PILLIGA STYGOFAUNA REVIEW

Santos Energy NSW Coal Seam Gas Exploration and Extraction Activities

Prepared for
Santos Limited
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Executive Summary

Eco Logical Australia (ELA) was commissioned by Santos Limited (Santos) to conduct a review of stygofauna presence across the proposed Energy NSW Coal Seam Gas (CSG) Exploration and Appraisal Program (the program) near Narrabri in northern New South Wales. The purpose of the desktop review was to assess the likelihood of stygofauna occurring in the program area, and whether gas extraction activities are likely to pose a threat to stygofauna communities.

Stygofauna are known to occur in the Namoi River alluvial aquifer. This aquifer is not part of the project area but is a potential source of colonisation for stygofauna. Thin sedimentary aquifers associated with Bohena, Cowallah and Bibblewindi Creeks extend south into the Pilliga and are potentially suitable habitat for stygofauna. It is possible that communities may be present in permanently saturated parts of these aquifers, especially if they have an occasional hydrological connection to the larger Namoi alluvium.

Stygofauna may also be present in the shallower sandstone aquifers present on-site, such as the Pilliga Sandstone and Keelindi Beds (Orallo Formation). For these to be suitable for stygofauna, they would have to be fractured or weathered enough to allow stygofauna movement and a sufficient flux of water and organic matter. The suitability of these rock aquifers as stygofauna habitat diminishes with depth from the surface because:

- Stygofauna rely on organic matter derived from the surface. Without a good hydrological connection to the surface, there is not likely to be enough organic matter or oxygen present
- The space available for stygofauna movement is reduced significantly with increasing depth
- With depth, there is an overall decline in water quality.

Stygofauna may also be present, although with decreasing likelihood with depth below ground distance from alluvium, in weathered sections of sandstone with high secondary porosity, and in the deeper colluvial sediments.

CSG operations potentially create the following risks to stygofauna:

- impacting suitable habitat during drilling
- impacts to groundwater levels or water quality associated with trans-boundary flow between aquifers due to improper drilling and/or completion techniques
- Depressurisation of underlying aquifers that alters the physical structure of stygofauna habitat and subsequently changes groundwater levels or quality

The proposed exploration and appraisal program does not include exploration wells that require drilling through alluvial aquifers, significantly reducing the potential for impact to stygofauna.

Provided drilling, operation and closure activities are undertaken in accordance with the relevant guidelines and legislation, the proposed CSG Exploration and Appraisal Program activities are highly unlikely to pose a threat to any known or likely stygofauna habitat.

1 Introduction

1.1 BACKGROUND AND SCOPE

ELA was commissioned by Santos NSW (Eastern) Pty Ltd (Santos) to prepare a review on the presence of stygofauna and assess the potential for any impacts from proposed Coal Seam Gas (CSG) activities in the Pilliga region of New South Wales, south of Narrabri. This report reviews what is known of stygofauna communities in the Namoi alluvial aquifer, and assesses the suitability of aquifers in the Pilliga area as possible stygofauna habitat. An assessment is then made of potential impacts to stygofauna from CSG activities.

1.2 SUMMARY OF EXPLORATION & APPRAISAL PROGRAM

Santos is proposing to undertake the Energy NSW Coal Seam Gas (CSG) Exploration and Appraisal Program (E&A Program) in the Narrabri area within Petroleum Exploration Licence (PEL) 238 and Petroleum Assessment Lease (PAL) 2 (referred to as the program). The program commenced in 2013 and will take two to three years. The program consists of a series of CSG exploration and appraisal activities, including recommencing operation of several existing pilot wells, drilling and operating new pilot wells and constructing and operating water and gas management facilities to support the program.

