[redacted]

From: Andrew Helps [redacted]
Sent: Friday, 14 May 2021 9:27 AM
To: Amy Selvaraj (DELWP)
Subject: Stygofauna
Attachments: StygofaunaEP158350.pdf

EXTERNAL SENDER: Links and attachments may be unsafe.

Good morning Amy,

Have any of the KALBAR consultants mentioned the Stygofauna in the Lindenow Groundwater ecosystem?

As you would be aware Stygofauna are protected by the EPBC Act and the RAMSAR Convention and a competent environmental ecologist would be producing a paper Vis a Vis the impact of the Lindenow mining operations and the destruction of the Stygofauna habitat at Lindenow.

There is an urgent need for KALBAR to retain a competent ecologist to write a report on the impact of flocculants on Stygofauna in the Lindenow sub surface aquifer.

I would suggest that KALBAR use the team at Macquarie University to do this.

Stygofauna have been the subject of a recent report (2015) funded by ACARP.

Kindest Regards

Andrew Helps
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UNEP Global Mercury Partnership
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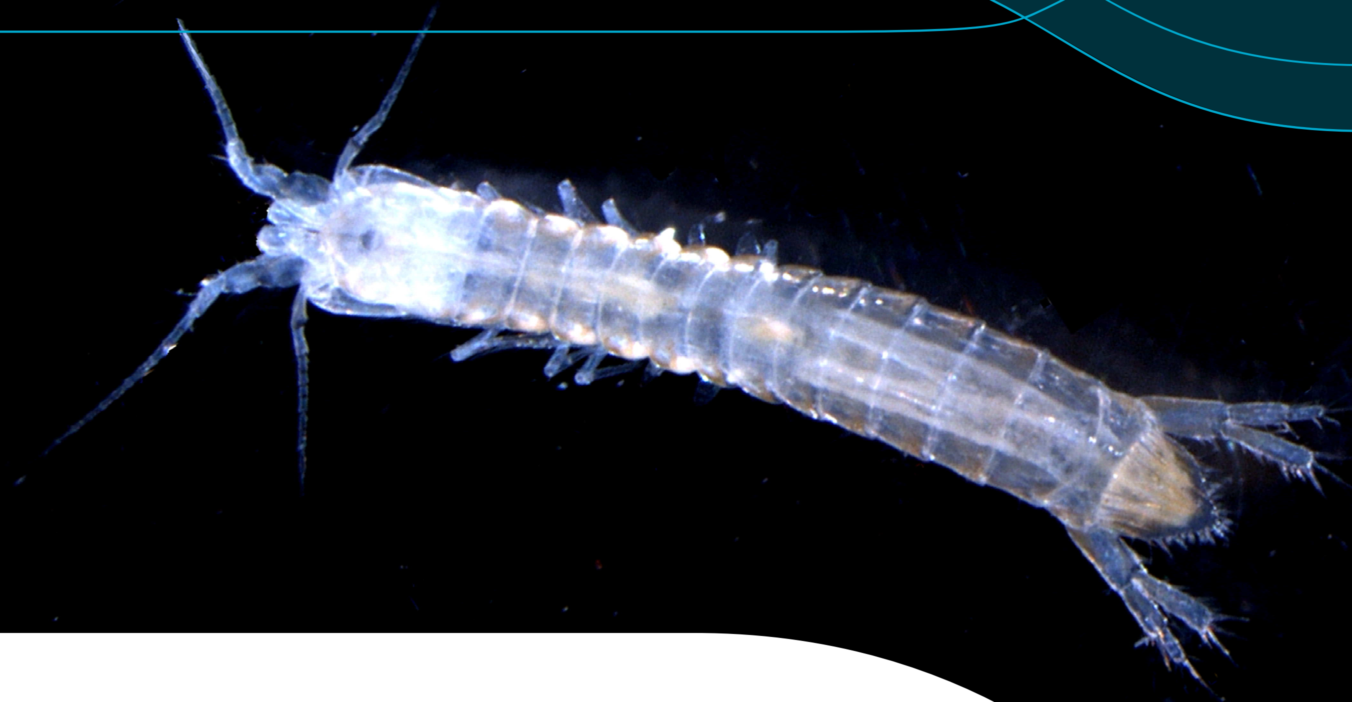
Stygofauna in Australian Groundwater Systems: Extent of knowledge

Grant C Hose, J Sreekanth, Olga Barron and Carmel Pollino

15 July 2015

Report to the Australian Coal Association Research Program (ACARP)



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Executive summary

The extraction of coal and gas from coal seams often intersects aquifers with the potential consequence of changing the volume, quality, pressure and movement of groundwater. While such hydrological changes are well understood and can be modelled relatively accurately, the effects of these changes on the ecosystem that exists within aquifers are not well known and, accordingly, are difficult to predict.

Once considered devoid of life, aquifers in Australia and worldwide are increasingly being recognised for their biodiversity. The invertebrates inhabiting aquifers, commonly referred to as stygofauna, are diverse and are morphologically and physiologically different from even closely related surface-dwelling species. It is the unique invertebrate fauna that may be at risk from the effects of mining activities.

The CSIRO was commissioned by ACARP to provide a review of the status of knowledge regarding stygofauna diversity, ecology and biogeography within Australia and to identify potential hazards and issues that may arise due to dewatering of aquifers and coal seams as part of mining operations and coal seam gas extraction. The objectives of this study were to

- undertake a desktop review of the state of knowledge and information available on the distribution and ecology of stygofauna in Australia and overseas (Sections 2 and 3);
- develop a preliminary identification of the potential hazards of dewatering on stygofauna (Section 4); and
- examine regional water balances associated with groundwater use in major production regions (Bowen, Surat and Hunter Regions) (Section 5);
- provide a survey of knowledge gaps, research priorities and recommendations for future research (Section 6).

Stygofauna are found in aquifers across Australia, predominantly in aquifers with large (mm or greater) pore spaces, especially alluvial, karstic and some fractured rock aquifers. The size of the pore spaces is a key determinant of the suitability of an aquifer as stygofauna habitat. Stygofauna have been recorded occasionally in coal seam aquifers, particularly where those aquifers are hydrologically connected to a shallow alluvial aquifer.

'Stygofauna' as a term encompasses a variety of different types of organisms that are found in groundwater, and includes animals that are obligate, groundwater-adapted organisms (stygobionts), and those that are not specifically groundwater-adapted but are able to survive the harsh conditions in aquifers (stygoxenes). Stygofauna are dominated by crustaceans, but also includes beetles, snails, mites and a variety of worms, and include groups that are only found in groundwaters.

The diversity of stygofauna in Australia is comparable to that of other regions of the world with more than 4000 groundwater-adapted stygobionts estimated to occur in Australia. The stygofauna of Australia reflect those types of organisms found elsewhere in the world, and indeed, the current global distribution of some species of stygofauna reflect past geological epochs, in which Australia was part of the supercontinents Pangaea and Gondwana.

Stygofauna are adapted to conditions of constant temperature, no sunlight, and low nutrient (particularly carbon) and oxygen content in the groundwater environment. The aquifer food web is based on inputs of carbon and nutrients that filter from the surface and so stygofauna are most abundant in shallow aquifers where food supply and oxygen are generally more plentiful. Their abundance decreases with depth and distance along groundwater flow paths as nutrient supplies also decline. Stygofauna are rarely found more than 100 m below ground level nor where dissolved oxygen concentrations in the groundwater are less than 0.3 mg O_2/L. Stygofauna are found across a range of water quality conditions (from fresh to saline), but most common in fresh and brackish water (electrical conductivity (EC) less than 5000 µS/cm).

The coal mining industry and the rapidly growing coal seam gas industry can, through their activity, reduce groundwater levels, and may pose a threat to stygofauna in the major production areas such as the Condamine-Balonne, Fitzroy (Surat and Bowen geological basins) and Hunter catchments. Aquifer depressurization and water level drawdown impacts are predicted for the confined and alluvial aquifers in the Surat and Bowen Basins, with the greatest drawdown predicted to occur in the Walloon Coal Measures and neighbouring confined aquifers. Water level drawdown is also plausible in the Condamine Alluvium. The long-term drawdown predicted for Walloon Coal Measures is 150 m. Both the Walloon coal measures and the Condamine alluvium support stygofauna. Similarly, changes to groundwater levels in the Hunter alluvium are likely to threaten the diverse stygofauna assemblages known from the region. A region-scale cumulative groundwater impact assessment for the Hunter catchment is currently being undertaken through the Bioregional Assessment programme of the Australian Government.

Stygofauna are particularly sensitive to groundwater environment disturbance because they are adapted to near steady-state environment conditions and have very narrow spatial distributions. Changes to such conditions, particularly groundwater levels, groundwater quality and or changes in aquifer pore media, are a threat to stygofauna. Under groundwater drawdown, stygofauna can be stranded and have limited ability to survive in unsaturated conditions for more than 48 h. However the effects of changes in aquifer pressure on stygofauna are unknown. Stygofauna are also sensitive to changes in water quality that deviate from the natural background conditions. Stygofauna also have limited capacity to recover from such disturbances because they have low mobility and low reproductive rates meaning recolonisation will be slow.

From our review of the literature and identified threats posed by mining and CSG activities, we have identified a number of knowledge-deficient issues. These are:

- the effects of water level drawdown and depressurisation on stygofauna;
- the role of coal seams as stygofauna habitat;
- water quality tolerance of stygofauna – toxicants and physico-chemical stressors;
- groundwater foodwebs as a pathway to impact stygofauna;
- taxonomy and distribution of stygofauna species; and
- links between hydrological modelling and impacts on stygofauna.

Research and new knowledge in these areas will inform and improve the risk assessments for groundwater ecosystems that are increasingly necessary as part of mining developments. Further, promoting and supporting research in these areas will promote the coal industry as a leader in the sustainable management of aquifers and biodiversity.

1 Introduction

Aquifers are a vital element of the natural, social and economic landscape of Australia. In the driest inhabited continent on Earth, aquifers are the primary source of water to many communities and industries, and support a diversity of ecosystems above and below ground that are partly or fully dependent on groundwater (Eamus et al., 2006). These include the iconic red gum forests of the Murray–Darling River system and the artesian mound springs across the central arid zone.

However, the ecosystem within the aquifer itself is perhaps the most diverse and unique. This ecosystem type is also one of the least studied globally. The movement of water through the subsurface sediments creates a mosaic of aquatic habitats which are inhabited by a unique suite of micro- and macro-organisms, many of which are not found in surface aquatic environments. Only in recent decades has the true biological diversity of aquifers begun to emerge, both in Australia and globally.

Groundwater abstraction, particularly associated with mine or coal seam gas operations (CSG) dewatering activity, can potentially threaten groundwater dependent ecosystems, including those which occur within aquifers. Yet these industries are an important contributor to the Australian economy. Coal extraction and related industries contribute 3.1% of the annual GDP (Davidson and DaSilva 2013). Coal provides around $40 billion in export income annually, supports 170,000 jobs and provides the raw materials for 75% of the nation's energy through coal-fired power stations (Davidson and DaSilva 2013, MCA indet.). Community expectations are that the extractive resource industry adheres to sustainability principles, which requires a robust evidence base and assessments of potential risks.

One of the emerging areas where knowledge is lacking is characterisation of aquifer ecosystems and associated risks to these ecosystems from extractive industry operations. Hence the purpose of this project is to provide advice to the Australian Coal Industry Research Program (ACARP) on the status of knowledge regarding stygofauna diversity, ecology and biogeography within Australia and to identify potential hazards and issues that may arise in the future due to dewatering of aquifers and coal seams as part of mining operations and coal seam gas extraction. Despite stygofauna being recognized as a focal issue for environmental consideration under the Queensland Environmental Impact Statement Guidelines and Western Australian Environmental Impact Assessment process, current ability to understand and subsequently predict impacts of dewatering/depressurization of aquifers on stygofauna communities is very limited.

