity. The higher hydraulic conductivity is likely to lead to a greater flux of organic matter and oxygen to support aquifer communities (Hancock and Boulton 2008).

2.4 Depth from surface

In karst regions, both microbes and invertebrates (and even vertebrates) are found in caves up to 800 m below the Earth's surface, but in non-karst (interstitial) environments few invertebrates penetrate deeply (Strayer 1994). Bacteria may be present in non-karst aquifers hundreds of metres below the earth's surface. More important than vertical depth below the surface for groundwater animals, is the degree of hydrological exchange with surface water (eg. Hahn 2006). The degree of hydrological exchange between groundwater and surface water will be controlled by the geohydrologic structure and water regime.

2.5 Water regime

The primary components of water regime are timing, frequency, duration, extent and depth, and variability (Boulton and Brock 1999). These variables are scale dependent and related to each other in space and time, analogous to flow path and flow history. The processes of recharge, through flow and discharge, and variability in these processes, will strongly influence the type of groundwater ecosystem that can be sustained.

The greater the distance or isolation of the groundwater from surface influence, the greater the affinity of the fauna to the groundwater. This isolation occurs in vertical depth of groundwater, lateral distance from recharge sources, and distance or time along groundwater flow paths (Dole-Olivier et al. 1994). Metabolic consumption of oxygen and organic carbon will occur along groundwater flow paths, and if not replenished will become gradually deleted. Removal of oxygen in confined or semi-confined aquifers, where replenishment is not possible, occurs over time in the order of 10^1 to

10^5 years depending on the organic carbon content of sediment (Malard and Hervant 1999).

2.6 Energy (food)

The other major limiting factor for groundwater animals is energy (food supply) in the form of dissolved organic matter (DOM), particulate organic matter (POM) and bacteria (Hahn 2006). Food supply for most groundwater communities is limited and dependent on import from the surface. Except for some rare chemautotrophic systems, food is largely derived from the downward movement of photosynthetically derived particulate or dissolved organic carbon reaching the watertable through the overlying matrix (Humphreys 2006). Thus the strength and direction of hydrological exchange with the surface is a key factor shaping the structure of groundwater communities (see references cited in Hahn 2006). Food (and oxygen) will likely become limiting factors in the portions of groundwater flow paths with distant temporal and spatial connectivity to the surface.

2.7 Salinity

Stygofauna globally are mostly restricted to freshwater, rarely mildly brackish, except in the special case of anchialine ecosystems, however the Western Shield of Western Australia uniquely contains a diverse assemblage of near-marine and ancient freshwater lineages inhabiting groundwaters ranging up to marine salinity (Humphreys 2008). In the centre of the Western Shield at Lake Way, Watts and Humphreys (2004) recorded a diverse stygal assemblage in a bore with surface salinity near seawater (30,000 mg L^{-1}) and a strong salinity gradient increasing to 69,000 mg L^{-1} at 6 m depth.

In the northern goldfields, stygofauna have been recorded from ground waters where salinity ranges between 30,000 and 60,000 mg L^{-1} TDS (ecologia 2006). The EPA Guidelines No. 54 suggests that salinities up to 50 ppK may be considered prospective for stygofauna. The finer scale vertical distribution of stygofauna inhabiting groundwaters in Western Australia, which may be strongly stratified with steep gradients in salinity at micro/meso-scales, remains largely uninvestigated.

The salinity tolerances of fauna in non-marine saline surface waters provide a basis for comparison because many taxonomic groups, including the same genera or species in some instances, occur both in groundwaters and saline surface waters with salinities > 50 ppK, for example: copepods, ostracods, decapods, isopods, molluscs, polychaetes, and insects (eg. Bayly and Williams 1981). While many species inhabiting salt lakes are specialised halotolerant animals, these records illustrate the potential salinity tolerances of aquatic macroinvertabrates. The genera *Haloniscus* and *Halicyclops* are represented in both salt lake and groundwater habitats in Western Australia (see Taiti and Humphreys 2000, Karanovic 2004, 2006; Cooper et al. 2008). In surface waters, species belonging to these genera have been recorded from salinities ranging from 8 to 62 ppK (*Halicyclops ambiguus*), and from 8 to 159 ppK (*Haloniscus searlei*) Bayly and Williams 1981). The stygoxenic copepod *Apocyclops dengizicus* has been recorded from groundwaters in the Yilgarn and Pilbara (Karanovic 2004, 2006), and is a widespread, commonly encountered species in surface waters including wetlands in the Western Australian wheatbelt and Carnarvon Basin with salinities ranging up to 180ppK (Blinn et al. 2004, Halse et al. 2000). Oligochaetes have been recorded in southwestern WA wetlands with salinities of 0.1 to 69.1 mS cm^{-1} (equivalent to approx. 34.5 ppK) (Kay et al. 2001). While low salinity groundwaters are often associated with high richness of stygofauna, groundwaters with high salinity should not necessarily be precluded as non-prospective for stygofauna simply on the basis of their salinity.

2.8 Dissolved oxygen

Dissolved oxygen (DO) in groundwater is spatially heterogenous at macro- (km), meso-(m) and micro- (cm) scales, and reflects changes in sediment composition and structure, groundwater flow velocity, organic matter content, and the abundance and activity of micro-organisms (eg. Malard and Hervant 1999). DO gradients along groundwater flow paths vary over several orders of magnitude in confined aquifers (eg. declines of 9×10^{-5} to 1.5×10^{-2} mg L^{-1} O_2 m^{-1}), and in unconfined parafluvial water (eg. 2 x 10-^{2} to 1 mg L^{-1} O_2 m^{-1}). Malard and Hervant (1999) attributed this strong variability among systems to differences in contact time of water with sediment, and observed that in confined groundwater systems, where replenishment of oxygen is impossible, the removal time of DO varies from a few years to more than 10,000 years, depending mainly on the organic carbon content of the sediment.

Oxygen is a limiting factor for macro-invertebrates in groundwater, but many stygobitic animals are highly resistant to low levels of dissolved oxygen, some only being known from oxygen deficient groundwaters, and they have an enhanced ability to tolerate hypoxia and recover from anaerobic stress (Malard and Hervant 1999).. In Germany Hahn (2006) found that fauna abundance decreased strongly below 1.0 mg L^{-1}, and that DO concentrations below 0.5 mg L^{-1} are critical for most groundwater metazoans.

The DO concentration in groundwater may be classified as suboxic (< 0.3 mg L^{-1} O_2), dysoxic (0.3 – 3.0 mg L^{-1} O_2), or oxic (> 3 mg L^{-1} O_2). Although hypogean animals are probably unsuited for life in groundwater extensively or permanently suboxic (< 0.3 mg L^{-1} O_2), they can be found in small or temporarily suboxic patches (Malard and Hervant 1999). Although groundwater macro-crustaceans are much more resistant to hypoxia than their epigean relatives, studies on some species of amphipods and isopods in Europe showed they cannot survive severe hypoxia (DO < 0.01 mg L^{-1} O2) for more than a few days (lethal time for 50 % population ranged 46.7 to 61.7 hours) (Hervant et al. 1998).

In an Australian context, stygofauna are commonly associated with dysoxic waters with DO levels well below 1 mg L^{-1}. The range in DO measured by Watts and Humphreys (2004, 2006) in calcrete aquifers in the Western Shield which supported stygofauna varied from 0.7 - 8.0 mg L^{-1}, while the anchialine community in Bundera Cenote at Cape Range occurs mostly in water with DO below 0.5 mg/L but not lower than 0.2 mg L^{-1} (Seymour et al. 2008).