The activities forming the E&A Program include:

- operation of the existing Bibblewindi Multi-Lateral Pilot (Bibblewindi 12, 13, 14, 15, 16, 17, 18H, 19H, 21H, 27, 28H and 29), the construction, drilling and operation of two additional pilot wells (Bibblewindi 31 and 32), and the operation of existing water flow lines from Bibblewindi Multi-Lateral Pilot to the Bibblewindi Water Transfer Facility
- operation of the existing Bibblewindi West Pilot (Bibblewindi 22, 23, 24, 25 and 26) and operation of existing water flow lines from the Bibblewindi West Pilot to the Bibblewindi Water Transfer Facility
- operation of the existing Dewhurst 13-18H Pilot (Dewhurst 13, 14, 15, 16H, 17H and 18H) and the construction, drilling and operation of additional lateral wells from well casing within Dewhurst 16H, 17H and 18H
- operation of the existing Tintsfield 2-7 Pilot (Tintsfield 2, 3, 4, 5, 6 and 7) and the construction and operation of a flare to support the pilot
- construction, drilling and operation of the Dewhurst 22-25 Pilot (Dewhurst 6, 22, 23, 24 and 25)
- construction, drilling and operation of the Dewhurst 26-31 Pilot (Dewhurst 26, 27, 28, 29, 30 and 31)
- construction of the Dewhurst Northern Water and Gas Flow Lines and operation the Dewhurst Northern Water Flow Line
- construction of the Dewhurst Southern Water and Gas Flow Lines and operation of the Dewhurst Southern Water Flow Line
- construction and operation of a produced water tank at the Bibblewindi Water Transfer Facility (Bibblewindi Water Transfer Tank) to facilitate the transfer of produced water from the pilot wells to the Leewood Produced Water Facility

- construction and operation of the Leewood Water Pipeline to transfer water produced by the operation of the above pilot wells from the Bibblewindi Water Transfer Facility to the Leewood Produced Water Facility
- construction and operation of the Leewood Produced Water Facility to store water produced by the operation of the above pilot wells
- transport of produced water from Leewood Produced Water Facility to an appropriately licensed facility
- construction and operation of ancillary and supporting infrastructure to facilitate the above activities and ongoing maintenance.

The proposed activities are necessary for the ongoing exploration, appraisal and evaluation of the CSG hydrocarbon potential in PEL 238 and PAL 2. The program will assist in gaining further knowledge of coal fines, gas composition and flow rates, the deliverability of the reservoir, and investigating well design, drilling and completion technologies. This information is essential to determine whether a commercial gas production project is viable and would be used in development planning for a potential commercial gas production project within the areas of PEL 238 and PAL 2.

CSG exploration, appraisal and production planning is an iterative process whereby the results of early stage activities are used to inform later stages of project development. As such, any future exploration, appraisal or production activities beyond the program will be proposed and assessed at a later stage.

1.3 OBJECTIVES OF THIS REVIEW

The principal objective of this desktop review was to determine whether suitable stygofauna habitat is likely to occur in the proposed Exploration and Appraisal Program area, and then determine whether the proposed CSG activities are likely to pose a threat to any stygofauna communities. The review does not consider the disposal or treatment of CSG water once it is extracted. The specific objectives of the stygofauna review were to:

- Determine whether there is any suitable or potentially suitable stygofauna habitat present
- Define the risks associated with the program on stygofauna communities
- Review the risks associated with the potential impacts associated with drilling and dewatering activities on overlying groundwater systems containing stygofauna

2 Overview of stygofauna habitat requirements

This section summarises the habitat requirements of stygofauna, and provides background to the stygofauna review.

2.1 FACTORS INFLUENCING BIOLOGICAL DISTRIBUTION IN AQUIFERS

Stygofauna are animals that live in groundwater. Recent estimates suggest there could be as many as 2680 species in the western half of the Australian continent, although only approximately 12 % of these have been described (Guzik et al 2011). It is difficult to estimate the diversity of eastern Australian aquifers, but they may be just as diverse as western aquifers.

As with all fauna, groundwater invertebrates require favourable conditions to inhabit an aquifer, but with this many species, there is a broad range of variability in ecological requirements. Not all aquifers are suitable for stygofauna, and those that are suitable may become unsuitable as a result of human activities or natural changes. Biological distribution in groundwater is influenced by historical, geological, hydrological, physico-chemical, and biological properties (Strayer 1994, Hancock et al 2005). There is still a lot being learned about stygofauna ecology, particularly in the eastern states where there have been relatively few surveys compared to Western Australia. Nevertheless, it is possible to briefly summarise what is already known about aquifer conditions likely to influence distribution.