This report provides an overview of the state of knowledge for stygofauna biology in Australia and internationally (Chapters 2 and 3) and explores the potential issues arising from the extraction of groundwater as part of extractive industry operations (Chapter 4 and 5). The report also offers a knowledge gaps analysis, identifies potential priority research areas, and makes recommendations for future research.

Mining and CSG are targeting the same resource but do so in different ways and in different locations. There are many similarities in the impacts associated with these activities, particularly with regard to the general effects on water resources and aquifers. However, the location (depth) and spatial scale of impacts of these operations differ considerably. In this report we have considered the following as general differences in the activities and impacts in these two operations. In short, coal mines sometimes cause greater groundwater drawdown impacts on a local scale than do CSG operations while CSG operations have a larger foot print of impact. More specifically:

1. Coal mining generally targets shallower resources than does CSG operations. The maximum depths of open cut coal mine are generally around 70 to 80 m and underground mining depths are typically in the range of 200 to 600 m (Commonwealth of Australia 2014a). Most CSG activities target coal seams at depths of 300 to 1000 m below ground surface (Commonwealth of Australia 2014b).

2. Coal mining (both underground & open cut) intersects shallow aquifers with open voids allowing groundwater ingress and affecting aquifers above and immediately below the coal seams. CSG operations that access specific coal seams via closed pipes should have little effect on shallow aquifers but may have effects on aquifers at depth.

3. Coal mining operations tend to have smaller footprints than CSG operations. For example, Moran and Vink (2010) report 105 CSG tenements in the Murray-Darling Basin with a total area of 18,903 km^2 (average 1890 km^2). The footprints of coal mines are typically < 50 km^2. CSG tenements by different proponents are often located close to each other, producing cumulative drawdown impacts which extend over hundreds of kilometres. Coal mines by different proponents are generally not close enough together to produce cumulative effects (although current proposals for the Galilee Basin may be an exception). The drawdown impacts by each individual mine are thus limited within tens of kilometres from the mine pit.

2 Diversity and distribution of stygofauna

Key points

- Stygofauna are found throughout Australian aquifers, including those within the major coal production regions.
- The diversity of stygofauna in Australia is comparable to that of other regions of the world.
- The diversity of stygofauna in Australia reflects the geological history of the continent.
- Stygofauna are dominated by crustaceans, but also includes beetles, snails, mites and a variety of worms.
- A number of stygofauna groups are found only in groundwater environments and not in surface waters.
- Stygofauna are adapted to groundwater environments and conditions of constant temperature, no sunlight and low nutrients and oxygen content.
- Stygofauna from different groups have evolved a variety of attributes such as lack of eyes and body pigments, hardened body parts, and long, thin (worm-like) body shapes as an adaption to the groundwater environment.
- Stygofauna have low metabolic rates and low reproductive rates relative to surface species, which makes them physiologically different from even related surface species, and enables them to survive in the low energy, low oxygen groundwater environment.

2.1 Background

Stygofauna live in groundwater systems or aquifers. Until recently, aquifers were considered to be devoid of life, but research in Australia and globally is highlighting a rich microbial and invertebrate fauna inhabiting subterranean environments. The limited supply of carbon reaching groundwater restricts the productivity of the ecosystem considerably, and constrains pristine aquifers to generally being low-energy environments, with, low biomass and low abundance of microbial and invertebrate fauna. Consequently, stygofauna live in environments with limited food supply.

With the exception of the occasional chemoautotrophic bacteria, groundwater ecosystems generally lack primary producers (such as plants or algae that cannot grow in the dark). It is thus the bacteria and fungi that use the carbon dissolved in the groundwater that are the basis of the simple food web (Humphreys 2006). Within the simple food web, microbes tend to occur as single cells or small colonies that are distributed sparsely and are mostly attached to sediments rather than being free-living (Gounot 1994; Griebler et al., 2002; Griebler and Lueders 2009; Anneser et al., 2010). Healthy, undisturbed aquifers tend to have very low microbial diversity and activity relative to surface waters (Griebler and Lueders 2009), due mainly to naturally low concentrations of nutrients, carbon and oxygen (Gounot 1994).

In aquifers where the sediments provide sufficient pore spaces, micro-fauna such as Turbellaria, Rotifera, Nematoda and Protozoa (Humphreys 2006) and larger meio-fauna may be present. The meio-fauna is generally dominated by crustaceans but may include insects, nematodes, molluscs, oligochaetes and mites. The crustaceans include Copepoda, Syncarida, Amphipoda, Isopoda and Ostracoda (Fig 1), as well as the Remipedia, Thermosbanacea and Speleaogriphacea which are groups found only in groundwater. Insects are relatively uncommon in groundwater (Humphreys 2006) although diverse coleopteran (beetle) assemblages have been recorded in some parts of Australia (Cooper et al., 2002; Leys et al., 2003, Watts et al., 2007). Stream insects can also migrate through alluvial aquifers and can be found in aquifers remote from surface waters (e.g. Stanford and Ward 1988).

Figure 1. Common crustacean stygofauna groups A. Cyclopoid copepod, B. Harpacticoid copepod, C: Amphipod, and D. Syncarid.

(Photo: A,C,D Kathryn Korbel, B Grant Hose)

Groundwater invertebrates are often highly-adapted to conditions in the groundwater environment. The dark, space-limited aquifer environment has shaped the evolution of groundwater fauna, with species from different biological groups having independently evolved common morphological traits such as lacking eyes, having hardened body parts, lacking body pigments, and having worm-like body shapes and enhanced non-ocular sensory appendages (Humphreys 2006). These traits are generally shared by *stygobionts* (stygobites), which are defined as being those organisms that are obligate groundwater inhabitants for some or all of their life (Sket 2008). While the conditions of the groundwater environment favour those organisms so adapted, surface dwelling taxa can also often survive. Surface-dwelling species that complete some or all of their life cycle in groundwater are referred to as *stygophiles*, whereas those found accidentally in groundwater are referred to as *stygoxenes* (Sket 2008). Typically, it is the stygobionts and stygophiles that are referred to collectively as stygofauna.

In terms of stygobionts, groundwater ecosystems are typified by having few species at any one locality and consequently low diversity and short food chains. However, the isolation of aquifers and limited dispersal abilities of groundwater organisms has created a fauna dominated by short-range endemic species (Harvey 2002), i.e., species with very narrow geographic ranges. This means that while there are few species within a locality, there are often many species across localities (Humphreys 2008). However, this trend is not evident in microbial assemblages which appear to be much more widely distributed (Griebler and Lueders 2009).

Vertebrates are rare in groundwater both in Australia and globally, and because of their large size, tend to be limited to karst aquifers where large water-filled voids exist. There are only two species of groundwater-adapted vertebrates known in Australia. These are the blind cave eel, *Ophisternon candidum* (Mees 1962) (Synbranchiformes: Synbranchidae) and the cave gudgeon, *Milyeringa veritas* Whitley 1945 (Perciformes: Eleotridae). These species co-occur in the karst of Cape Range (Humphreys 2006) and Barrow Island (Humphreys et al., 2013), north-western Australia. With vertebrates rare, invertebrates are often the highest trophic level in groundwater ecosystems.

2.2 Global diversity

In the year 2000, there were over 7800 known stygofaunal species known globally (Juberthie 2000). However, large research efforts in Australian (see Guzik et al., 2010) and European karst regions showed that this number is an underestimation. In 2010, Guzik et al., reported some 770 stygofauna taxa known in the west of Australia alone. From this they predicted that around 80% of the groundwater fauna are unknown, and the true richness for the region may be as high as 4140 stygobitic[1] species. Considering this, and also that the diversity of stygofauna in the eastern states is largely unexplored, it is likely that Australia is globally significant in terms of stygofauna diversity.

2.3 Australian diversity

The biota of Australian groundwater ecosystems reflects the history and evolution of the continent. Many groundwater fauna are descendants of species that were once common in surface environments but sought refuge in the stable groundwater environment as past climates changed. As a result, elements of the Australian groundwater fauna reflect the various stages in the evolution of the continent (Hose et al., 2015). Starting with the breakup of Pangaea and Gondwana, the drift north and the progressively drying climate, the early and continued emergence of large parts of the Australian continent from the sea, and the more recent evolution of the east coast landscapes, have all been key stages in the evolution of groundwater fauna and the causes of its high diversity of in Australia.

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[1] [1] Species restricted to subterranean groundwater habitats

It appears that glaciation that occurred across much of northern Europe has been a key event in the evolution and subsequent diversity of stygofauna in that region (Guzik et al., 2010). Unfavourable climates and glaciation during the Pleistocene forced surface fauna into subterranean environments, and the subsequent isolation has given rise to a diversity of subterranean species (Humphreys 1993). The Australian continent was little influenced directly by glaciation during the Pleistocene, although the aridity of the Australian continent during the Pleistocene may have also pressured invertebrates to seek subterranean environments. Australia was long considered depauperate of specialised groundwater fauna, but extensive surveys of caves and aquifers since the 1990s, particularly in Western Australia, Tasmania and New South Wales, have highlighted a great range of subterranean animals in both terrestrial and aquatic habitats and very high biodiversity at both landscape and continental scales (Humphreys 2008, 2012; Guzik et al., 2010).

2.3.1 The evolution of the Australian continent and its groundwater fauna

The arid interior

As the Australian continent was part of the supercontinent of Pangaea during the Palaeozoic (~550-250 My BP) a large area of Western Australia, referred to as the Western Shield, emerged from the sea. Unlike much of Australia that has seen various marine inundations over subsequent millennia, the Western shield has remained emergent since that time.

The Western Shield is a mineral-rich region of Western Australia that includes the Yilgarn and Pilbara regions. Surveys of the Pilbara region associated with mineral resource development projects highlighted a diverse subterranean aquatic fauna inhabiting non-karst and non-alluvial aquifers, such as fractured rocks. The 220,000 km^2 Pilbara region is now recognised as a highly diverse region for stygofauna. This is particularly the case for the crustacean order Ostracoda, 25% of the known species of the family Candonidae coming from this region (Reeves et al., 2007; Humphreys 2012; Karanovic 2012). The great known diversity in this ostracod group, and indeed others, may reflect the great intensity of research and survey work in this region (see Halse et al., 2014).

Although the Pilbara and Yilgarn subterranean fauna regions are contiguous, they have very little overlap of taxa, even at the genus level (Hose et al., 2015). The reason for this disjunction in the composition of the fauna is unclear and is difficult to reconcile given that the entire Western Shield has been emergent and shared a similar geological history at least since the Palaeozoic.

Within the Yilgarn region, a diverse fauna comprising diving beetles (Dytiscidae) and crustaceans, such as Amphipoda, Isopoda, Bathynellacea and Copepoda, was discovered in small, isolated, karstic calcrete aquifers (Guzik et al., 2008, 2009, Bradford et al., 2010, Karanovic et al. 2013). Calcretes are shallow (10-20 m thick) carbonate deposits formed by near-surface evaporation of carbonate-rich groundwater. Hundreds of isolated calcrete bodies exist in the region, occurring upstream of salt lakes (playas) along ancient palaeovalley systems. Groundwater and episodic surface flows have resulted in dissolution of the carbonates and the formation of karstic groundwater habitat (Humphreys et al., 2009).