2.9 Redox status of groundwater

Redox potential (Eh) is the ability of a solution to oxidise or reduce. In sediments, there is a gradient of conditions, indicated by ‘cutoffs’ that correspond roughly to the zones where different inorganic compounds are used as electron acceptors by bacteria in the sediments to oxidise organic matter (Boulton and Brock 1999). Oxidised conditions are indicated by a redox potential (at pH 7) exceeding +400 mV; nitrite (NO_2) is reduced at Eh less than approximately +225 mV; manganese (Mn^{+3} to Mn^{+2}) at about +200 mV; Fe^{+3} at +120 mV; and SO_4^{-2} at -150 mV (Boulton and Brock op. cit.). Methane is only generated at strongly negative (< -150 mV) Eh potentials.

Redox (Eh) conditions can exert a powerful control on the distribution of biota. Along flow paths in confined aquifers or most deep unconfined aquifers, to which oxidants are not added in large amounts, the redox potential will decline as oxygen, nitrate, manganese, iron, and sulphate are progressively reduced (Strayer 1994).

2.10 Other environmental correlates

Stygofauna are rich in calcareous systems where the pH is typically between 7.2 – 8.2 (Humphreys 2008). In the Pilbara, the presence of ostracods was predominantly determined by pH and carbonate saturation. Water of low pH, redox values (Eh) indicating reducing conditions, or with total nitrogen > 10 mg L^{-1} rarely contained Ostracoda (Reeves et al. 2007). Nonetheless, ostracods were found in groundwaters varying from pH 4.40 to 8.69, Eh -421 to +837, TDS 49 to 13000 mg L^{-1}, and %Ca^{2+} saturation 0.22 to 68.64.

Carbonate rocks typically produce a water chemistry conducive for stygofauna due to its slightly alkaline pH, but water in igneous and metamorphic sedimentary rocks may be acidic and less suitable for stygofauna (Humphreys 2008). This is probably the case in palaeo valleys to the south of the mulga-eucalypt line (or south of latitude ca. 29^0 S) in Western Australia where carbonaceous deposits from Eocene marine inundation of the southern palaeo channels resulted in the reduction of sulphur, extensive anoxic conditions, and consequently a lack of calcrete (Morgan 1993 cited in Humphreys 2008). Lake Rason is located close to the mulga-eucalypt line at latitude 280 40’ S, at an elevation of ca. 335 m above present sea level.

Morgan (1993) noted a separation in hydrogeological style between northern and southern parts of the Yilgarn Craton, the palaeochannels of the northern Yilgarn Craton have developed isolated but similar hydrochemical cells in response to a semi-arid climate, whereas the palaeochannels in the southern parts of the craton, in more temperate conditions, form single hydrogeological systems along their linear flow paths. The hydrogeological discontinuity which characterises the separation of calcrete aquifers in the northern Yilgarn has undoubtedly contributed to the isolation and evolution of multiple short range endemic stygofauna lineages there (Humphreys 2001). Lake Rason lies just to the south of the major calcrete aquifers depicted on the 1:250,000 hydrogeological map of Western Australia.

2.11 Biogeographic and historical factors

On the macroscale, the significance of biogeography and historical factors in explaining the broad scale patterns in stygofauna distribution is obvious (Hahn in review). Similar to the concept of bioregions developed for surface environments, Gibert et al. (2005) proposed an analogous term ‘stygoregions’ for groundwater environments.

The long emergent portions of the Australian continent, including the Western Shield which have not been inundated by the sea since the Proterozoic, contain many ancient freshwater lineages (see references cited in Humphreys 2008). Those areas inundated by the sea in the Cretaceous and more recently, particularly the Eocene inundation which reached approximately 300 m above present sea level, are largely devoid of these more ancient lineages (Bradbury 1999, Wilson and Johnson 1999), although there is some intrusion of fauna across the inundated/emergent ‘divide’(Humphreys 2008). Marine waters deeply penetrated the palaeo valleys of the southern Yilgarn (Jones 1990, Worrall cited in Humphreys 2008), and these ancient high sea level stands are prospective sites for invasion of continental groundwaters by marine lineages (Humphreys 2008).

During the Early Cretaceous, an arm of the Tethys Sea penetrated from north-western Australia and formed a vast shallow epicontinental sea (the Eromanga Sea) which connected with the southern seaway in the region of the Eucla Basin (White 1994). Thus a potential route existed for colonisation of the eastern margin of the Western Shield by Tethyan fauna during the late Mesozoic. The recent discovery of a speleophriid copepod, a member of the “Tethyan” faunal suite such as occurs at Cape Range, raises the likelihood that other Tethyan near-marine lineages may be found in groundwaters located near the palaeoshorelines of the Western Shield (Karanovic and Eberhard submitted). Lake Rason and the Minigwal trough are situated in a sedimentary basin between the Yilgarn Craton and the Frazer Range, which forms the eastern margin of the Western Shield. Lake Rason is situated at an elevation of ca. 335 m above present sea level, which is close to the level of the Eocene sea level highstand.

2.12 Existing Knowledge (Western Australia)

In Western Australia, stygofauna have been documented from most regions and areas including the Kimberley, Pilbara (Pilbara craton and Barrow Island), Carnarvon (Cape Range), Murchison, Goldfields, South West (Perth Basin and Leeuwin Naturaliste Ridge), South Coast (Albany and Nullarbor Plain). In the Pilbara region, sampling conducted in the last decade has revealed the Pilbara to be a globally significant hotspot for stygofauna diversity (Humphreys 2000b; Eberhard, Halse and Humphreys 2006). Stygofauna is widespread and occurs in a range of hydrogeological environments including karstic, fractured rock, vuggy pisolite and porous aquifers, in addition to springs, parafluvial and hyporheic environments (Eberhard et al. 2005). Stygofauna are found in oxygenated groundwater ranging from fresh to brackish, but they may occur in salinities up to seawater (Humphreys 1999), and possibly even in more saline waters.

Calcretes in the northern Yilgarn have been sampled extensively for stygofauna, which revealed the diverse dytiscid (diving beetle) fauna consisting of over 100 species (Cooper et al. 2002; Humphreys 2006; Watts and Humphreys 2003; Watts and Humphreys 2004). Numerous calcrete deposits in the Leonora area have previously been sampled including those within the Carey Palaeodrainage of which Lake Rason forms a part. All these calcrete deposits, which are nested within the alluvium filling palaeo-channels, contain significant stygofaunal communities.

Stygofauna appears to be less common within the surrounding alluvial deposits, despite limited sampling over several years (WA Museum unpublished data), however stygofauna has been collected from alluvial aquifers several kilometers from calcretes, in palaeo-channels near Wiluna (Subterranean Ecology 2007, Biota 2006). Stygofauna collected at Mount Margaret were collected from within the calcrete resource as well as the alluvial sands above the palaeochannel aquifers and the silcretes in the Marshall Pool Borefield (EPA 2001 cited in ecologia 2007). While the most diverse stygofauna communities are found in calcrete aquifers, including the air-breathing stygobiont diving beetles which are apparently restricted to calcretes, some stygofauna may be expected in surrounding porous or other non-calcrete matrices.

3. CONTEXT FOR THIS STUDY

3.1 PREVIOUS WORK

Ecologia Environment (2007) prepared a desktop review on stygofauna for the Tropicana Gold Project's operational area. Ecologia's regional overview confirmed that there was very little published or unpublished data concerning stygofauna from the Great Victoria Desert. The regional summary of the Great Victoria Desert Central and Great Victoria Desert Shield subregions makes no mention of stygofauna species collected (CALM 2002). Ecologia (2007) commissioned the Western Australian Museum (WAM) to conduct a search of their stygofauna database, based on the following latitudinal and longitudinal coordinates (which include Lake Rason and the proposed water supply borefield):

29 30.00 S; 123 00.00 E;
29 30.00 S, 125 00.00 E;
31 30.00 S, 123 00.00 E;
31 30.00 S, 125 00.00 E.

The WAM database search returned no records of subterranean fauna from within those coordinates, but Bill Humphreys (WAM) indicated that there are subterranean fauna records at that latitude both to the east and west of the search area, and that the result therefore reflects a lack of sampling being undertaken, rather than an absence of subterranean fauna in the area (Ecologia 2007). The locations at that latitude both to the east and west of the search area were not specified in the report by ecologia.