2.1.1 Aquifer type

Stygofauna have been collected from many aquifer types, including fractured basalt, fractured sandstone aquifers, and pesolithic aquifers, but are most common in karstic and alluvial aquifers. Critical aquifer characteristics are the hydraulic conductivity, depth to water table, and porosity.

Generally, stygofauna occur more frequently in alluvial aquifers and karst than in other geological formations (Hancock et al 2005, Humphreys 2008). Alluvial aquifers occur beneath floodplains, which often provide the following conditions favourable to stygofauna:

- Water table is shallow, so there is recharge of infiltrating rainwater and organic matter, and the water table is accessible to floodplain tree roots
- There is often some degree of hydrological connectivity with surface rivers. This is particularly influential in regulated rivers where artificial flow releases from upstream dams may provide aquifer recharge of organic matter and oxygen in periods where natural surface flow would be absent
- Compared to deeper aquifers, water in alluvial aquifers is young and has a rapid flux.

2.1.2 Hydraulic conductivity

Hydraulic conductivity indicates how rapidly water flows through an aquifer. This is important to stygofauna communities because the flux of water through an aquifer often influences how rapidly organic matter and oxygen concentrations can be replenished. In aquifers, stygofauna diversity is generally higher in areas where hydraulic conductivity is also high provided all other habitat features are suitable (Datry *et al*. 2005).

2.1.3 Depth of water table

Depth to water table influences the amount of organic matter and oxygen that are available to aquifer foodwebs. With increasing depth below the land surface, the concentration of organic matter dissolved in infiltrating rainwater diminishes as it is absorbed in transit by soil bacteria and plant roots. Shallow water tables of less than 15 m have been found to favour high stygofaunal diversity in alluvial aquifers in eastern Australia (Hancock and Boulton 2008).

Another source of organic matter to aquifer invertebrates are phreatophytic trees (Jasinska et al. 1996). Root density is likely to be higher in shallower aquifers, and the resultant availability of organic matter provides food to stygofauna communities (Hancock and Boulton 2008).

2.1.4 Connectivity to recharge areas

A large proportion of the organic matter that fuels aquifer food webs has its origin at the surface and enters groundwater in particulate or dissolved forms. Therefore, sections of aquifers near recharge areas often have higher diversity and abundance than those that are further away, since the transfer of organic matter and oxygen is greater at these sites (Datry et al 2004).

2.1.5 A space for living

Stygofauna can only live in aquifers with enough space for them to move around in. Space is present in the solute cavities in karst, between pesolithic sediments in calcrete, and fractures in sandstone and basalt. For rock aquifers such as sandstone and basalt, it is the secondary porosity (that which is due to fracturing) rather than the primary porosity (in pores between sediment grains) that is important. In unconsolidated sedimentary aquifers such as alluvium, the size of pore space between particles often correlates to the size of the animals present, with larger species occurring in aquifers of coarser material (Strayer 1994).

Also important when considering the space available for living is the connectivity between pores, cavities, and fractures. These act as migration pathways to allow fauna to move around in the aquifer and are likely to be important in recolonising following disturbance.

2.1.6 Evolutionary history

Most stygofauna evolved from ancestors that once lived in surface freshwater or marine environments. As a result, it is possible that they have retained some of the traits and environmental tolerances of their ancestry. As an example, in coastal areas where ancestral stygofauna species may have come from a marine origin, contemporary taxa may be tolerant of high salinity (Humphreys 2008). Conversely, taxa with a freshwater ancestry may prefer lower salinities (Hancock and Boulton 2008).