The identification of much of the stygofauna collected in the Yilgarn is ongoing, but studies to date, including molecular phylogenetic and phylogeographic analyses of the beetles, amphipods and isopods, have shown that the many species found are often restricted in their distribution to single calcrete bodies, leading to the description of the calcrete system as a subterranean archipelago (Cooper et al., 2002, 2007, 2008; Leys et al., 2003, Watts and Humphreys 2009). Molecular clock analyses suggest that these stygobitic lineages evolved 5-8 My BP, during the period of increasing aridity on the Australian continent, and, consequently, widespread disappearance of rainforest and permanent sources of water from the interior of Australia. This climatic and habitat change is considered as the primary driver for the colonisation of the subterranean realm, as aquifers became a refugium from the drying surface environments.

Many of the groups of aquatic organisms found in the Yilgarn calcretes are also found in other Australian arid zone freshwater “refugia”. These include the wetlands associated with mound springs of the Great Artesian Basin in South Australia, which contain isopod and amphipod crustaceans that are related to species found in the calcretes (Murphy et al., 2009). Calcretes of the Ngalia basin, northwest of Alice Springs in the Northern Territory, also harbour many of the taxa found in the Western Australian calcretes, including dytiscid beetle species (e.g. Balke et al., 2004) and a diverse *Haloniscus* isopod fauna (S. Taiti, unpub. data).

Research of alluvial aquifers of the Flinders Ranges and Eyre Peninsula in the South Australian arid zone has also unearthed a diverse stygofauna including a dytiscid beetle (Leys et al., 2010) and parabathynellids (Abrams et al., 2013). Amphipoda (family Chiltoniidae) are also particularly diverse in these groundwater systems, and also suggest connections between once connected, now isolated freshwater systems (R. King and R. Leijs Pers. Comm.).

Tethyan Connections

The Tethys Sea formed during the Jurassic period as the supercontinent Pangaea began to break up and Laurasia moved northward and separated from Gondwana. The Pilbara-Ningaloo coast in Western Australia was once the coastline of the Tethys Sea. The fauna in the anchialine habitats of the Pilbara-Ningaloo coast have a close affinity to those in other anchialine habitats in the Canary Islands and northern Caribbean which were also on the Tethys coastline.

Anchialine systems are groundwaters that are affected by marine tides, usually with little or no surface exposure (Iliffe 2000). In Australia, anchialine systems occur in small karst areas along the coast at Ningaloo Reef, Barrow Island and the adjacent Pilbara coast in north-western Australia. The groundwater in these areas is highly stratified, with brackish water overlying sea water. The groundwater level fluctuates with tides and the environment is in total darkness (Jaume and Boxshall 2009).

The deeper marine waters of the Australian anchialine systems includes many unique taxa. The Bundera Sink hole in Cape Range is the only known location of the Cape Range remipede (*Kumonga exleyi*) (Yager and Humphreys 1996). Remipedes are a unique class of Crustacea first described from the Caribbean in 1981 and known only from anchialine environments. The Bundera sinkhole is also the type location of the unique copepods from the Misophrioida and families Epacteriscidae and Ridgewayiidae

Halosbaena tulki is a shrimp-like crustacean in the Order Thermosbaenacea that is one of the many unique stygobionts in the region that share the ‘Tethyan’ distribution. Thermosbanaceans are characterised by the females brooding their eggs in a pouch on their back instead of beneath the body. *H. tulki* was recorded from the Pilbara region (Eberhard et al., 2009) and is the only member of the order known from the Southern Hemisphere. The Pilbara region also supports a number of unique copepod taxa such as *Stygocyclopia australis* and *Speleophria bunderae* that share the Tethyan affinities (Juame et al., 2001). The subterranean atyid shrimps of the genus *Stygiocaris* that are found in the region are only distantly related to the other atyid shrimps in Australia, but are much more closely related to species that occur in anchialine habitats in Mexico and the Carribean (Page et al., 2008; von Rintelen et al., 2012, Botello et al., 2013).

Gondwanan associations

A number of stygobiont crustacean taxa have current distributions that reflect a common ancestry and distribution across the supercontinent Gondwana. These include the phreatoicid isopods, bathynellid syncarids and Spelaeogriphacea.

The crustacean order Spelaeogriphacea comprises four species of stygobionts. These are currently known from caves in Cape Town, South Africa, in Mato Grosso do Sul, western Brazil, and two species in the Fortescue Valley, Pilbara. All living spelaeogriphaceans occur in geological formations that are Cretaceous (145-65 Ma BP) or older. The colonization of Gondwanan freshwater by the Spelaeogriphacea is likely to have occurred after the retreat of the Gondwanan ice sheet (after 320 Ma BP) and prior to the breakup of Gondwana (142-127 Ma BP) (Jaume 2008).

Phreatoicidean isopods have a Gondwanan distribution and occur widely across southern Australia, in tropical Arnhem Land and the Kimberley. Their distribution is strongly associated with the areas of the continent that were not submerged by Cretaceous seas (Hose et al., 2015). The blind hypogean species of the isopod family Hypsimetopidae known from mainland Australia and Tasmania are closely related to the hypogean genera found in India, which separated from the western shore of Australia around 130 My BP (Wilson 2008).

Phreatoicids of the genus *Crenoicus*, are found in wetlands and swamps along the great dividing range of eastern Australia (Wilson and Ho 1996), often in areas that coincide with coal mining activities. These species are more closely related with those from South Africa than the Hypsimetopidae in western Australia and India (Wilson 2008), and suggest dispersal across Gondwana prior to the separation of Africa around 154 My BP. Further diversification of the east Australian species occurred prior to the separation of New Zealand from Australia 80 My BP (Wilson 2008).

Bathynellid syncarids are a common component of Australian groundwater biota. They are found only in groundwater and, as a group, have a global distribution suggestive of Pangean origins. However, most taxa have very limited distributions and many belong to monotypic genera so it is not surprising that their phylogeography shows strong continental affinities (Hose et al., 2015). Some genera such as *Kimberleybathynella, Brevisomabathynella, Billibathynellla* and *Octobathynella* are endemic to Australia (Schminke 2011), while some taxa, such as *Atopobathynella* are known from Chile, India and southeastern Australia, indicating affinities with eastern Gondwana. Other Australian genera have a broader distribution, with *Hexabathynella* being found in eastern Australia, New Zealand, southern Europe, Madagascar, and South America.

Eastern Australia

In contrast to the west of the continent, eastern Australia comprises relatively newer landscapes, having had marine inundations through the Cretaceous period, and overall a much more dynamic geological history than parts of the west (BRM Palaeogeographic Group 1990). Accordingly, Guzik et al., (2010) have predicted lower stygobiont diversity in the newer east compared to the older west.

The groundwater fauna in eastern Australia is structurally similar to that in the west. The same higher taxa are present, although as expected given the geographical separation, taxa collected from eastern Australia often form separate lineages within continental phylogenies (e.g. Leys and Watts 2008; Abrams et al., 2013). Further, there appear to be differences in the relative abundances of different taxa. While amphipods and isopods are widespread across the west (e.g. Eberhard et al., 2009, Schmidt et al., 2007), they are encountered less frequently in the east (e.g. Hancock and Boulton 2008, 2009), which may reflect the history of marine inundations in the east, which elsewhere are considered to be responsible for the absence of some of the more ancient crustacean lineages of Amphipods and Isopods in the groundwater fauna (e.g. Bradbury 1999; Wilson and Johnson 1999). Instead, crustacean faunas are dominated by syncarids (Bathynellidae, Parabathynellidae and Psammaspididae) and harpacticoid and cyclopoid Copepoda (e.g. Cook et al., 2012, Schulz et al., 2013). Anaspidacea are only found in eastern Australia (Hobbs 2000), with several families found across the region (Serov 2002). Hancock and Boulton (2008) reported stygobitic elmid and dytiscid beetles from the Hunter and Peel River valleys, NSW, (Watts et al., 2007, 2008). Recent surveys associated with mining developments in the Hunter catchment have extended the know ranges of these genera (Eco Logical Australia 2013). There are no other records of stygobitic beetles inhabiting alluvium in Australia. Although diverse dytiscid water beetle assemblages are present in the calcretes of the Yilgarn (Leys et al., 2003, Watts et al., 2008), such beetles are rare in the east, and this rarity may reflect the lack of ancient karstic habitat.

Karstic and limestone habitats are traditionally the hotspots of groundwater diversity, and these habitats are somewhat rarer in eastern Australia than in the western shield and throughout Europe. However, much of the karst of New South Wales is impounded and as such is geologically isolated, and in some cases is of Devonian origin (Osborne et al., 2006) so there is great potential for these environments to support novel taxa through such long isolation. To date 82 stygobitic species have been recorded in the east coast karsts (summarised in Thurgate et al., 2001). Caves of Tasmania and New South Wales have the most diverse groundwater faunas (Thurgate et al., 2001), although this richness may also reflect the greater sampling effort in those states. The richness of most cave and karst regions in eastern Australia is low by world standards (Thurgate et al., 2001) but this may be a consequence of the small, impounded nature of these features.

The deep alluvial deposits of the eastern Australia have yielded a rich fauna. Hancock and Boulton (2008) examined parts of the Peel and Hunter Valley alluviums in NSW, and the Burnett and Pioneer Valley alluviums in Queensland. The study recorded 87 taxa, with seven to 33 taxa per aquifer. Little (2014) surveyed the stygofauna in the alluvium of the Condamine-Balonne, Dawson and Lockyer Valley catchments in southern Queensland and reported between six and eight stygobiont taxa were heterogeneously distributed in each catchment. Further north, Cook et al., (2012) report stygofauna in a small number of bores sampled in the alluvium of Burdekin River catchment in northern Queensland. They reported four distinct lineages within the Bathynellidae and a single lineage within the Parabathynellidae, as well as single taxa of Cyclopoida and Harpacticoida. Schulz et al., (2013) recorded Cyclopoida, Harpacticoida and Bathynellacea among bores in alluvial and fractured rock systems in the border rivers regions of NSW and Queensland, and it seems likely, based on the work of Cook et al., (2012), that this represents a number of distinct Bathynellacean taxa. Indeed, Asmyhr et al., (2014a) showed that genetic diversity among Bathynellacea in the Macquarie R catchment (NSW) can occur over very small spatial scales with intra-specific genetic structuring occurring over distances of less than 50 m.

Tomlinson (2008) expanded on Hancock and Boulton's (2008) survey of the Peel alluvium and reported 54 taxa of which 33 were obligate groundwater inhabitants. More recent surveys of the alluvial aquifers associated with inland rivers in NSW has yielded similar richness, with 20 taxa in the Gwydir (Korbel and Hose 2011; Korbel et al., 2013a), 15 in the Namoi (Korbel et al., 2013b), and ten taxa in a small area of the Macquarie River alluvium (Hancock and Boulton 2009). Asmyhr and Cooper (2012) report a range of taxa from a variety of aquifers across NSW, including the Macquarie River catchment. Similar higher taxa were recorded across all studies, but it was often the Acarina that were the most (morpho-) species-rich group. Although detailed species–level taxonomy has not been performed on many of the specimens collected in these studies, it is likely that each taxon represents a new species, with perhaps the exception of potential hydrologic connectivity and hence species overlap between the Peel and Namoi Rivers.