Ecologia (2007) noted that stygofauna have been recorded at a number of sites within 300 km of the Tropicana operational area, including from calcretes at Windarra (Maczurad and Murphey 1997) and Mount Margaret (EPA 2001), which are located approximately 250 km northwest of the operational area. Stygofauna collected at Mount Margaret were collected from within the Sturt Meadows calcrete resource as well as the alluvial sands above the palaeochannel aquifers and the silcretes in the Marshall Pool Borefield (EPA 2001). A Threatened Ecological Community (TEC) of stygofauna also exists in a northeast goldfields aquifer at Depot Springs (Syrinx 2006 cited in Ecologia 2007).

For the TGP Operational area, which is geographically and geohydrologically distinct from the proposed Minigwal water supply area, ecologia's (2007) desktop review concluded that it was likely that stygofauna would occur in some groundwater bodies around the Tropicana operational area. Ecologia (2007) drew this conclusion based on:

> "Firstly, despite the lack of stygofauna records from the TGP area (and other AGAA leases in the region) in the databases of Western Australian Museum (WAM) and Department of Environment and Conservation (DEC), a number of stygofauna records exist to the north, east and west of Tropicana (B. Humphreys, pers.comm.). The lack of records from within the TGP Operational Area is considered to be due to the paucity of

targeted sampling rather than a genuine absence of stygal species (B. Humphreys, pers. comm.; A. Pinder, pers. comm.).

Secondly, a relatively large number of calcrete formations are present within the project area and adjacent regions, with some up to 10m in thickness. As the majority of stygofauna records in WA come from calcrete aquifers (Humphreys 2001), the possibility of stygofauna presence in the Tropicana calcrete formations is realistic.

Finally, the groundwater salinity within the project area falls within the ranges that stygofauna species have been recorded from previously. In the northern goldfields, for example, stygofauna are regularly recorded from ground waters where salinity ranges between 30,000 and 60,000mg/L TDS (ecologia 2006B. Humphreys pers. comm.). As the salinity in the project area does not exceed 60,000 mg/L TDS, no water-quality barriers should exist to prevent stygofauna from colonising the Tropicana calcrete formations."

While the paucity of regional sampling and groundwater salinity are relevant in the context of this report, it should be noted that ecologia's assessment was centred on the TGP Operational area which is concerned with superficial unconfined aquifers that contain calcrete, whereas the proposed water supply borefield is concerned with the deep and confined sandstone aquifer which is separated from the superficial aquifers by a relatively impermeable layer of shale that acts as an aquitard.

Ecologia (2007) recommended a two-phase stygofauna sampling program be conducted to determine the presence or absence of stygofauna in the operational area, and, if present, to determine the impact of the proposed pit and associated infrastructure and activities (eg dewatering) on the species present. Alternatively, a preliminary sampling program could be conducted, with the intent to carry out additional sampling if stygofauna are recorded (Ecologia 2007).

3.2 LOCAL GEOLOGY and HYDROGEOLOGY

Lake Rason (330 to 350 m AHD), which comprises a lower part of the Carey palaeodrainage system, is located in the Minigwal Trough which abuts the eastern margin of the Yilgarn Craton and the western margin of the Frazer Range. The geology and hydrogeology of the Lake Rason area is described by Pennington Scott (2007) with relevant text and figures from this report reproduced as below. The Minigwal Trough is an informal name given herein to describe a 300 kilometre long by 50 kilometre wide north-south sedimentary basin abutting the western margin of the Frazer Range, which is the Archaean province hosting the gold deposit that is the focus of the TGP. The trough sedimentary succession comprises at least three sedimentary groups, being:

1. Cainozoic deposits comprising palaeochannel and eolian deposits, and weathering/digenetic alteration products;
2. Permian lacustrine shales and fluvial tillite deposits of the Canning or Gunbarrel Basins; chiefly the Paterson Formation; and
3. The neo Proterozoic Officer Basin formations of the Balya Group, which unconformably overly crystalline rocks of the Yilgarn Craton and Albany-Fraser Orogen.

Figure 2 shows a schematic geological cross-section through the Minigwal Trough and stratigraphic relationship between the formations.

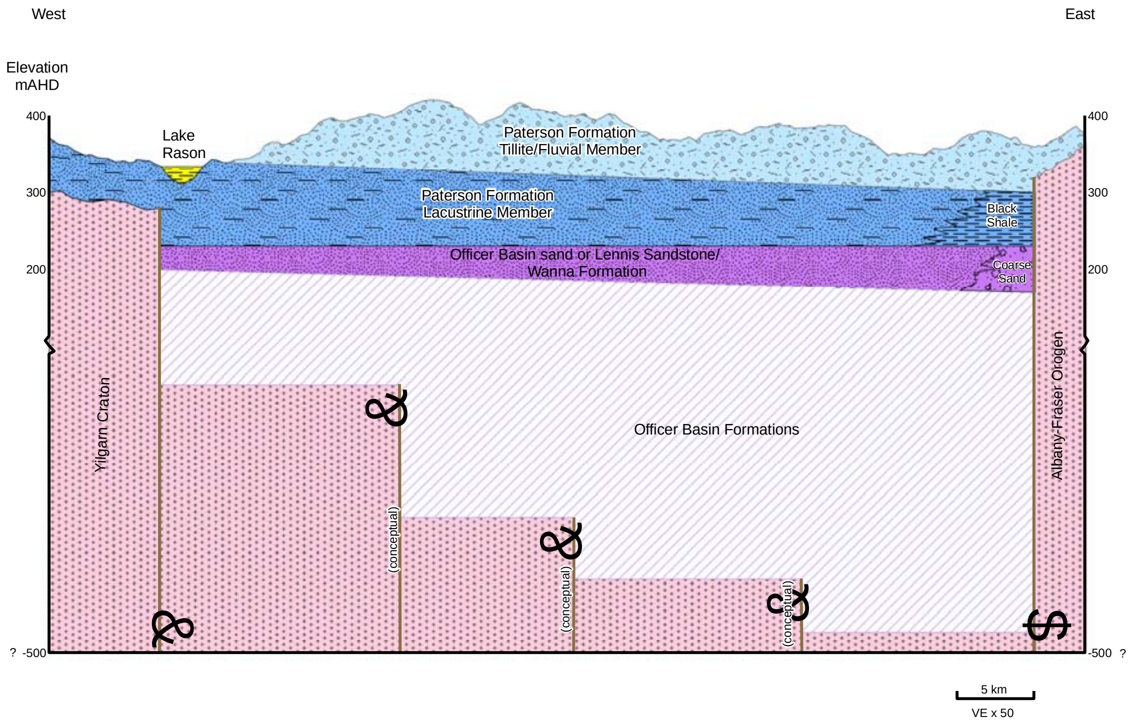

Figure 2 Geological cross-section of the Minigwal Trough. From Pennington Scott (2007).

Groundwater in the Minigwal Trough occurs almost exclusively within the primary interstitial pore spaces in the sandy units, or within dissolution cavities in the shallow duricrust. There are two main sand aquifers present within the Trough:

1. a lower Sandstone aquifer, probably part of the Officer Basin sequence; and
2. an upper mixed tillite/fluvial member of the Paterson Formation.

The lower sandstone aquifer is potentially a highly permeable aquifer along the eastern margin of the trough where the sediments are coarse grained, but elsewhere the well sorted fine-grained sands (0.1mm) with moderate clay content result in low to moderate permeability. The sandstone aquifer is confined and fully saturated, with a sub artesian piezometric pressure head above the top of the aquifer.

The tillile/fluvial member of the Paterson Formation may be relatively thin, but it forms an important regional aquifer. The aquifer can yield significant fresh domestic water supplies, however the unpredictable distribution of permeable fluvial sands and low permeability clay, silt and sand mixtures within the tillite means that these supplies are difficult to locate with any level of certainty. Where saturated, the tillite aquifer tends to be phreatic, with the watertable occurring within the aquifer.