2.1.7 Food availability

Stygofauna have adapted to the resource-starved conditions in aquifers and can tolerate low concentrations of organic matter (Hahn 2006, Strayer 1994). Food is available to stygofauna as particulate organic matter, groundwater bacteria, or as roots of phreatic trees. In its dissolved or fine particulate form, organic matter enters aquifers with recharging water. Dissolved organic matter is taken up by groundwater bacteria, which are then imbibed by smaller stygofauna. Most stygofauna are opportunistic omnivores.

2.1.8 Water regime

Local or regional climate and river-flow regimes can influence aquifer recharge, and so affect the organic matter flux in the aquifer. Periods of high, steady rainfall can increase hydrological connectivity between the land surface and the aquifer and can reduce depth to water table. Exchange between rivers, the hyporheic zone, and aquifers can be an important source of nutrients to stygofauna communities (Dole-Olivier et al 1994), so flow fluctuations that enhance hyporheic exchange can subsequently enrich stygofauna communities in deeper parts of the aquifer.

2.1.9 Salinity

Stygofauna in inland aquifers are generally restricted to fresh or partly brackish water. Hancock and Boulton (2008) suggest that most taxa collected from alluvial aquifers in NSW and Queensland prefer EC less than 5,000 μS/cm. In surveys of coastal areas and near salt lakes in Western Australia, stygofauna were collected from aquifers with salinities at or exceeding sea water (Watts and Humphreys 2004). *EPA Guidance Statement 54a* recommends 60,000 mg/L as the salinity above which stygofauna are unlikely (EPA 2007).

2.1.10 Dissolved oxygen

Stygofauna are able to tolerate very low concentrations of dissolved oxygen. Hahn (2006) observed a strong decrease in concentrations below 1.0 mg/L, but found some fauna in concentrations down to 0.5 mg/L. Some taxa are able to survive with virtually no oxygen for temporary periods for up to 6 months (Malard and Hervant 1999, Henry and Danielopol 1999). Aquifers can be heterogeneous environments, so may contain patches of water with sufficient oxygen concentration to be suitable for stygofauna. As dissolved oxygen is measured from water pumped from bores, it can be difficult to identify where these patches occur.

3 Suitability of aquifers in the Exploration and Appraisal Program area as habitat for stygofauna

3.1 STYGOFAUNA KNOWN FROM THE NAMOI RIVER ALLUVIUM AND ITS TRIBUTARIES

There has been a limited amount of sampling conducted for stygofauna in the Namoi River Alluvial aquifer and its tributaries. Nevertheless, previous surveys (summarised below) have established the Namoi as an aquifer with a relatively diverse stygofauna community. The presence of a large river with a well-developed alluvial aquifer make the Namoi comparable to other large rivers in Australia and overseas with diverse stygofauna communities (e.g. alluvial aquifers of the Hunter River, Pioneer River, Burnett River, Macquarie River – Hancock and Boulton 2008).

In 2013, Eco Logical Australia conducted a preliminary stygofauna survey for Santos at 2 bores at 'Leewood' and three bores along Bohena Creek. The Leewood bores had water tables of 21 and 26 m below ground level and sampled the lower section of saturated colluvial sediments, while the Bohena Creek bores had water only 2-3 m below ground level in the alluvial aquifer of the creek. None of the bores sampled had stygofauna.

Andersen (2008) reported at least 3 stygofauna taxa from the alluvial aquifer of Maules Creek, a tributary of the Namoi River. Stygofaunal syncarids, amphipods, and copepods have been collected from the Namoi alluvial aquifer by the NSW Office of Water, and the alluvial aquifer of the Peel River, a tributary of the Namoi, also has a rich stygofauna community with at least 20 species (Hancock and Boulton 2008).

In a study conducted between 2007 and 2008, Korbel (2012) collected at least 7 stygofauna taxa from 15 monitoring bores near Wee Waa, approximately 50 km west-northwest (and downstream) of Narrabri. The taxa collected included Ostracoda, Cyclopoida, Harpacticoida, Amphipoda, Oligochaeta, and three genera of Bathynellaceae.