Upland swamps are distinctive features of low-relief plateau areas in eastern Australia (Young 1986; Dodson et al., 1994). They form in shallow depressions in the landscape and, fed by rainfall and regional groundwater, provide a unique, shallow groundwater ecosystem. Sampling of swamps in the Southern Highlands and Blue Mountains of NSW has identified assemblages variably dominated by harpacticoid and cyclopoid copepods, nematodes and ostracods, but also containing syncarids, mites and amphipods (Hose 2008; 2009; unpublished data). While not all species are likely to be stygobitic, these systems are potentially a diverse source of fauna. Initial studies show particularly fine-scale endemism, with swamps in the Southern Highlands separated by only several hundred metres containing genetically distinct harpacticoid copepod populations (Hose 2009). Similar patterns of endemism are likely in Blue Mountains swamps as seen in other taxa (e.g. Dubey and Shine 2010).

The fractured rock systems of eastern Australia appear somewhat less diverse than those of the west (e.g. Eberhard et al., 2005), but nevertheless, stygofauna have been recorded in the fractured Triassic Hawkesbury sandstone to the north (11 stygobitic taxa, Hose and Lategan 2012, Asmyhr and Cooper 2012) and south of Sydney (three stygobitic taxa, Hose 2008, 2009), with the likelihood that each area contains locally endemic taxa. The assemblages are dominated by copepods (Harpacticoida and Cyclopoida), but syncarids are also common in some areas. The fauna appears spatially limited within the aquifers, and constrained to shallow water bearing zones (Hose pers. obs.). There is a clear need to extend these surveys to better describe and contextualise the diversity of this region.

The coastal sand aquifers are a common feature of the east coast of Australia. The pore space provided by sand aquifers is generally too small to permit stygofauna, although sampling in the coastal sands of the Tomago-Tomaree, Woy Woy and Umina sand beds on the NSW central coast has revealed three stygobitic taxa (Hose unpub. data). Sampling of the heavily contaminated

Botany aquifer in Sydney did not reveal meiofauna, but diverse prokaryote and eukaryotes assemblages were present, with changes in assemblage structure evident and associated with the contamination gradient (Stephenson et al., 2013).

Across the eastern half of the Australian arid zone, springs arising from the Great Artesian Basin, have created a series of unique wetlands that are recognised and listed nationally for their diversity values. The aquatic invertebrate fauna of the springs has a high degree of endemism (see review Commonwealth of Australia 2014c). Thirty-eight species of aquatic snails are endemic to the GAB, with many restricted to a single group of springs (Ponder 1995; Worthington Wilmer et al., 2008). The springs also support other unique and narrowly distributed aquatic invertebrate including isopods (Guzik et al., 2012), amphipods (Murphy et al., 2009, 2013), and ostracods (DeDeckker 1979).

2.4 Stygofauna of major coal regions

Stygofauna surveys are an increasingly common component of environmental impact statements for mining operations. Accordingly, there is a growing number of reports available publicly that record the stygofauna diversity of coal seams and associated aquifers across most of the major coal mining regions of Australia. The following descriptions of stygofauna in major coal basins is solely based on reports that are available publicly on mining company and government agency websites. A map of the major coal production regions is shown in Figure 2.

2.4.1 Perth Basin, WA

While iron ore production has led to a now detailed understanding of the stygofauna diversity of the Pilbara, a survey of the Enneaba region, north of Perth as part of the Central West Coal Project discovered an undescribed Bathynellid (Syncarida: Bathynellaceae; Bathynellidae) (WA EPA 2011). This taxon does not appear to be limited to the coal mining zone.

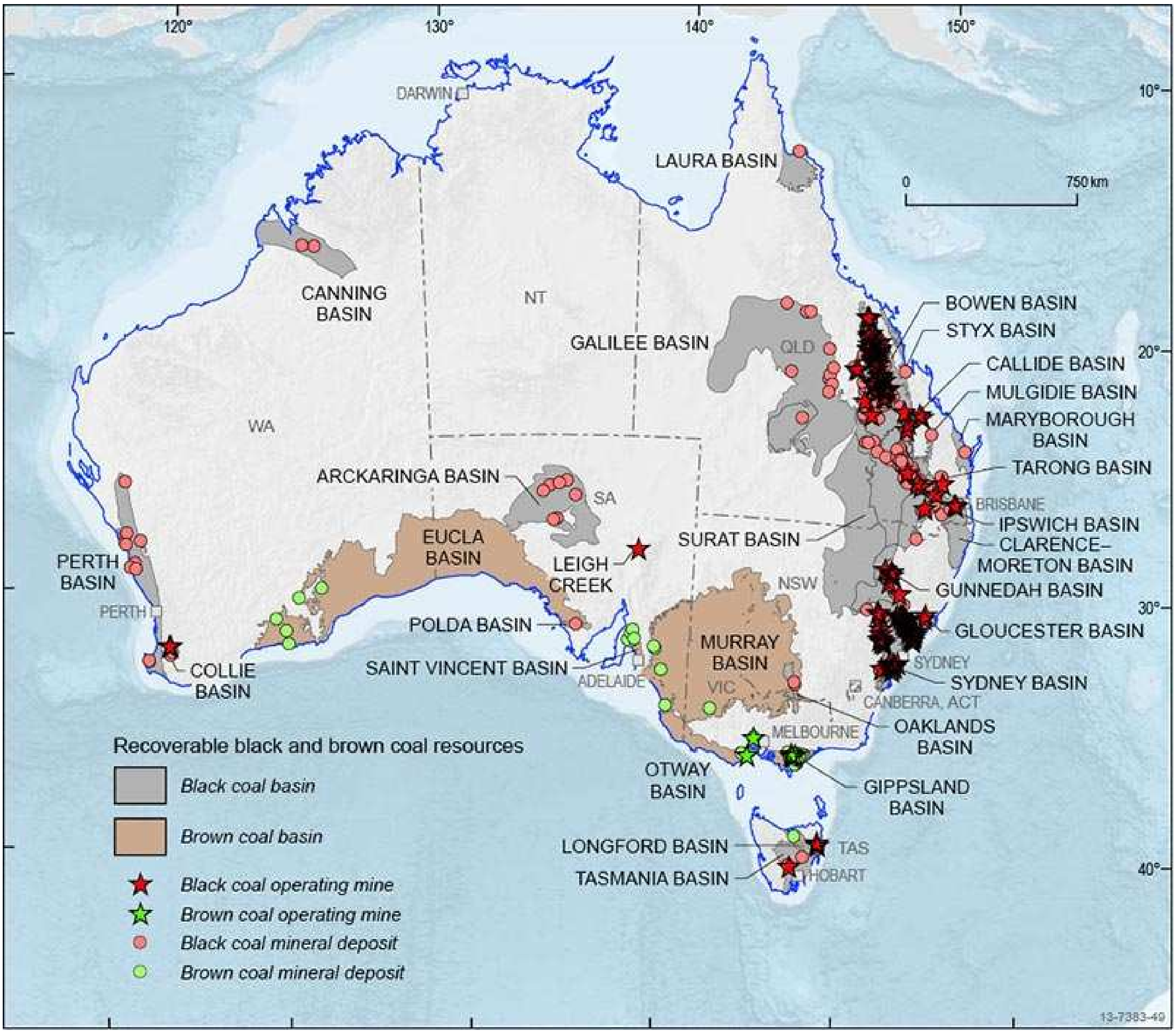

Figure 2. Major coal production regions of Australia and operating black and brown coal mines as at December 2012. Source: Geoscience Australia. www.ga.gov.au/data-pubs/data-and-publications-search/publications/australian-minerals-resource-assessment/coal

2.4.2 Sydney Basin, NSW

Available information on the stygofauna of the coal fields In the Sydney Basin is scarce. Surveys of stygofauna in the Illawarra region have been completed, but were not publicly available for inclusion in this report. However, surveys of fauna in swamps on the sandstone plateaux overlying parts of the southern coalfields have reported diverse stygobiont assemblages including syncarids, ostracods and harpacticoid and cyclopoid copepods (Bailey 2008, Hose 2008, 2009). Surveys of the regional fractured rock aquifers have unearthed a similar diversity of stygobionts (Hose 2008; 2009).

Expansion of Centennial Coal operations in the western coal fields near Lithgow has required surveys of stygofauna in the regional fractured sandstone aquifers, as well as in temperate highland peat swamps on sandstone occurring above the mines. Surveys of the swamps have yielded stygobiontic cyclopoid copepods, harpacticoid copepods and bathynellid syncarids, as well as Rotifera, Tardigrada and phreatoicid isopods (Cardno 2014a,b). Copepods, mites and rotifers were recorded in the local unconfined sandstone aquifer (Cardno 2014a,b). Surveys of stygofauna have been undertaken associated with the Berrima Colliery operations but there are no publically available reports from those surveys.

Despite existing CSG extraction operations and plans for expanding CSG production in the region, we are not aware of stygofauna surveys undertaken as part of these developments.

2.4.3 Hunter Valley, NSW

Extensive early work in the Hunter River catchment by Hancock and Boulton (2005; 2008), and more recently by Hose and Lategan (2012), Asmyhr et al., (2014b) and Lategan et al., (2012), have identified a rich stygofauna (including microbiota) in the region. This has been complemented by surveys associated with mine developments that have expanded the known ranges of several taxa (e.g. Eco Logical 2013b, 2013c, 2015). The majority of fauna has been collected from shallow alluvial aquifers, although Eco Logical Australia (2013c) report isopods and cyclopoid copepods being collected from a deeper aquifer linked to the mine workings.

Available data for the Hunter region indicate that stygofauna have been recorded in bores with a standing water level between 3.8 and 14.9 m below ground level (bgl), EC between 804 and 9224 µS/cm, circum-neutral pH conditions, and DO as low as 0.5 mg/L (Table 1).

Table 1 Ranges of aquifer and water quality attributes of sites (bores) in major coal production basins at which stygofauna have been collected.

LOCATION	STANDING WATER LEVEL (M BGL)	ELECTRICAL CONDUCTIVITY (µS/CM)	pH	DISSOLVED OXYGEN (MG/L)
Hunter	3.8-14.9	804-9244	6.35-7.45	0.5-6.85
Surat	1.8-30.8	758-6454	7.34-8.08	1.07-8.11
Bowen	1.4-45.0	342-9975	6.39-10.27	0.93-6.54

2.4.4 Gunnedah Basin, NSW

Alluvial deposits of the Namoi and Gwydir River catchments support a well-studied stygofauna (Korbel et al., 2013a,b, Tomlinson 2008). Korbel et al., (2013a) and Tomlinson (2008) describe diverse assemblages in the alluvium of the Peel River and the Namoi River, upstream and downstream of the Maules Creek mining area respectively. ALS (2011c) provide a list of stygofauna collected from the Maules Ck area but the details of the sampling locations and methods used in these surveys are not provided. Maules Ck Community Inc. (unpub.) indicate that fauna have been collected from several bores in the Maules Creek area but do not provide detail on the fauna collected.

2.4.5 Surat Basin, QLD

Repeated sampling of aquifers in the Horse Creek alluvium and Walloon coal measures near Wandoan in the Surat Basin, identified stygobionts (Subterranean Ecology 2012a; 2012b). The copepod *Mesocyclops* sp. and unidentified nematodes were collected from the Walloon coal aquifer while a number of copepods, oligochaetes, mites and a syncarid were found in the alluvium (Subterranean Ecology 2012a; 2012b). These fauna were collected from bores in which the standing water level ranged between 1.8 and 30.8 m below ground. The pH of the water was between 7.3 and 8.1, the EC ranged up to 6454 µS/cm in the coal measures and 2445 µS/cm in the alluvium. The bores had dissolved oxygen concentrations greater than 1 mg/L (Table 1).