The fine grained shale and mudstone units of the lower Lacustrine Member of the Paterson Formation contains virtually no primary porosity and permeability, albeit marginal permeability may be developed in secondary defects such as faults and jointing adjacent to the Frazer range. Being generally 70 to more than 200 metres thick, this member of the Paterson Formation acts as an extensive aquitard (a layer of hydraulic impedance) separating the deeper sandstone aquifer from the upper tillite/fluvial aquifer. The unconsolidated clayey and silty sediments that infill the Lake Rason palaeodrainage are also considered to have predominantly aquitard properties.

The aquifer recharge and groundwater flow through the Minigwal Trough is likely to be extremely low due to the low rainfall rates over the Great Victoria Desert region. Recharge, when it does occur, would likely occur following rare extreme rainfall and flooding associated with tropical depressions (usually ex-cyclones) that pass over the region. Discharge of groundwater is mostly through evapotranspiration by plants in areas with a shallow watertable and via direct evaporation from the surface of Lake Rason.

Figure 3 shows a schematic hydrogeological cross-section for Lake Rason. Most interaction between Lake Rason and groundwater is associated with groundwater flow within the Paterson Formation tillite/fluvial aquifer and colluvium fringing Lake Rason. There is poor hydraulic connection between the deeper Sandstone aquifer and watertable due to the intervening Paterson Formation Lacustrine aquitard.

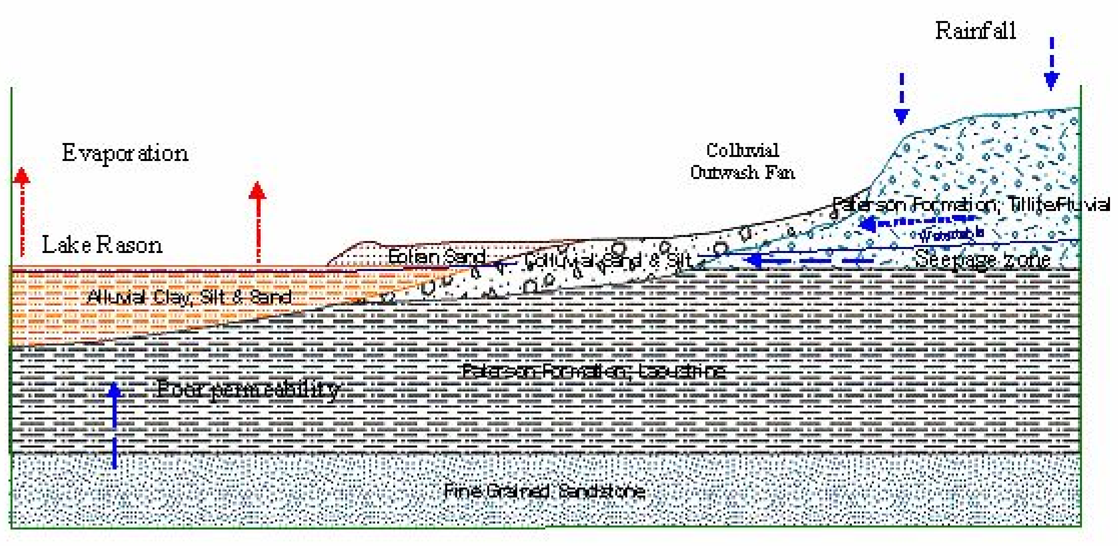

Figure 3 Schematic hydrogeological cross-section through Lake Rason. From Pennington Scott (2007).

Groundwater within the Minigwal Trough/Lake Rason area is saline, mostly with salinity between 10 000 mg L^{-1} and 270 000 mg L^{-1}. Evaporative concentration of salts within the Lake Rason valley result in groundwater brine coincident with the valley, and a pattern of groundwater salinity decreasing away from the valley. There may be some differences in groundwater salinity patterns between the deeper Sandstone and upper Paterson Formation tillite/fluvial aquifers that are yet to be identified.

3.3 POTENTIAL PROJECT IMPACTS

A preliminary environmental impact assessment was provided by Pennington Scott (2007), with sections relevant to stygofauna reproduced below.

Any borefield in the Minigwal Trough would be screened in the sandstone aquifer that lies beneath the Paterson Formation. The borefield would pump up to 20 ML/day of water with a salinity of less than 40,000 mg L^{-1} for a project life of 10-15 years, after which time the aquifer will be allowed to recover.

An appraisal of the environmental issues arising from development and operation of the project water supply in the Minigwal Trough identified the following issues relevant to groundwater dependant ecosystems and stygofauna (Pennington Scott (2007):

- “The borefield should not impact any groundwater dependant ecosystems because the only areas where the water table is sufficiently shallow for vegetation to access it would be adjacent to and beneath the Lake system, where groundwater quality is hypersaline. Although halophytes communities exist around the lake system which may use the hypersaline groundwater contained in shallow Patterson Fm sand lenses, these aquifers, if present, are separated from the main pumping aquifer by 70 metres or more of low permeability shale and therefore unlikely to be discernibly impacted by the proposed abstraction;”
- “the borefield operations are not expected to adversely impact the stygofauna diversity and abundance. Although not yet sampled, stygofauna populations are not anticipated due to the high salinity of the groundwater and the fine grainsize of the aquifer. Borefield operations are not expected to adversely impact the stygofauna diversity and abundance;”
- “From other Stygofauna studies throughout Western Australia suggest that the Stygofauna tend not to be found in groundwaters greater than 40,000 mg/L TDS, which would be much of the Minigwal Trough. Furthermore, the deep aquifer is known to have a very fine uniform grainsize of 0.1mm. Thus the likely interstitial pore spaces size is mostly smaller than the 0.05 mm net used to trap stygofauna.”

The appraisal by Pennington Scott (2007) is valid with respect to the very fine grainsize of the aquifer and corresponding small interstitial pore space size, which excludes most stygofauna groups except possibly burrowing forms. Importantly also, compact sediment texture implies reduced hydraulic conductivity, which in turn controls supply rates of dissolved substances such as oxygen, organic carbon and nitrate (Strayer 1994). In relation to salinity, the appraisal by Pennington Scott (2007) is correct in noting that stygofauna tend not to be found in groundwaters greater than 40,000 mgL-1 TDS, however, the occurrence in Western Australia of some species of stygofauna in groundwaters of higher salinity is not mentioned.

3.4 DESKTOP REVIEW CONCLUSIONS

The review of literature supported the conclusion that the lower sandstone aquifer of the Minigwal Trough has a very low likelihood of supporting stygofauna because:

1. The aquifer geohydrology is deep, confined and fully saturated. Most stygofauna are known from shallow depths in unconfined and unsaturated aquifers. Stygofauna is less likely to occur in deep, confined and fully saturated aquifers, and to my knowledge, no stygofauna have been recorded from this type of aquifer in Western Australia.
2. The aquifer typology is compact with very fine grain size (0.1 mm), so there is lack of interstitial living space which will exclude most stygofauna groups except possibly burrowing forms.
3. The compact sediment texture implies reduced hydrologic conductivity for exchange of nutrients and oxygen;
4. The aquifer is deep and isolated from overlying superficial aquifer by an aquitard, so vertical inputs of energy and oxygen from surface are prevented;
5. Recharge and through flow rates are likely to be extremely low, so nutrients and oxygen inputs are likely to be limited, and gradually depleted along confined flow path;
6. The high salinities probably exclude many species which occur in fresher groundwaters. Some measured salinities lie near the upper limits or exceed the tolerance limits recorded for stygofauna;
7. Lake Rason is located near southern boundary of the Yilgarn stygoregion coinciding with absence of major calcrete aquifers that elsewhere habor rich stygofauna communities in the northern Yilgarn.
8. The Eocene marine transgression may have eliminated freshwater lineages from Lake Rason area.