A baseline survey of three bores at 'Rockdale' in the Pilliga collected three invertebrate taxa in 2012 (Stygoecologia 2013). Two families of worm (Oligochaeta) and one family of mite (Acarina) were collected from an unconsolidated sedimentary aquifer (Stygoecologia 2013). The aquifer sampled is variably referred to as the 'Pilliga Sands' or 'Pilliga Sandstone', so it is unclear whether the specimens come from the shallow colluvial/alluvial sediments or the underlying sandstone aquifers. There are some taxonomic groups known from groundwater samples in the region whose status as stygofauna needs to be interpreted with caution. While crustaceans such as bathynellids, amphipods, and isopods, are unambiguously groundwater obligates because of their aquatic ancestry and troglobitic morphological features, there are other taxa that are likely to be in groundwater accidentally. These are taxa that occur more commonly in the soil profile, but regularly fall into bores/wells and are collected during sampling and include worms and mites, and the larval stages of terrestrial insects. Soil fauna are not considered as significant as stygofauna because species are more widespread and have fewer incidences of short-range endemism.

3.2 SUITABILITY OF AQUIFERS FOR STYGOFAUNA

3.2.1 Shallow alluvial aquifers along creeks

There is a moderate chance that stygofauna occur in the alluvial aquifers of creeks in the Pilliga. The small alluvial aquifers associated with ephemeral creeks in the Pilliga consist of unconsolidated sands and fine gravels extending to depths of up to 40 m (Halcrow 2013). The main creeks in the study area are Bohena, Cowallah, Jacks, Bundock, and Bibblewindi Creeks, and all of these are dry for long periods of time. While parts of these aquifers potentially dry out after extended periods of no rainfall, there are likely to be sections that remain saturated because they hold a sufficient volume of water to resist evapotranspiration. These deeper saturated sediments may be suitable for stygofauna provided the water chemistry is suitable.

3.2.2 Colluvial sediments

Shallow colluvial sediments cover large sections of the northern part of the program area. These form temporary aquifers following periods of heavy rain, but the shallower sections often dry out (Halcrow 2013). It is unlikely that these aquifers have diverse stygofauna communities because they are shallow and probably dry out, however permanently saturated sections may have stygofauna if conditions are suitable. Given the homogenous nature of the colluvium, and the large area covered by colluvium between the program area and the Namoi River, there are unlikely to be any species endemic to the program area. These areas may provide suitable stygofauna habitat but communities are unlikely to have a high diversity. The colluvium is more likely to have stygofauna present in sections close to the Namoi River.

3.2.3 Sandstone aquifers underlying the program area

Pilliga Sandstone and the Keelindi Bed formations (inclusive of the Orallo Formation) underlie the superficial sediments in most of the program area. These have a low to moderate chance of providing suitable stygofauna habitat in the shallow sections where there is sufficient weathering and fracturing (i.e. a high secondary porosity). Habitat suitability increases with proximity to alluvial aquifers and recharge areas, and where there is a large amount of fracturing and interconnectedness between pore spaces. The chance of these sandstone strata being suitable for stygofauna diminishes with depth below ground surface.

4 Impact assessment

4.1 ASSESSMENT OF IMPACTS TO STYGOFAUNA FROM CSG DRILLING AND EXTRACTION

An assessment for the potential impacts to stygofauna from CSG drilling and extraction activities is included in **Table 1**.

Table 1: Risks and their likelihood of occurring as a result of CSG drilling in the Pilliga