2.4.6 Bowen Basin, QLD

There are a large number of studies of stygofauna associated with mining activity in the Bowen Basin. Several studies have identified stygofauna assemblages in alluvial aquifers that contain common stygobionts such as copepods, amphipods and syncarids (ALS 2011b, 2013a; AARC 2013a; Austral Research & Consulting 2014; Eco Logical Australia 2013a, QCoal Group 2013, frc environmental 2013b, GHD 2013). Among these reports there have also been several records of stygobionts occurring in coal seams.

GHD (2013) report unpublished records of harpacticoid and cyclopoid copepods and amphipods occurring in coal seams. The harpacticoid was collected from a shallow coal seam aquifer (50 m deep) that was connected to an alluvial aquifer and had relatively low salinity (<2000 µS/cm). The cyclopoid and amphipod were collected from a bore that tapped a shallow coal seam aquifer (Fort Cooper Coal Measures 59.5 m deep) in the northern Bowen Basin that had a high EC of 9975 µS/cm (GHD 2013).

From a review of 12 stygofauna studies with the Bowen Basin, the attributes of sites at which stygofauna were recorded are listed in Table 1. Stygofauna were most frequently recorded from alluvial aquifers but also from basalt aquifers and coal seams. Fauna were recorded from bores in which EC was below 9975 µS/cm, pH was between 6.39 and 10.27, dissolved oxygen was at or above 0.93 mg/L and the standing water level was between 1.4 and 45.0 m bgl.

2.4.7 Galilee Basin, QLD

AARC (2011) report the collection of the stygobiontic syncarid *Notobathynella* sp. in the alluvium of Native Companion Creek and the cosmopolitan copepod *Macrocyclops albidus*. Studies by GHD (2012b) also found a species *Notobathynella*, along with a stygobiontic mites (Trombibiidae and two species of Pezidae) in a coal seam aquifer (89 m deep). The same study also reported a potentially stygobiontic copepod occurring in a high salinity (>21000 µS/cm) clay-dominated aquifer.

2.4.8 Fitzroy Basin, QLD

Several studies in the Fitzroy Basin (i.e. upper Dawson River, FRC Environmental unpublished data; upper Connors River, ALS 2012) have reported stygofauna as present within alluvial aquifers (FRC 2013a). Two potentially stygobitic cyclopoid copepods, and five ostracods, were found from a bore in the Callide Creek Catchment just north of Biloela within the Callide Valley alluvial aquifer (SKM 2008). However, no stygofauna have been recorded in coal bearing formations (AARC 2010).

2.4.9 Gippsland, VIC

No publically available stygofauna survey reports are available in the Gippsland region.

3 Factors determining the presence of stygofauna in aquifers

Key points

- Stygofauna are predominantly found in aquifers with large (mm or greater) pore spaces, which a more common for alluvial, karstic and some fractured rock aquifers.
- Stygofauna are found occasionally in coal seam aquifers.
- The abundance and diversity of stygofauna typically decreases with depth below ground. Fauna are rarely found more than 100 m below ground level.
- Stygofauna are found across a range of water quality conditions (from fresh to saline), but most common in fresh and brackish water (electrical conductivity less than 5000 µS/cm).
- Stygofauna are rarely found in hypoxic groundwater (< 0.3 mg O_2/L.
- Stygofauna are more abundant in areas of surface water-groundwater exchange, compared to deeper areas or those further along the groundwater flow path remote from areas of exchange or recharge.

3.1 Background

Groundwater ecosystems are unique environments, with physical environments differing greatly from surface water environments. The major physical differences are temperature; the habitat matrix; and a low energy environment.

1. No sunlight: the groundwater environment is dark and groundwater temperature is constant below approximately 10 m bgl.

Without sunlight there is often little change in groundwater temperature over days, months and years. This means that fauna have evolved under relatively stable thermal conditions and so may be sensitive to changes in the thermal environment.

2. The available habitat and groundwater flow are determined by the pore spaces in the aquifer matrix.

The pore spaces within an aquifer matrix are a critical determinant of whether the aquifer can support large-bodied organisms. The physical structure of the aquifer environment is determined by the local geology. Broadly speaking, there are three main types of aquifers, all of which occur in Australia. These are; fractured rock aquifers, karstic aquifers and alluvial aquifers. In fractured rock aquifers, water moves through cracks or fractures in consolidated material/bedrock. These aquifers occur commonly in granitic, basalt or sandstone bedrock. The size of the pore spaces in fractured rock depends on the properties of the parent rock and the processes that have led to the fracturing, but typically these are narrow, ranging from sub-millimetre to centimetre scale. Karstic aquifers occur in soluble rocks such as limestone or dolomite, and, because of the solutional processes from which they form, the void spaces within the aquifer can range from small pores to large caverns. Alluvial aquifers occur in unconsolidated sediments, often sands and gravels associated with river flood plains and deposits. The porosity of these aquifers is dependent on the particle size of the sediments.

Typically, sand and silt dominated sediments have small pore spaces and few invertebrates. Coarse sand and gravel deposits, and large fractures or karstic voids commonly have pores large enough to support invertebrate fauna.

3. Limited sources of nutrients to support living organisms

Without sunlight there is no photosynthesis, so the ecosystem is largely dependent on external inputs of carbon, oxygen and nutrients, which predominantly arrive vertically with water filtering down through the soil from the surface above or laterally, from exchange with surface waters. The supply of these nutrients dwindles with distance from source, making the groundwater environment generally a low energy environment.

The porosity of the aquifer matrix (i.e. hydraulic conductivity) and hydraulic gradients dictate the rate of water flow within an aquifer and thus the distribution and replenishment of nutrients (such as oxygen and carbon). In general terms, groundwater flow is slow and laminar, but also complex and rarely uniform, giving rise to an equally heterogeneous distribution of oxygen, nutrients and suitable habitat conditions within an aquifer, even at a small spatial scale.

The geology of an aquifer also influences the groundwater quality. Contact of the groundwater with the sediments can change the water chemistry through dissolution of minerals, for example, dissolution of carbonates leading to high pH of groundwater in karstic aquifer systems. The origins of the geological formation making up the aquifer further influences the water quality, for example, with formations of marine origin often having high salinities. As such, water quality may vary considerably between aquifers. However, water quality conditions often do not vary greatly within aquifers. This means that fauna have evolved under relatively stable water quality conditions characteristic of their location and so may be sensitive to changes.

In summary, within the unique physical environment, the likelihood of stygofauna occurring in an aquifer is determined by the following attributes:

- aquifer type, geology and hydraulic conductivity;
- groundwater depth and distance from exchange or recharge areas; and
- water quality (including nutrient availability).

3.2 Aquifer geology and hydraulic conductivity

Differences in geology and aquifer type account strongly for differences in biota between aquifers (Hahn 2006, Stein et al., 2012, Johns et al., 2015). Stygofauna are known to occur in alluvial, limestone, fractured rock, calcrete aquifers and coal seams in Australia and whilst evidence suggests that the composition of the fauna differs with aquifer type, regional or continental-scale comparisons of aquifer types have not been explicitly made.

The structure of the aquifer matrix, the particle size and composition of hosting material influence the size of interstitial spaces and thus the suitability of an aquifer as stygofauna habitat (Hancock et al., 2005; Humphreys 2008). There are few data that relate the presence of stygofauna to quantified attributes of the aquifer matrix. Korbel and Hose (2015) found the greatest numbers of stygofauna in samples from sites with coarse gravel/sand dominated alluvium and no large animals in sites with alluvial sediments dominated by clays and silts. Similarly, Hancock and Boulton (2008) found greater richness and abundance of stygofauna in areas of fractured rock aquifers and unconsolidated sediments where there were larger pore spaces. Korbel and Hose (2015) also reported more stygofauna were collected from bores from which large volumes of sediment were removed when sampling (by pump), which may reflect greater hydraulic conductivity and sediment mobility.

Recent research has demonstrated the difficulties encountered by hyporheic amphipods in burrowing into sediments containing a high proportion of fine sediments (Vadher et al., 2015). Although analogous data are currently limited for stygofauna, laboratory studies clearly show a preference of stygobiontic amphipods for coarse rather than fine substrates (Hose pers. obs.).

The size of the interstitial spaces also influences the hydraulic conductivity and flow of water, which controls the delivery of C and O_2 throughout the ecosystem. Hahn and Fuchs (2009) rarely found stygofauna in areas with hydraulic conductivity (K_f) less than 10^{-4} cm/s. Table 2 shows the typical ranges of hydraulic conductivity in different aquifer types (Freeze and Cherry 1979). Based on the observations of Hahn and Fuchs (2009), it may be unlikely to expect stygofauna in coal seam aquifers.

Table 2 Hydraulic conductivity (K_f) values for aquifer matrices of different geologies.

ROCK FORMATION	K_f RANGE (CM/SEC)
Unconsolidated sediments	$10^{-10} – 10^{2}$
Fractured Rocks	$10^{-6} – 10^{-2}$
Porous sedimentary rocks	$10^{-8} – 10^{-4}$
Karstic Limestone	$10^{-4} – 10^{0}$
Coal seams	$10^{-11} – 10^{-7}$

Source: Freeze and Cherry (1979)

3.3 Groundwater depth and distance from exchange

Surface water to groundwater interactions are critical for the delivery of nutrients, such as carbon and oxygen, to aquifers (Datry et al., 2005). Nutrients concentrations decrease along groundwater flow paths, being greatest near areas of recharge and declining with depth and horizontal distance (Datry et al., 2005). With nutrients being generally more abundant close to the surface, there is a common trend of stygofauna richness and abundance also being greater in shallower (< 10 m below ground) rather than deeper areas of aquifers (Humphreys 2000; Hancock and Boulton 2008). 4T (2012), in their review of stygofauna data from Australia, report that stygofauna have been found in bores with a standing water level 64 m below ground[2]. Indeed, stygofauna can occur at depths exceeding 100 m bgl, but assemblages are generally less abundant and diverse, and may include different taxa compared to those occurring at shallower depths (Humphreys 2000; Datry et al., 2005).

It has been shown widely that the richness and abundance of invertebrates decreases with the degree of surface water–groundwater exchange, i.e., with depth and increasing distance from exchange zones (Bork et al., 2009; Bretschko, 1992; Danielopol et al., 1997; Dumas et al., 2001; Hahn, 2006; Stanford and Ward, 1988; Strayer, 1994; Ward and Voelz, 1997). Indeed, hydrological exchange between aquifer and surface water can be more important than other hydrogeological conditions in shaping stygofauna assemblages (Schmidt et al., 2007).

However, areas remote from the riverine exchange can provide a more constant environment that better suits stygofauna. This was discussed by Mencio et al., (2014), who found greater richness and abundance of stygofauna in areas of Gwydir River alluvium (NW NSW, Australia) that had little riverine exchange compared with those areas having high riverine exchange. The latter results in more variable exchange zones most suited for stygoxene taxa.

3.4 Water quality

Water quality, including dissolved carbon, oxygen and other chemical constituents, is a key factor determining the suitability of the subterranean habitat for stygofauna. As discussed above, both natural and anthropogenic gradients in water quality influence stygofauna (Malard et al., 1996, Danielopol 2000) assemblages.

Water quality and the ionic composition of the groundwater are influenced by geochemical characteristics of the aquifer-hosted formations due to dissolution of the parent rock. In some cases, the geological history and origin of the parent rock can influence water quality, particularly, for example, in areas previously inundated by sea waters, giving rise to saline geological strata and naturally saline groundwater. 4T (2012) in their review of stygofauna data from Australia, report that stygofauna have been found in hypersaline groundwater (86900 µS/cm), but are most commonly found at salinities below 10000 µS/cm.