4. FIELD SURVEY METHODOLOGY

4.1 SURVEY APPROACH & LIMITATIONS

The EPA guidance statement no. 54 states;

> "It should be assumed that all sites in the Pilbara and Yilgarn / Goldfields will support significant stygofauna and troglofauna assemblages, unless there is strong evidence that subterranean habitats lack pore spaces, have a geology that renders conditions completely anoxic, or contain groundwater of salinity > 60,000 mg L-1. Note, however, that fresh water lying above a hypersaline lens may support stygofauna."

The desktop review (refer above) concluded there is a very low likelihood of stygofauna occurring in the proposed water supply because there is strong evidence that the lower sandstone aquifer does not contain habitat suitable for stygofauna. Although the review concluded there was a low likelihood of stygofauna, a pilot study was designed to validate the desktop assessment under the Precautionary Principle.

For pilot studies the EPA guidance no. 54 states;

> "In some cases, proponents may believe there is little likelihood of subterranean fauna occurring in a project area but desktop review does not provide convincing evidence to support this position. A pilot study may be an effective method of determining whether subterranean fauna occur. Much less sampling is required to characterize the type of community present than to document all species. If the area supports significant subterranean fauna, the results of the pilot study can be used to focus the more comprehensive survey that will be required to document all species and assess their conservation status."

> "The design of pilot studies is likely to vary according to situation. The aim will usually be to determine whether a project area has significant subterranean faunal values, which can be achieved with low sampling effort (Culver et al., 2004; Eberhard et al., 2007). It is expected that 6-10 stygofaunal samples or 10-15 troglofaunal samples will be collected in pilot studies. If the pilot study reveals the occurrence of significant subterranean fauna, more intensive investigation is likely to be required."

For the pilot survey of the Minigwal Trough, one general limitation, and two site-specific limitations, were identified (listed below):

4. Probability of a false negative, viz. the sampling fails to detect the presence of stygofauna when in fact they are present.
5. Relatively few (11) bores available for sampling within the proposed water supply borefield area, and;
6. Construction of the bores only commenced in December 2007, so all bores were less than six months old at the time of sampling.

These limitations do not preclude or invalidate the desktop review and pilot field survey undertaken herein, see below.

The first limitation is a general one affecting all stygofauna surveys, and it concerns their low predictability of capture and the possibility of recording a false negative result (Eberhard et al. 2007). Thus, concluding the absence of stygofauna based on a small number of samples carries some uncertainty, unless other environmental factors such as water physico-chemistry, sediment texture, and hydrogeology serve as convincing surrogate support. Applying the Precautionary Principle for this pilot survey, water physico-chemistry, sediment texture, and hydrogeology were investigated in detail to minimise the possibility of recording a false negative result. Particular attention was given to accurate measurement of dissolved oxygen (DO), as this is a critical limiting factor for macro-invertebrates in groundwater.

In relation to the second limitation, the EPA guidance recommends pilot studies, which require fewer samples (6 to 10) to be collected, in cases where there is little likelihood of subterranean fauna occurring (EPA 2007). The desktop review clearly indicated that there was little likelihood of subterranean fauna occurring in the lower sandstone aquifer of the Minigwal Trough, and hence the pilot survey approach is justified.

In relation to the third limitation, the EPA guidance states;

> "It is recommended that all bores sampled are at least six months old. Ideally, relatively new bores will have been 'developed' by pumping to remove contaminants and improve water flow into the bore before sampling occurs. Sometimes the timelines for EIA are such that proponents wish to undertake stygofaunal assessment using bores less than six months old. This may be done provided bores are more than three months old. However, sampling of bores less than six months old must be conducted over two seasons and, if the yield per bore is significantly greater in the second season than it was in the first, a third round of sampling will be required (i.e. first round will be deemed to have been inefficient)."

For the pilot survey the age of the bores was noted to be less than optimal (3 bores were > 3 months old, all bores < 6 months old), however the proponent wished to undertake the survey due to timelines for EIA. To my knowledge there are no published studies dedicated to measuring the time frames required by stygofauna to colonise bores, although, it is relevant to note that stygofauna have been collected from bores less than 3 months old (P. Hancock pers. comm. 2008, H. Barron pers. comm. 2005). It is also relevant to note that the uncertainty concerning the validity of samples collected from recently constructed bores may be circumvented to some extent by pump sampling of the surrounding aquifer water. Pumping overcomes the issue of bore age because pumping draws water from the surrounding aquifer, once the water inside the bore has been purged. Based on this concept, pump sampling was undertaken as opportunity allowed, at two bores visited during this survey.

4.3 SAMPLE SITES

The TJV provided a list of potential available bores in the Lake Rason area, of which eleven bores were selected for sampling in May 2008 (Figure 4, Table 1). Other bores were excluded from sampling because they were incompletely developed. Of the 11 bores sampled, four were screened in the superficial aquifer to provide comparative context, and the other seven bores were screened in the underlying deep sandstone aquifer at depths from 50 to > 200 m below the surface.

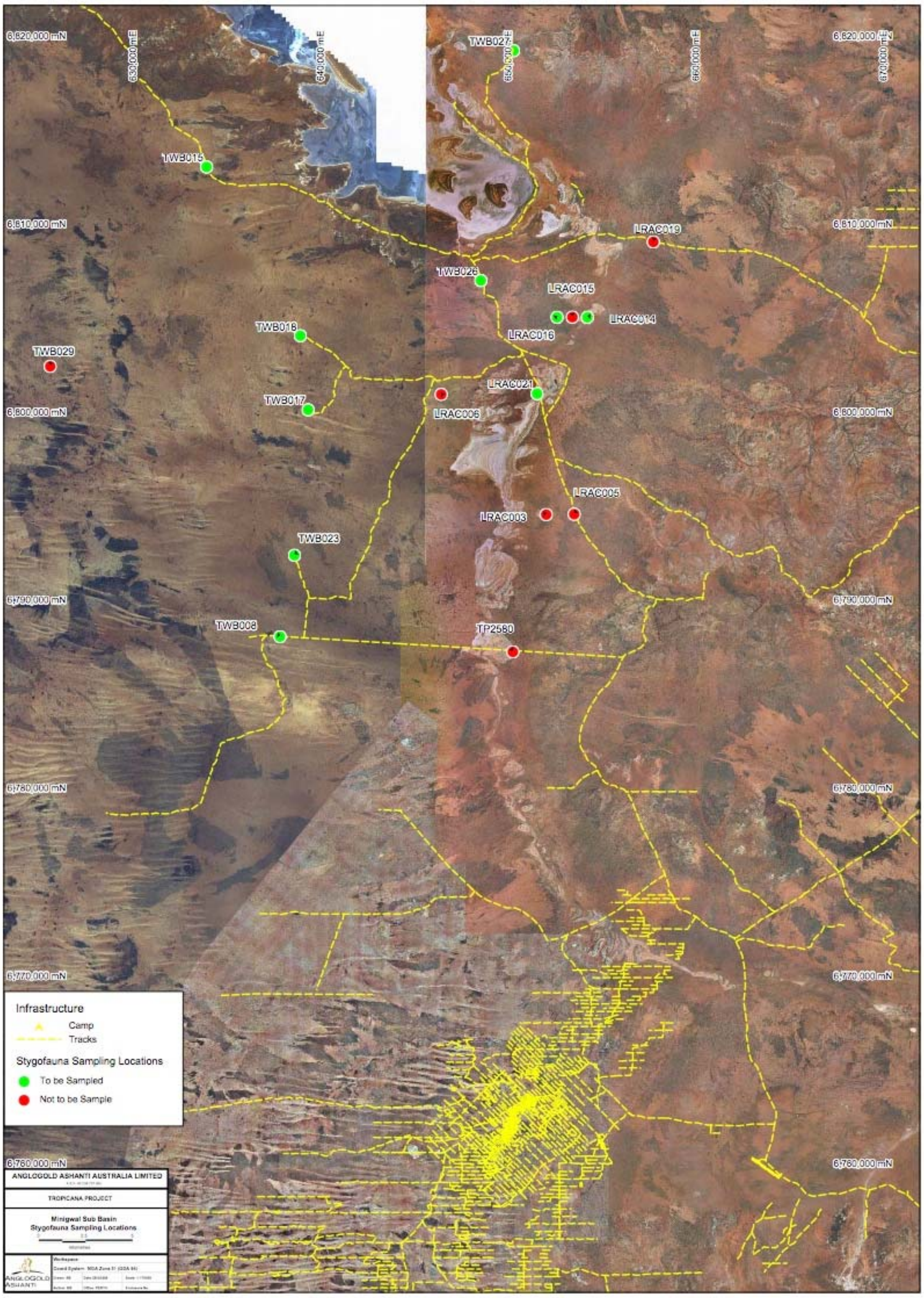

Figure 4 Stygofauna sampling sites May 2008.