Risk	Likelihood
Drilling through potential stygofauna habitat leads to changes in groundwater level or quality, impacting stygofauna	NEGLIGIBLE- While the colluvial and sandstone aquifers may have stygofauna, there are unlikely to be any species endemic to the impact area. Drilling will adhere to the *NSW Code of Practice for Coal Seam Gas Well Integrity*, which means that the risk of aquifer drainage will be negligible.
Drilling through potential stygofauna habitat creates preferential flow paths and cross-transfer of water between aquifers, impacting stygofauna.	NEGLIGIBLE- While the colluvial and sandstone aquifers may have stygofauna, drilling will adhere to the *NSW Code of Practice for Coal Seam Gas Well Integrity*. The use of proper drilling and grouting techniques will mean the risk of changes to water levels within aquifers is negligible.
Extraction of CSG from deep coal seams leads to drawdown or damage to stygofauna habitat	NEGLIGIBLE – Gas removal will occur at depths too great to have a significant impact on the physical structure of aquifers suitable for stygofauna. If stygofauna are present they are likely to occur in the upper 50 m. Depressurisation from extraction will occur much deeper than this and groundwater modelling to date suggest there will be no greater than 0.5m drawdown on alluvial (where present) and sandstone aquifers overlying the project area. The continuous monitoring of groundwater pressures in overlying shallow aquifers across the program area will assist in detecting any unexpected changes in ground, water level during operation of the exploration and appraisal program,
Pollution of shallow aquifers from chemicals used in drilling	NEGLIGIBLE –Drilling will adhere to the *NSW Code of Practice for Coal Seam Gas Well Integrity* and all precautions will be made to prevent contamination from chemicals used in drilling, as such the risk of drilling fluids having an impact on Stygofauna populations is considered negligible

5 Management and mitigation measures

The chance of any stygofauna species being endemic to the program area is low. The cumulative groundwater impact assessment for the Exploration and Appraisal Program shows that depressurisation of the target coal seam as a result of pilot activities indicates a negligible decline in water levels. Therefore the potential for CSG extraction to have a significant impact on stygofauna at the species level is considered negligible. Where risks may be present, **Table 2** provides a list of suggested mitigation measures, to further reduce these risks. An assessment of the potential for residual risks once the suggested mitigation has been implemented is also provided.

Table 2: Suggested mitigation measures.

Risk	Mitigation Measures	Residual risk to any endemic stygofauna populations
Disturbance to overlying aquifer systems during drilling process	Adopt the NSW Drilling Code of Practice. Ensure that aquifers are properly isolated during well drilling and construction, and that the integrity of the isolating barrier is maintained during operation.	NONE
Change to water chemistry in stygofauna habitat due to interconnectivity with aquifers	Adopt the *NSW Drilling Code of Practice.* Ensure that aquifers are properly isolated during well drilling and construction, and that the integrity of the isolating barrier is maintained during operation.	NONE
Structural damage, due to depressurisation, to stygofauna habitat or to the underlying strata of alluvial aquifers	The implementation of a shallow aquifer monitoring bore network across the program area to monitor for changes in water pressure. This will assist in identifying any unexpected changes in groundwater during the operation of the Exploration and Appraisal program.	NONE

6 Conclusions

The small alluvial aquifers flowing through the Pilliga, such as the Bohena Creek aquifer and its feeding streams and tributaries, are the most likely areas to have suitable stygofauna habitat, particularly in sections that remain permanently saturated and have a hydrological link to the main Namoi River aquifer. To date, there have been limited surveys of these aquifers because of restricted access and low bore numbers. Characteristics of the alluvial aquifers that make them suitable for stygofauna include:

- The water table is relatively shallow
- Electrical conductivity in the aquifers is likely to be low
- Sediments in the bed of the creek consist of coarse sand to medium gravel, which is likely to have sufficient porosity below the creek bed to have space for stygofauna.

Stygofauna may also be present, although with decreasing likelihood with depth below ground distance from alluvium, in weathered sections of sandstone with high secondary porosity, and in the deeper colluvial sediments.

The risks of impacting stygofauna through drilling activities includes changing groundwater quality or levels and introducing preferential flow pathways between aquifers. It is noted that the wells will be drilled and constructed in accordance with the methodology presented in the *NSW Code of Practice for Coal Seam Gas Well Integrity* and therefore the likelihood of this potential impact is considered to be negligible.

The cumulative groundwater impact assessment indicates that depressurisation of the target coal seam as a result of pilot activities will result in a negligible decline in water levels (less than 0.5 metres and within the natural range of annual fluctuations) in the Bohena Creek Alluvium and the Pilliga Sandstone groundwater. Therefore it is highly unlikely there will be any impacts to shallow aquifers that may contain stygofauna as a result of CSG extraction.