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[2] It is a limitation of current data that depths from which stygofauna are collected are mostly referred to in terms of depth of water table (m bgl) or bore depth. The slot/screen depth of the bore provides the best indication of the depth at which stygofauna are occurring but this is rarely reported making comparisons of depth of collection between studies difficult.

Parent rock can also strongly influence pH, particularly for carbonate rocks. 4T (2012) in their review of stygofauna data from Australia, report that stygofauna have been recorded in groundwater with pH ranging from 4.3 to 8.5.

Without photosynthesis, groundwater ecosystems are reliant on inflowing water for oxygen and, as are result, are generally low oxygen environments. Stygofauna are particularly adapted to low dissolved oxygen conditions (Mosslacher 1998, 2000). 4T (2012) in their review of stygofauna data from Australia, report that stygofauna have been recorded in groundwater with dissolved oxygen concentrations ranging from 0.2 to 15.3 mg/L.

Seasonality and its influence on the hydrologic cycle may also have an effect on groundwater biota and its distribution. Groundwater ecosystems are generally buffered against seasonal changes in temperature, which are particularly strong drivers in surface environments. Nevertheless, seasonal changes in aquatic and terrestrial surface environments, such as changes in rainfall or river flow, or cropping and irrigation cycles, can strongly influence surface water and groundwater interactions (Brunke and Gonser 1997, Korbel et al., 2013a). In addition to seasonal changes, factors operating at the site scale (such as presence of phreatophytic trees, land use, and proximity to surface waters), also influence the distribution of groundwater biota (Jasinska and Knott 2000, Korbel et al., 2013a).

4 Regional water accounts associated with groundwater use

Key points

- The coal mining industry and the rapidly growing coal seam gas industry are two significant users of groundwater in the major production areas like Condamine-Balonne, Fitzroy and Hunter catchments.
- Over 90% of Queensland's future CSG associated water production is expected to be in the Condamine-Balonne catchment
- Coal seam gas water production from the Surat and Bowen Basins in 2013-14 was 26 and 5.5 GL respectively (Queensland Government, 2014). The water consumption by the operational coal mining projects in the Surat Basin is estimated to be between 3.6 GL/year and 11.9 GL/year (Kaye et al., 2012)
- While CSG associated water production in the Hunter catchment is very small as the CSG industry there is still at exploration stage, the estimated water consumption by the coal mining industry is between 25.4 GL/year and 111.8 GL/year (Kaye et al., 2012)
- CSG depressurization induced pressure and water level drawdown impacts have been predicted for the confined and alluvial aquifers in the Surat and Bowen Basins. The long-term drawdown predicted for the coal bearing formation, Walloon Coal Measures, is 150 m (QWC, 2012). Water level drawdown are also plausible in the Condamine Alluvium.
- Regional scale cumulative groundwater impact assessment for the Hunter catchment is currently being undertaken through the Bioregional Assessment programme of the Australian Government.

4.1 Background

In Queensland and New South Wales, coal mining and the rapidly growing Coal Seam Gas (CSG) industries are amongst the major stressors of groundwater in addition to agriculture and other industries. While the coal mining has been in commercial operation for more than a century, coal seam gas operations are relatively new. The first commercial production of CSG in Australia commenced in 1996 at the Dawson Valley project adjoining Moura coal mine in Queensland (Australian Government, 2015). A complex suite of factors influences the development of mining, gas and other industries (including agriculture) and the rate of their expansion. All of the extractive industry sector have a stake in the water resources which is often conflicting amongst themselves and also with the environmental services offered by the water resource.

In general, all aquifer-interfering activities in Queensland and New South Wales are regulated by relevant water management policies. In New South Wales this is the section 60I of the Water Management Act (2000) and in Queensland it is called The Water Act (2000). Water extraction limits are set out for both surface and groundwater resources in the relevant water sharing plans (New South Wales) and water resource plans (Queensland). As of July 2014, the Queensland Department of Natural Resources and Mines released a Consultation Regulatory Impact Statement Strategic Review of the Water Act which outlines a proposal to give mining companies a statutory right to take associated water (water required to be extracted for mining purposes) subject to obligations to undertake monitoring and management of impacts (National Water Commission, 2014)

Australia's national environment law, the Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act) was amended in June 2013, to provide that water resources are a matter of national environmental significance, in relation to coal seam gas and large coal mining developments. This amendment implies coal seam gas and large coal mining developments require federal assessment and approval if they are likely to have significant impact on a water resource. The recent changes in this regulatory framework is in the context of increased stress on water resources caused by dynamically evolving coal mining and gas industries and the ramifications they have on the environment.

The objective of this section is to assess regional water accounts in these major coal mining and coal seam gas development regions: the Surat and the Bowen Basins in Queensland and the Hunter region in New South Wales. In this context, the major components of water uses in the coal and CSG production areas, Surat and Bowen Basins and Hunter catchment are described in this section. Estimates of groundwater extractions by the agricultural, coal mining and coal seam gas industry are discussed. It may be noted that comprehensive hydrological analysis using surface water and groundwater models are required for the assessing the changes in the regional water balance and potential impacts on water dependent assets triggered by mining and coal seam gas development. Such assessment are currently being carried out for different regions in Australia through the Bioregional Assessment programme of Australian Government.

4.2 Surat and Bowen Basins

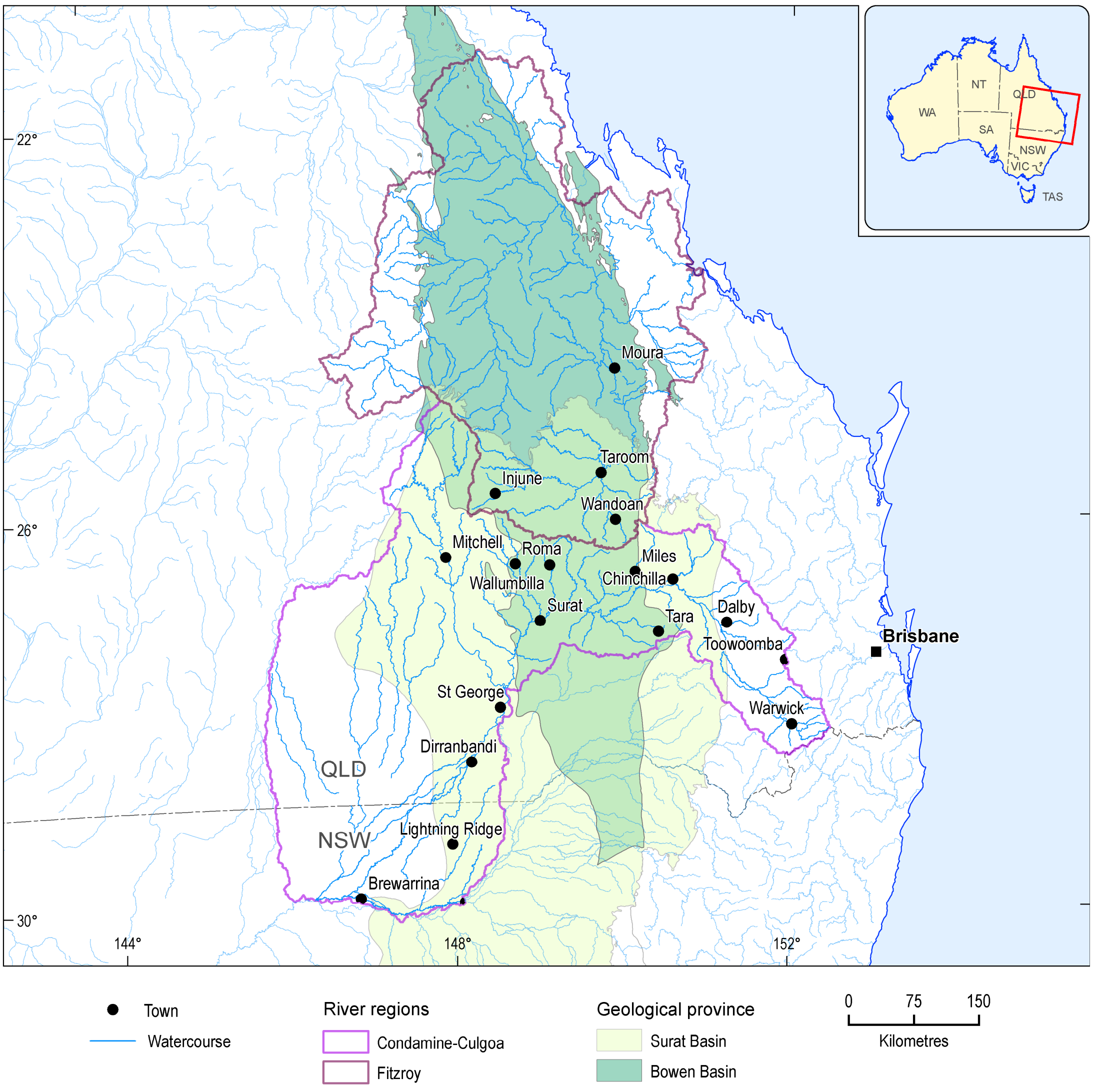
Currently, Australia's largest known proven coal seam gas reserves are in the Bowen and Surat Basins in Queensland. Figure 3 shows a map of the Surat and Bowen Basins in relation to the Condamine-Balonne and Fitzroy catchments. The Bowen Basin contains virtually all of the state's hard coking coal and Surat Basin with its large resources of thermal coal continues to be explored for coal projects. As of 2010, the Surat and Bowen Basins together have around 33 recently commenced and advanced coal mines and the majority of them are open-cut mines (DEEDI, 2010; Kaye et al, 2012). The majority of the mines are in the Bowen Basin, with proposed projects also targeting the Surat Basin.

Water resource management in these basins is largely implemented by the Condamine-Balonne Water Resource Plan and the Fitzroy Water Resource Plan. In Australia, over 90% of the future CSG associated water is expected to be generated in Queensland, largely in the Condamine-Balonne and Fitzroy water resource plan areas. Coal mining and coal seam gas development is active in parts of the Surat Basin in the Namoi catchment in New South Wales, but this region is not discussed in detail in this report.

The majority of the coal seam gas development from the Surat Basin occurs from the Walloon Coal Measures and is located within areas regulated by the Condamine-Balonne Water Resource Plan. The CSG development in the Bowen Basin is associated with the Bandanna Coal Seams, located within the Fitzroy Water Resource Plan Area. Hence, the water account for the Surat and Bowen Basins is presented in the subsequent sections in terms of the respective water resources plan areas: Condamine-Balonne and Fitzroy.

4.2.1 Condamine-Balonne Catchment

Condamine-Balonne catchment forms the head of the Queensland Murray-Darling Basin. A broad scale water account for the Condamine-Balonne catchment and the underlying Surat Basin is given in this section. Figure 4 provides an account of the annual water extraction (flux) by the agriculture, coal mining and CSG industries in the Surat Basin and the respective aquifers/formation from which water is extracted. All the aquifer formations are lumped together and shown as GAB aquifers in this schematic representation. It may be noted that water extraction from the surface water and groundwater sources are governed by different regulatory frameworks like water management plans which are applied for different geographic units. Thus, figures 4, 5 and 7 does not represent the water balance components for any single water source/management



unit.

Figure 3: Map of the Surat and Bowen Basins together with the Condamine-Balonne and Fitzroy surface water catchments. Part of the Bowen Basin underlies the Surat Basin.