Table 1 List of potential sampling bores and bores selected for sampling during May 2008.

Hole Name	Easting	Northing	Diameter	Bore Depth (m)	Drill Date	Slotting Interval	SWL	Salinity	pH	Air Lifting	May Sampling
TWB008	638895	6788175	200mm	276	08-Jan-08	50 - 80m (134mm)	61m	N/A	N/A	N/A	Y
TWB015	634879	6812465	250mm	268	28-Apr-08	78-90m(200mm), 108-120m (150mm), 126-132(150mm), 150-216m(150mm)	N/A YET	N/A YET	N/A	N/A	y
TWB017	639110	6800381	250mm	334	22-Mar-08	60 - 108m (200mm), 108-138m (150mm), 180 - 216m (150mm)	46m	41ppt	7.08	480KL/day	y
TWB018	638695	6804318	195mm	317	05-Dec-07	68 - 152m (200mm)	47.5m	66ppt	N/A	500KL/day	y
TWB023	638387	6792634	250mm	334	28-Jan-08	120 - 222m (134mm)	46m	N/A	N/A	270KL/day	y
TWB028 (previously known as TWB025)	625366	6802691		NOT DRILLED AT TIME OF SURVEY							n
TWB026	648320	6807260	300mm	245	25-Apr-08	54 - 156m (200mm)	44.5m	68ppt	6.61	270KL/day	y
TWB027	650061	6819480	250mm	149	10-May-08	24 - 78m (100mm)	N/A YET	N/A YET	N/A	N/A	y
TP2580	650023	6787499	195mm	150	04-Apr-08	42 - 144m (200mm)	N/A YET	190ppt	6.61	306KL/day	n
LRAC003	651806	6794806	50mm	32.45	20-May-08	Hole cased with slotted PVC to EOH					n
LRAC005	653293	6794827	50mm	22.54	20-May-08	Hole cased with slotted PVC to EOH					n
LRAC006	646202	6801203	50mm	31.84	20-May-08	Hole cased with slotted PVC to EOH					n
LRAC014	654000	6805302	50mm	19.27	21-May-08	Hole cased with slotted PVC to EOH					Y
LRAC015	653199	6805307	50mm	26.6	21-May-08	Hole cased with slotted PVC to EOH					n
LRAC016	652381	6805298	50mm	13	21-May-08	Hole cased with slotted PVC to EOH					y
LRAC019	657509	6809312	50mm	31.53	22-May-08	Hole cased with slotted PVC to EOH					n
LRAC021	651310	6801237	50mm	69	01-May-08	Hole cased with slotted PVC to EOH					y

Table 2 Bores sampled May 2008 including sample methods and other observations.)

Bore-hole ID	Easting MGA94	Northing MGA94	Date Sampled	Aquifer sampled	Sample methods	Sampled depths (m) or volume (L)	Notes
LRAC14	654005	6805304	30/5/08	Shallow	Bailer / net haul	1m / 17m	
LRAC16	652406	6805372	30/5/08	Shallow	Bailer / net haul	1m / 11m	
LRAC21	651309	6801241	30/5/08	Shallow	Bailer / net haul	1m / 69m	Grey sediments, contaminated with blue glue
TWB023PIEZO	638371	6792647	27/5/08	Shallow?	Bailer	1 m / na	Net catching, no stygofauna sample
TWB023S	638379	6792640	27/5/08	Deep	Bailer / net haul	120m / 276m	Black sediments, sulphurous odour
TWB008s	638893	6788169	27/5/08	Deep	Bailer / net haul	1m / 75m	Black sediments, strong sulphurous odour
TWB015S	634879	6812465	28/5/08	Deep	Bailer / net haul	1m / 114m	Grey sediments, developed 2 weeks earlier
TWB017S	639190	6800330	28/5/08	Deep	Bailer / net haul	1m / 239m	Grey sediments, sulphurous odour
TWB018	638695	6804318	30/5/08	Deep	Pump	25 500 L	Pump at 100m depth, pump rate 300 L/min
TWB026S	648337	6807253	29/5/08	Deep	Pump	480 L	Pump rate 60 L/min
TWB027S	650061	6819481	28/5/08	Deep	Bailer / net haul	1m / 149m	Development incomplete, samples invalid

4.3 SAMPLING METHODS

Of the ten bores successfully sampled for stygofauna, eight bores were sampled by net hauling and two bores, which had pump equipment installed, were sampled by pumping water through a 50 µm mesh net.

Groundwater quality (temperature, pH, salinity, conductivity, redox, dissolved oxygen) were measured in the field at the same time as stygofauna sampling. Prior to net haul sampling for stygofauna, water samples were collected by bailer at 0-1 m water depth except TWB018 and TWB026 where a pumped sample was collected. At sites which were pump sampled, measurements were taken of pumped water some time after pumping had commenced and when parameter readings were stable. Measurements were made with a TPS 90-FLMV water quality logger which had been calibrated prior to the field measurements. This instrument has the following specified resolutions and accuracies:

- Temperature: 0.1 0C , ± 0.2 0C;
- pH: 0.01 Ph, ± 0.01 pH;
- TDS (0 - 100.0 ppk): 0.1 ppk, ± 0.5 % of full scale of selected range at 25 0C;
- Conductivity (0 to 200.0 mS/cm): 0.1 mS/cm, ± 0.5 % of full scale of selected;
- range at 25 0C;
- Redox: 1 mV, ± 1 mV;
- Dissolved Oxygen (0 to 32.00 ppM): 0.01 ppM, ± 0.2 ppM; and
- Dissolved Oxygen (0 to 320.0 % saturation): % saturation, ± 0.3 % saturation.

In measuring dissolved oxygen (DO), the 90-FLMV instrument has solubility correction for temperature, and salinity correction via the conductivity/TDS sensor. Because of the highly saline waters occurring in a deep aquifer where solubility equilibrium for DO is not so readily available and hence the salinity effect gains importance, salinity corrected ppM units were used for DO readouts in this study as recommended by the instrument manufacturer.

Field work was conducted by Stefan Eberhard and Jacquie Brisbout (Subterranean Ecology), Travis Bates and Steve Catomore (AngloGold Ashanti Australia Ltd).

Collecting methods used were essentially the same as those used by the Department of Environment and Conservation (DEC) Pilbara Stygofauna Survey (Eberhard *et al.* 2004) and consistent with the EPA Guidance Statements No.'s 54 and 54A (EPA 2003, 2007). Bores were sampled for stygofauna using a plankton net of suitable diameter (45mm to 300 mm) to match the bore/well. The net (50 or 150 µm mesh), with a weighted vial attached, was lowered into the bore and then hauled slowly up through the water column. The net was dropped to the base of the bore then agitated up and down (±1 m) several times to disturb the bottom sediment. At most bores six hauls of the entire water column were conducted, comprising three hauls with a 150 µm net and three hauls with a 50 µm net. The 50 µm net was used to ensure capture of the smallest invertebrate fauna including harpacticoids, candonids, nematodes and rotifers. The 150 µm net was used to capture larger fauna, and reduce the collection of fine sediment and bow wave effects during hauling. Samples with large quantities of sediment were elutriated prior to preservation. Each net haul sample was transferred to a labelled polycarbonate container and preserved in 100% alcohol. To minimise the possibility of faunal contamination between sites, the nets were thoroughly rinsed in water and air-dried. Between different aquifers, the nets were treated with Decon 90 solution.