The monitoring of groundwater pressures in overlying shallow aquifers across the program area will assist in detecting any unexpected changes in ground, water level during operation of the exploration and appraisal program.

References

Anderson, M.S. 2008. *Investigation of surface water groundwater exchange in Maules Creek Catchment.* Presentation to the IAH , 9 Sept, 2009. WRL UNSW Sydney.

Datry, T., Malard, F. and Gibert, J. 2005. Response of invertebrate assemblages to increased groundwater recharge rates in a phreatic aquifer. *Journal of The North Benthological Society* 24(3), 461-477.

Dole-Olivier, M.-J., Marmonier, P., Creuzé des Châtelliers, M., Martin, D. 1994. Interstitial fauna associated with the alluvial floodplains of the Rhöne River (France). In: Gibert J, Danielopol DL, Stanford JA (eds) *Groundwater Ecology*. Academic Press, San Diego, 313–346

Guzik, M.T., Austin, A.D., Cooper, S.J.B., Harvey, M.S., Humphreys, W.F., Bradford, T., Eberhard, S.M., King, R.A., Leys, R., Muirhead, R.A., and Tomlinson, M. 2011. Is the Australian subterranean fauna uniquely diverse? *Invertebrate Systematics* 24, 407-418

Hahn, H.J. 2006. The GW-Fauna-Index: A first approach to a quantitative ecological assessment of groundwater habitats. *Limnologica* 36, 119-137.

Halcrow 2013. *Groundwater Impact Assessment, Narrabri Gas Project*. Report for Santos Ltd.

Hancock, P., Boulton, A., and Humphreys, W. 2005. Aquifers and hyporheic zones: toward an ecological understanding of groundwater. *Hydrogeology Journal* 13, 98-111.

Hancock, P.J. and Boulton, A.J. 2008. Stygofauna biodiversity and endemism in four alluvial aquifers in eastern Australia. *Invertebrate Systematics* 22, 117-126.

Henry, K.S. and Danielopol, D.L. 1999. Oxygen dependent habitat selection in surface and hyporheic environments by *Gammarus roesli* Gervais (Crustacea, Amphipoda): experimental evidence. *Hydrobiologia* 390, 51-60.

Humphreys, W. F. 2008. Rising from down under: developments in subterranean biodiversity in Australia from a groundwater fauna perspective. *Invertebrate Systematics* 22, 85–101.

Jasinska, E. J., Knott, B., and McComb, A. R. 1996. Root mats in ground water: a fauna-rich cave habitat. *Journal of the North American Benthological Society* 15, 508–519.

Korbel, K.L. 2012. Robust and sensitive indicators of groundwater health and biodiversity. PhD Thesis, UTS.

Malard, F. and Hervant, F. 1999. Oxygen supply and the adaptions of animals in groundwater. *Freshwater Biology* 41, 1-30.

Strayer, D.L. 1994. 'Limits to biological distributions in groundwater.' pp. 287-310 In: *Groundwater Ecology,* eds. J. Gibert, D.L. Danielopol, and J.A. Stanford. Academic Press.

Stygoecologia. 2013. Final Baseline Stygofauna Survey Report for Rockdale. January 2013.

Watts, C.H.S. and Humphreys, W.F. 2004. Twenty-six new Dytiscidae (Coleoptera) of the genera *Limnobodessus* Guignot and *Nirripirti* Watts and Humphreys, from underground waters in Australia. *Transactions of the Royal Society of South Australia* 130, 123-185.

Western Australia Environmental Protection Authority. 2003. Guidance for the Assessment of Environmental Factors: Consideration of Subterranean Fauna in Groundwater and Caves during Environmental Impact Assessment in Western Australia. Guidance Statement No. 54. Western Australian Government, Perth, Australia

Western Australia Environmental Protection Authority. 2007. Sampling methods and survey considerations for subterranean fauna in Western Australia. Guidance Statement No. 54. Western Australian Government, Perth, Australia.

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