Water Resources

The primary rivers in the Condamine-Balonne catchment are the Condamine, Balonne and Culgoa rivers. The estimated annual average flow in the Condamine-Balonne is 1,363 GL/year (Kaye et al., 2012). The catchment has an estimated water storage capacity of 1,582 GL including 1,300 GL on the lower Balonne floodplain. The Condamine Alluvium is one of the most important groundwater source in the region and has been overexploited in the recent years. Other important groundwater sources include aquifers hosted in the main range and tertiary volcanic Basalt in the east of the catchment. The estimated groundwater use from the Main Range and Tertiary Volcanics Formations include 36.8 GL for agriculture, 2.7 GL for industrial, 5.9 GL for urban and 17.3 GL for stock and domestic use (Kaye et al., 2012). The Great Artesian Basin (GAB) aquifers are also reasonably developed close to the intake beds in this part of the Basin.

Walloon coal measures in the target formation for coal mining and coal seam gas development in the Surat Basin. At some locations, hydraulic separation between the Walloon Coal Measures and Condamine Alluvium is thin and there is high likelihood that drawdown associated with coal and CSG depressurization impacts can propagate from the Walloon Coal Measures to Condamine Alluvium. Similarly the drawdown propagation can affect the water availability from the Main Range Volcanic aquifer.

Surface and groundwater interaction varies along the river course: the Upper Condamine River is classified as ‘maximum losing’ river upstream of Chinchilla Weir and low-medium gaining river downstream of the weir (CSIRO, 2008).

Non-CSG and non-mining water use

Irrigated agriculture is the dominant water use in the catchment. Total surface water allocation for the year 2010/11 was about 612 GL with an estimated use of about 549 GL (DERM, 2011). The current level of surface water use is extremely high as 53% of the average available water is diverted. Groundwater extraction accounts for about 18% of the total water use in the Condamine-Balonne. Approximately 41.5 GL/year of water is estimated to be used for agriculture while the allocations for industrial, urban and stock and domestic uses are respectively 0.5, 4.4 and 8.6 GL/year (QWC, 2012). This amounts to a total of 55 GL/year. However it is noteworthy that this is current use under ongoing annual announced allocations administered by DNRM. The total underlying entitlement is around 99 GL/year (QWC, 2012). A more detailed account of the water resource exploitation is available in Kaye et al., (2012).

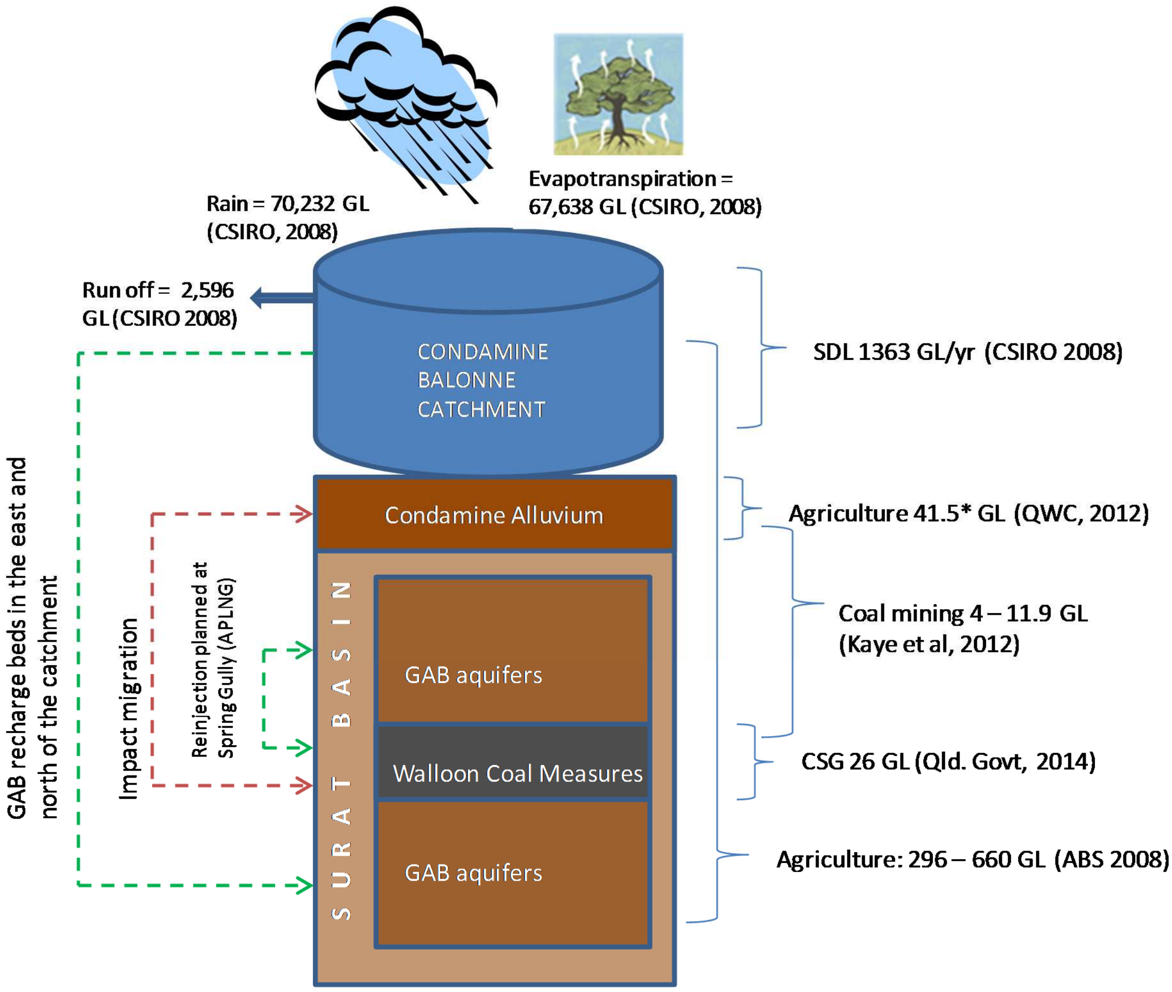


Figure 4: Water account for the Condamine-Balonne region (modified from Kaye et al., 2012)

Coal Seam Gas Water Production

Coal Seam Gas development commenced in the Surat Basins in 2002. Coal Seam Gas water production in Queensland totalled 26.7 GL in 2013-14 of which 21.4 GL was produced from the Surat Basin and 5.3 GL from the Bowen Basin (Queensland Government, 2014). This volume of water was produced from a total of 2519 CSG wells out of which 1863 are in the Surat Basin and 629 in the Bowen Basin. The majority of the CSG produced water was produced by the gas fields in the Upper Condamine region and predominantly by four major projects QCLNG (QGC), GLNG (Santos), APLNG (Origin) and Surat Gas Project (Arrow LNG). Table 3 gives an account of the coal seam gas water production from the Surat and Bowen Basins from July 2013 to June 2014.

Table 3: Account of CSG water production from Surat Basin in 2013-14 (Queensland Government, 2014)

Operator	Field	Reservoir	Water production ML (2013 - 2014)

Arrow Energy	Daandine	Walloon Coal Measures	1208.7
Arrow Energy	Kogan North	Walloon Coal Measures	415.8
Arrow Energy	Tipton West	Walloon Coal Measures	610.7
Arrow Energy	Stratheden	Walloon Coal Measures	0.0
Origin	Combabula	Walloon Coal Measures	0.0
Origin	Combabula North	Walloon Coal Measures	0.0
Origin	Condabri	Walloon Coal Measures	492.6
Origin	Condabri North	Walloon Coal Measures	486.6
Origin	Condabri South	Walloon Coal Measures	0.0
Origin	Orana	Walloon Coal Measures	0.0
Origin	Orana North	Walloon Coal Measures	0.0
Origin	Reedy Creek	Walloon Coal Measures	0.0
Origin	Talinga	Walloon Coal Measures	2924.1
Origin	Wolleebee	Walloon Coal Measures	0.0
QGC	Argyle	Walloon Coal Measures	767.0
QGC	Argyle	Walloon Coal Measures	886.7
QGC	Argyle East	Walloon Coal Measures	0.0
QGC	Avond Downs	Walloon Coal Measures	0.0
QGC	Avond Downs, McNulty	Walloon Coal Measures	0.0
QGC	Bellevue	Walloon Coal Measures	833.1
QGC	Berwyndale	Walloon Coal Measures	483.7
QGC	Berwyndale South	Walloon Coal Measures	22.7
QGC	Broadwater	Walloon Coal Measures	0.0
QGC	Broadwater, Harry, Glendower	Walloon Coal Measures	2761.9
QGC	Broadwater (Mini)	Walloon Coal Measures	0.0
QGC	Codie, Lauren, Kenya	Walloon Coal Measures	1416.3
QGC	Berwyndale, Berwyndale South	Walloon Coal Measures	972.0
QGC	Cameron	Walloon Coal Measures	0.0
QGC	Clunie	Walloon Coal Measures	0.0
QGC	Clunie, Barney	Walloon Coal Measures	21.6
QGC	Cougals	Walloon Coal Measures	0.0
QGC	Cougals, Barney, Clunie	Walloon Coal Measures	0.0
QGC	Glendower, Harry	Walloon Coal Measures	0.0
QGC	Golden Grove	Walloon Coal Measures	0.0
QGC	Jammat	Walloon Coal Measures	0.0
QGC	Jen East	Walloon Coal Measures	0.0
QGC	Jen, Ruby Jo, Isabella	Walloon Coal Measures	4126.1

QGC	Jordan	Walloon Coal Measures	0.0
QGC	Jordan, Celeste	Walloon Coal Measures	0.0
QGC	Kathleen, Cam, Mamdal, Woleebee Creek	Walloon Coal Measures	256.7
QGC	Kenya, Codie, Kate	Walloon Coal Measures	1428.8
QGC	Kenya East	Walloon Coal Measures	0.0
QGC	Kenya East	Walloon Coal Measures	0.0
QGC	Kenya East, Jammat, Margaret	Walloon Coal Measures	12.0
QGC	Matilda-John, Lauren	Walloon Coal Measures	74.7
QGC	Matilda-John	Walloon Coal Measures	0.0
QGC	McNulty	Walloon Coal Measures	0.0
QGC	McNulty	Walloon Coal Measures	0.0
QGC	Owen	Walloon Coal Measures	0.0
QGC	Paradise Downs, Carla, Lawnton, Alex	Walloon Coal Measures	0.0
QGC	Penrhyn, Charlie, Phillip, Arthur, Cameron	Walloon Coal Measures	0.0
QGC	Polaris, Acrux, Cassio	Walloon Coal Measures	0.1
QGC	Polaris, Acrux, Cassio	Walloon Coal Measures	0.0
QGC	Portsmouth, Cameron	Walloon Coal Measures	0.0
QGC	Sean	Walloon Coal Measures	0.0
QGC	Sean, David, Poppy	Walloon Coal Measures	1158.2
QGC	Woleebee Creek, Ross, Kathleen, Cam, Mamdal	Walloon Coal Measures	69.2
QGC	Woleebee Creek	Walloon Coal Measures	0.0
Santos Ltd	Coxon Creek (RSG RandC)	Walloon Coal Measures	0.0
Santos Ltd	Coxon Creek (RSG RandC)	Walloon Coal Measures	0.0
Santos Ltd	Coxon Creek (RSG ICB (R))	Walloon Coal Measures	0.0
Santos Ltd	Coxon Creek (RSG ICB (R))	Walloon Coal Measures	0.0
Santos Ltd	Coxon Creek (RSG ICB (R))	Walloon Coal Measures	0.0
Santos Ltd	Coxon Creek (RSG ICB (R))	Walloon Coal Measures	0.0
Santos Ltd	Coxon Creek (RSG ICB (R))	Walloon Coal Measures	0.0
Santos Ltd	Roma	Walloon Coal Measures	0.0
		Totals (ML)	26738.4

CSG operations in the Surat Basin target the Walloon Coal Measures composing of Juandah and Taroom Coal Measures typically lying at depths of 100 to 800 m. UWIR report (QWC, 2012) indicates that Hutton Sandstone, Springbok Sandstone, Precipice Sandstone, Gubberamunda

Sandstone and Condamine Alluvium are the fresh water aquifers that are likely to be impacted by the depressurization of Walloon Coal Measures.