Sorting occurred in the laboratory under a 40x dissecting microscope. Each taxon was identified to the lowest taxonomic rank possible using published keys and descriptions, and the numbers of each taxon were recorded. Where necessary, identification of microfauna and dissected macrofauna used a compound microscope. Examples of new and undescribed (morpho-) species were retained in a voucher collection and used for checking identifications and designating new species.

5. RESULTS

5.1 STYGOFAUNA SAMPLING

Ten out of the 11 bores visited were sampled for stygofauna. One bore (TWB023PIEZO) could not be sampled for stygofauna due to the net catching in the bore casing; however a water sample was obtained from this bore.

Of the ten bores sampled for stygofauna, eight bores were sampled by net hauling and two bores which had pump equipment installed were sampled by passing the pumped water through a 50 µm mesh net (Table 2).

No stygofauna was detected in any of the ten bores sampled.

5.2 GROUNDWATER PHYSICO-CHEMISTRY

Groundwater quality was measured in all ten bores. Four bores were sampled with screened intervals in the superficial aquifer, and six bores were sampled in the deep aquifer (Table 3). Two of the deep aquifer water samples were obtained by pumping, while all other water samples were obtained by bailing from 0-1 m below water surface. The bailed water samples therefore reflect conditions at the water surface inside the bore casing, and may not accurately represent conditions in the surrounding aquifer due to evaporation, diffusion of gases from the atmosphere, and surface temperature fluctuations. Water quality measured in the water pumped from bores TWB018 and TWB026 more accurately reflected conditions in the deep aquifer surrounding these two bores at the time of sampling, although the measured DO values may be elevated above natural conditions due to diffusion of oxygen into the sample during pumping. Pump sampling was limited by the time available for pumping and to the equipment already installed in two of the bores. The volumes of water pumped at each bore was estimated at 0.76x (TWB018) and 6x (TWB026) the water volume inside the bore casing (Table 3). TWB027 water sample was excluded from analysis due to foreign water which had been recently pumped into the bore during bore development.

Temperature

Temperature of bailed water samples ranged from 18.5 to 27.1 °C, the wide range probably affected by variations in atmospheric temperature depending on the time of day when sampling occurred. The temperature of the two pumped water samples was very similar (25.2 and 25.5 °C), and most accurately represents groundwater temperature in the deep aquifer at the sampled depths.

Salinity (TDS and Conductivity)

Salinity was characterised by measuring conductivity and total dissolved solids (TDS). All measured ground waters were saline to hypersaline, with TDS ranging from 25.6 to 133.0 parts per thousand (ppK). Seawater has a TDS around 35 ppK which is equivalent to 35,000 mg L^{-1}. In both the shallow and deep aquifers, salinity was quite variable between bores, and ranged by a factor of x3 (shallow) to x5 (deep). Conductivity measured in the shallow aquifer ranged from 54.0 to 128.1 mS/cm, and in the deep aquifer 25.6 to 133 mS/cm. There was no significant difference between shallow and deep aquifers in the values measured for conductivity (t=0.595, df=8, P=0.57) and TDS (t=0.499, df=8, P=0.63).

pH

All measured groundwaters were acidic (pH range 4.84 to 6.90), except one bore (LRAC014) in the shallow aquifer which was near neutral to slightly alkaline (pH 7.09).

Redox

Redox potentials (Eh) measured in bores screened in the shallow aquifer were mostly positive (range 130 – 199 mV) except for bore TWB023PIEZO which was near zero (-4 mV). In contrast, Eh values in bores screened in the shallow aquifer were mostly negative (range -332 to -113 mV) except for bore TWB026 which was +72 mV. The sulphurous odour detected in the sediments from three bores (TWB8, TWB17, and TWB23) was consistent with their strongly negative Eh values (-332, -185, -148 mV) indicating sulphate reduction which commences at Eh < -150 mV. The black and grey coloured sediments in these three bores was also consistent with anaerobic conditions, as anoxic sediments are typically black due to iron sulphide (FeS_2) (Boulton and Brock 1999).

Dissolved Oxygen

In bores screened in the shallow aquifer, dissolved oxygen (DO) ranged from 1.27 to 4.29 parts per million (ppM) or 13.8 to 40.1 % saturation, while in bores screened in the deep aquifer DO ranged from 0.25 to 0.89 ppM, or 2.4 to 10.0 % saturation. There was a significant difference in DO (t=3.956 df=8,P=0.004)** between the bores screened in the shallow versus the deep aquifer.

Table 3 Groundwater physico-chemistry measured 28-30th May 2008. Water samples collected by bailer at 0-1 m water depth except TWB018 and TWB026 where a pumped sample was collected. TWB027 water sample excluded due to incomplete development.

Aquifer	Name	Temp (^{o}C)	pH	TDS (ppt)	Conductivity (mS)	Redox (mV)	D.O. sal (ppm)	D.O. (% Sat.)	Notes
Shallow	LRAC14	23.6	7.09	65.2	91.2	130	3.34	40.1	
Shallow	LRAC16	25.8	4.84	42.2	61.6	199	2.14	32.0	
Shallow	LRAC21	27.7	6.84	96.9	128.1	145	1.27	13.8	Grey sediments, contaminated with blue glue
Shallow?	TWB023PIEZO	18.5	6.37	33.9	54.0	-4	4.29	39.0	Net catching, no stygofauna sample
Deep	TWB023S	23.4	6.40	25.6	61.1	-185	0.69	9.2	Black sediments, sulphurous odour
Deep	TWB008s	26.0	6.90	63.1	88.6	-332	0.25	2.4	Black sediments, strong sulphurous odour
Deep	TWB015S	24.4	6.58	109.1	139.4	-5	0.89	7.9	Grey sediments, developed 2 weeks earlier
Deep	TWB017S	19.4	6.42	36.3	54.3	-148	0.65	10.0	Grey sediments, sulphurous odour
Deep	TWB018	25.2	6.62	62.1	87.6	-113	0.65	6.7	Pump sample
Deep	TWB026S	25.5	5.52	133.0	163.9	72	0.72	8.2	Pump sample

6. DISCUSSION AND EVALUATION

The pilot field survey detected no stygofauna in the sampled bores, consistent with the conclusion of the desktop review reported above, and the hydrogeology summary for environmental referrals (Pennington Scott 2007). The conclusion that stygofauna is unlikely to occur in the lower sandstone aquifer is probably correct, but this may not be entirely attributable to high salinity or very fine uniform grainsize, as suggested by Pennington Scott (2007). While the high salinities and fine grainsize in the lower sandstone aquifer of the Minigwal Trough are strong contributing indicators, the review of literature revealed the potential for stygofauna to occur in salinities > 40 ppK, and similarly, fine grain size should not preclude burrowing organisms in unconsolidated sediments. Relevant in this context, the field survey recorded salinities < 40 ppK in some bores, and across all surveyed sites salinities ranged from 25 to 133 ppK indicating considerable spatial heterogeneity and lateral gradients in groundwater salinity as indicated by Pennington Scott (2007; p. 15, Figure 2.6).

Some variability in salinity measured during this survey compared with earlier measurements at the same sites (cf. Pennington Scott 2007; p. 15, Figure 2.6) is evident, which may be due to temporal changes in salinity at sites, vertical salinity gradients in bores, or differences measured between the superficial and deep aquifers. The salinity values measured in the study area bores do not account for vertical salinity gradients which may possibly exist in the aquifer profile. Many aquifers in the Yilgarn and Pilbara regions of Western Australia exhibit strong salinity gradients and stratification (cf. Watts and Humphreys 2004, Humphreys 2008).

The high salinities measured in the lower sandstone aquifer of the Minigwal Trough probably preclude the occurrence of many stygofauna species which tend to be associated with fresh groundwaters, however the measured salinities and data from literature do not entirely preclude the possible occurrence of halotolerant species. Nonetheless, the measured salinities in the lower sandstone aquifer lie near the upper limits or exceed the tolerance limits recorded for stygofauna anywhere. The strongly negative redox values, acidic pH, sulphurous odours and black-grey sediments, indicate anoxic conditions in some of the sampled bores or bore sediments. Stygofauna are not known from anoxic habitats, and they are probably unsuited for life in extensively or permanently suboxic (DO < 0.3 to mg L^{-1}) groundwater, although they can be found in small or temporarily suboxic patches (Malard and Hervant 1998). The acidic conditions in the lower sandstone aquifer, while not precluding stygofauna, suggest that conditions may be less suitable than found in the circum-neutral to alkaline conditions of carbonate aquifers favoured by many species of stygofauna.

To evaluate, in an Australia-wide context, the suitability of the lower sandstone aquifer of the Minigwal Trough to support groundwater fauna, the geohydrology, aquifer typology and physico-chemical attributes were compared with data from other studies where stygofauna have been recorded (Table 4). Table 4 reveals major geohydrological, aquifer typological and some groundwater quality differences between the lower sandstone aquifer in the Minigwal Trough and other sampled aquifers which contain stygofauna. Firstly, the geohydrologic setting of the lower sandstone aquifer in the Minigwal Trough is confined and fully saturated with a sub artesian piezometric pressure head above the top of the aquifer. In contrast, all other aquifers were unconfined and unsaturated with a piezometric surface corresponding to the water table. To my knowledge, in Western Australia, stygofauna have only been recorded from unconfined and unsaturated aquifers, and no stygofauna have been recorded from confined aquifers. In porous unconfined and unsaturated aquifers, most stygofauna are found within a few metres of the watertable, where inputs of food and oxygen occur (Strayer 1994).

The lower sandstone aquifer is separated from the overlying superficial aquifers by the fine grained shale and mudstone units of the lower Lacustrine Member of the Paterson Formation which contains virtually no primary porosity and permeability, and acts as an extensive aquitard (a layer of hydraulic impedence) (Pennington Scott 2007). The hydraulic isolation of the lower sandstone aquifer from overlying superficial aquifers and surface waters implies that energy (food) and oxygen are likely to be limited, and progressively depleted along the groundwater flow path. The dissolved oxygen (DO) values measured from bores screened in the lower sandstone aquifer lay within the dysoxic range (DO 0.3 to 3.0 mg L^{-1}) which is sufficient to support subterranean Crustacea (cf. Malard and Hervant 1998), although the measured values may have been elevated by diffusion of atmospheric oxygen during sampling. The sediment organic carbon (SOC) or the dissolved organic carbon (DOC) content in the lower sandstone aquifer has not been tested.

The recharge zone and rate, through-flow rate and distance from recharge zone for the lower sandstone aquifer are not quantified, but they are likely to be extremely low due to the low rainfall rates over the Great Victoria Desert region, and recharge, when it does occur, would likely occur following rare extreme rainfall and flooding associated with tropical depressions (usually ex-cyclones) that pass over the region (Pennington Scott 2007).

The lower sandstone aquifer, with its very fine uniform grain size of 0.1mm (Pennington Scott 2007), falls into the typology of a compact aquifer as defined by Hahn (2007), whereas all other aquifers containing stygofauna were of the open type, including open porous, open fractured and open karstic types Table 4). Lack of living space, reduced hydraulic conductivity and hydrologic exchange with surface waters which thus limits replenishment of food and oxygen, contribute to the paucity or absence of groundwater fauna in compact aquifers Hahn (2007). The very fine uniform grain size of the lower sandstone aquifer means that the interstitial pore space available as living space for animals is very small, although burrowing worms may be able to exist if the sediments are sufficiently loosely unconsolidated.

Table 4. Range in physico-chemical attributes of groundwater in the lower sandstone aquifer compared with data from other Australian studies where stygofauna have been recorded. Aquifer typology follows Hahn (2007).

Source	Stygoregion	Geohydrology	Aquifer typology	no. sites	Temp	pH	SC mS/cm	TDS ppt	DO mg/L	Redox mV
Subterranean Ecology this study	Great Victoria Desert (Minigwal Trough)	sandstone, confined, saturated	compact	6	19.4 - 26.0	5.52 - 6.90	54.3 - 163.9	25.6 - 133	0.00025 - 0.00089	-332 to +72
Watts & Humphreys 2004	Western Shield: Yilgarn	calcrete, unconfined, unsaturated	open karstic	9	19.81 - 26.47	7.39 - 8.53	1.8 - 4.88	0.91 - 8.68	4.36 - 7.72	+71 to +448
Watts & Humphreys 2006	Western Shield: Yilgarn & NT Ngalia Basin	calcrete, unconfined, unsaturated	open karstic	21	16.4 - 29.5	7.0 - 8.3		1.0 - 18.3	0.7 - 8.0	-129 to +398
Humphreys 2006	Western Shield Yilgarn (Lake Way)	calcrete, unconfined, unsaturated	open karstic	1	23.7 - 24.3			30 - 69	0.2 - 2.5	
Subterranean Ecology 2007	Nullarbor (Roe Plains)	karst, unconfined, unsaturated	open karstic	1	16.3 - 17.2	6.83 - 7.38		30.4 - 32.1	2.3 - 6.9	
Seymour et al. 2007	Cape Range (Bundera)	karst, anchialine, unsaturated	open karstic	1	25.2 - 26.2			15.7 - 34.8	0.2 - 4.9	
Reeves et al. 2007	Western Shield: Pilbara	various unconfined, unsaturated	open porous, fractured, karstic	> 300	19 - 35.5	4.40 - 8.69	0.09 - 17.4	0.05 - 13.0		-421 to +837
Hancock and Boulton 2008	Eastern Australia	alluvium, unconfined, unsaturated	open porous	77	16.0 - 26.6	4.33 - 7.37	0.2 - 18.9		0.23 - 6.63	

Other factors, either geologic, hydrologic, biogeographic or historical, may explain the apparent absence of stygofauna in the Lake Rason area, which is located close to the mulga-eucalypt line at latitude 28^0 40' S. The limited development of calcretes south of the mulga-eucalypt line (ca. latitude 29^0 S) (Morgan 1983) appears to correspond with the southern distributional limit of the Yilgarn stygoregion, that is characterised by diverse stygofauna assemblages including dytiscid diving beetles and several ancient freshwater crustacean lineages (Humphreys 2008). Lake Rason is located at ca. 335 m above present sea level, an elevation where past sea level changes may explain the apparent absence of freshwater lineages. Those areas of Western Australia inundated by the sea in the Cretaceous and more recently, particularly the Eocene inundation which reached approximately 300 m above present sea level, are largely devoid of many ancient freshwater lineages (Bradbury 1999, Wilson and Johnson 1999), although there is some intrusion of fauna across the inundated/emergent 'divide' (Humphreys 2008). Marine waters deeply penetrated the palaeovalleys of the southern Yilgarn (Jones 1990, cited in Humphreys 2008), and would have eliminated any freshwater lineages. Conversely, these ancient high sea level stands are prospective sites for invasion of continental groundwaters by marine lineages (Humphreys 2008).

In conclusion, the lower sandstone aquifer of the Minigwal Trough is not considered to be highly prospective for stygofauna, and additional field sampling is not considered necessary for further validation of the assessment made herein. This assumes that pumping from the lower sandstone aquifer will cause no adverse impact to the water regime of overlying superficial aquifers in the Lake Rason area. If superficial aquifers are likely to be affected by pumping from the lower sandstone aquifer then further sampling of superficial aquifers may be warranted.

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