4.2.2 Coal mining water use - Surat Basin

The total water consumption by the operational coal mining projects in the Surat Basin was estimated at 3.6 – 11.9 GL (Kaye et al., 2012). The coal mining operations in the Surat Basin targets the Walloon Coal Measures. At present there are five open cut mines in the Queensland part of the Surat Basin viz, Commodore, New Acland, Kogan Creek, Cameby Downs and Wilkie Creek. Activities only for the closure of the Wilkie Creek mine are currently taking place. Table 4 provides another independent estimate of water use by the existing and proposed mines in the Maranoa-Balonne-Condamine subregion (Sander et al., 2014).

Table 4: Estimated volumes of water use by existing and EIS approved mines (as of 2012) in the Queensland part of Surat Basin (Sander et al., 2014)

Mine status	Mine name	Reported water use (ML/year)	Comment
Existing	Commodore	150	Overland flow, coal not washed, water used only for irrigation and dust suppression
	New Acland Stage 2	6870	1370 ML of groundwater and the rest purchased
	Kogan Creek	0.5	Mainly used for dust suppression ,coal not washed
	Cameby Downs	-	Water usage not reported
	Wilkie Creek	-	Mine closing down
EIS approved	New Acland Stage 3	1572	1412 ML/year from groundwater license
	The Range	2868	Estimated maximum

It is noteworthy that an expansion project for the Cameby Downs mine owned by Yancoal Australia Ltd has been proposed with a comparatively high estimated water use of 8,000 to 10,000 ML/year for coal washing, coal dust suppression and production of potable water. Similarly, Columboola Project a joint venture between MetroCoal Limited and SinoCoal Resources Pty Ltd is targeting coal seams near the Cameby Downs area and the project is in the exploration stage. Kaye et al., (2012) report that the mine water use in the Condamine-Balonne catchment is expected to increase 3-fold to 12.6-41.9 GL under the future development scenarios.

4.2.3 Fitzroy catchment water balance

The Fitzroy catchment encompasses a wide range of landscapes and climatic regimes from semi-arid grasslands to subtropical rainforest. The water use is also diverse across a ranges of industry sectors including grazing, cropping and horticulture, mining, forestry and heavy industry and manufacturing.

Water Resources

The surface water resource in the catchment is comprised of the Fitzroy River and its major tributaries: the Isaac Connors, Nogoa-Mackenzie and the Dawson and Don-Callide river systems. Estimated mean annual discharge is 6,000 GL (Fig. 5, Kaye et al, 2012).

There are four significant public water storages comprising of the Fairbairn Dam (1301 GL), Callide Dam (127 GL), Fitzroy River Barrage (67.5 GL) and the Eden Bann Weir (26.3 GL) (Kaye et al., 2012). There are no major groundwater resource allocations other than in the Callide Valley Groundwater Area.

Non-mining and non-CSG water use

The major water use in the Fitzroy catchment is for irrigated agriculture. Irrigation volumes range 180 – 255 GL out of which 88% comes from surface water diversions and 10% from groundwater sources (ABS, 2008). Another major allocation is for five water supply schemes with a total allocation of 410.8 GL. The total use of water was estimated to be 148.6 GL (DERM, 2011) of which 53% was taken for the Nogoa-Mackenzie water supply scheme, which includes the Emerald irrigation area. Groundwater extraction in the Callide Valley Groundwater Management Area and Isaac-Connors totalled 32.23 GL/year and 6.9 GL/year respectively (SKM, 2008).

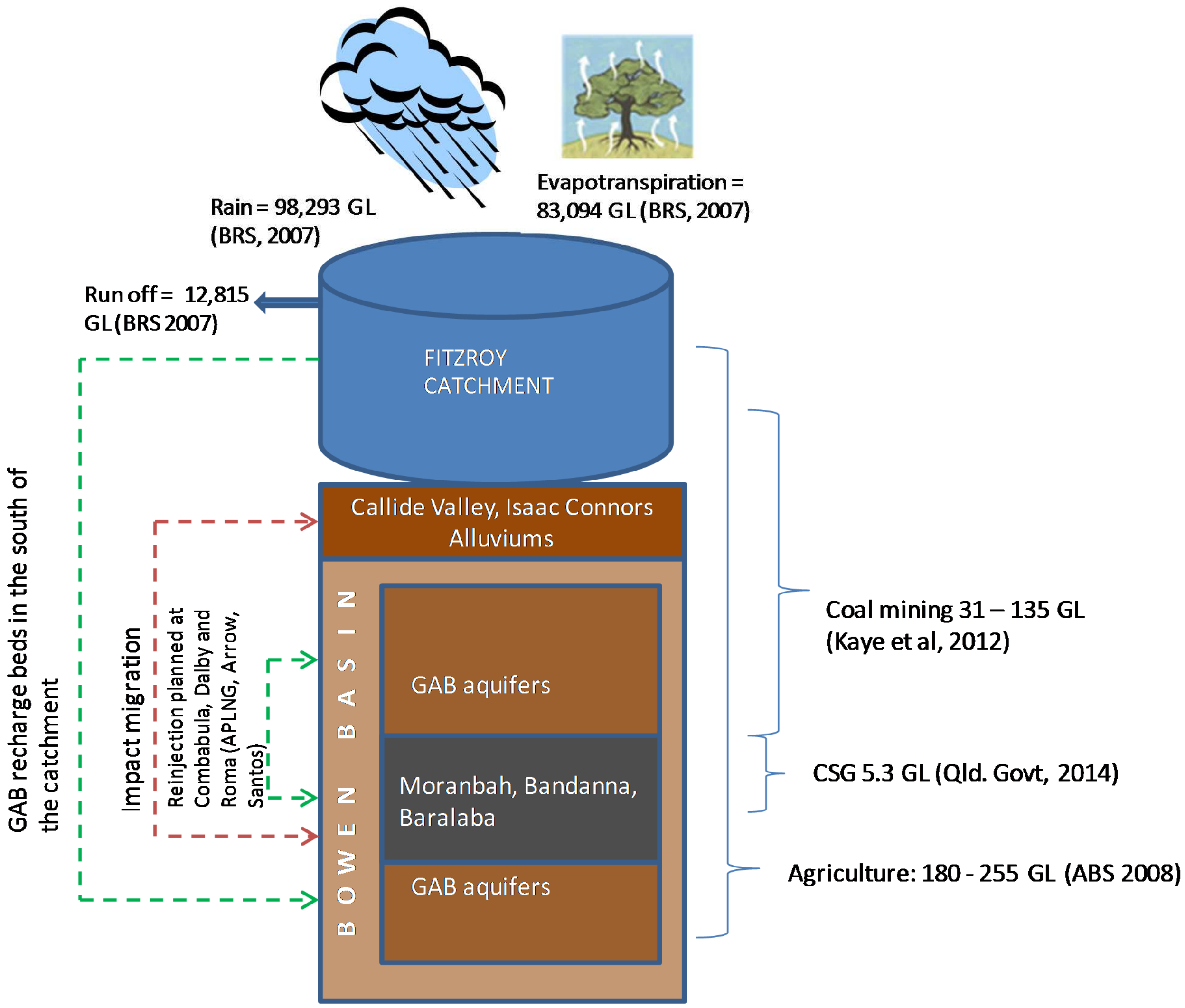


Figure 5: Water account for the Fitzroy region (modified from Kaye et al., 2012)

4.2.4 Coal Seam Gas Water Production – Bowen Basin

Coal Seam Gas development commenced in the Bowen Basin in 1996. Queensland government established the Surat Cumulative Management Area (Surat CMA) in 2011 and Queensland Water Commission prepared the Underground Water Impact Report which reported the groundwater impacts resulting from the development of the coal seam gas industry in the Surat CMA.

Coal Seam Gas water production in Bowen Basin totalled 5.3 GL in the twelve month period from July 2013 to June 2014. This volume of water was produced from a total of 629 CSG wells. The majority of the CSG produced water was produced by the Spring Gully gas field (APLNG), MGP gas field (Arrow Energy), Fairview and Scotia gasfield (Santos). Table 5 gives an account of the coal seam gas water production from the Bowen Basin from July 2013 to June 2014 (Queensland Government, 2014).

Table 5: CSG associated water produced from the Bowen Basin from July 2013 to June 2014 (Queensland government, 2014).

Operator	Field	Reservoir	Water production ML
Anglo Coal	Dawson	Baralaba CM	0.0
Anglo Coal	Dawson Valley	Baralaba CM	0.0
Westside Corporation Ltd	Dawson River	Baralaba CM	18.3
Westside Corporation Ltd	Moura	Baralaba CM	1.9
Molopo	Mungi	Baralaba CM	0.0
Westside Corporation Ltd	Nipan	Baralaba CM	11.4
Arrow Energy	MGP	GM	205.5
Arrow Energy	MGP	P	104.8
Arrow Energy	MGP	Q	0.0
Arrow Energy	MGP	GM	56.0
Arrow Energy	MGP	GML	0.0
Arrow Energy	MGP	P	1.2
Arrow Energy	MGP	GM	20.7
Arrow Energy	MGP	P	2.1
Origin	Lonesome	Bandanna Coal Seams	0.0
Origin	Membrance	Bandanna Coal Seams	0.0
Origin	Peat	Bandanna Coal Seams	6.9
Origin	Spring Gully	Bandanna Coal Seams	1311.6
Origin	Spring Gully	Bandanna Coal Seams	0.0
Origin	Spring Gully	Bandanna Coal Seams	256.6
Origin	Spring Gully	Bandanna Coal Seams	765.3
Origin	Spring Gully East	Bandanna Coal Seams	0.0
Origin	Spring Gully	Bandanna Coal Seams	0.0
Santos Ltd	Fairview	Bandanna Coal Seams	0.0
Santos Ltd	Fairview	Bandanna Coal Seams	187.4
Santos Ltd	Fairview	Bandanna Coal Seams	751.6
Santos Ltd	Fairview	Bandanna Coal Seams	1026.0
Santos Ltd	Fairview	Bandanna Coal Seams	580.1
Santos Ltd	Fairview	Bandanna Coal Seams	0.7
Santos Ltd	Fairview	Bandanna Coal Seams	0.0
Santos Ltd	Fairview/Arcadia	Bandanna Coal Seams	0.0
Santos Ltd	Scotia	Upper Bandanna	0.6
Santos Ltd	Springwater	Cattle Creek	0.0
		Totals (ML)	5308.7

4.2.5 Coal mining water use - Bowen Basin

There are 28 operating coal mines in the Bowen Basin. Coal mining water use was estimated at 30.6 – 134.8 GL in the Fitzroy catchment. There are 8 expansions and 20 new projects planned in the Bowen Basin. The water consumption is predicted to increase by 2-fold to 68.4-300.8 GL under future development scenarios. The largest future water demands are likely to occur in the Isaac-Connors with the likely increased activity in this region. Majority of the new projects plan to source water from surface water diversions and third party provides. Kaye et al., (2012) gives an account of the raw water demand and supply sources for the new coal projects planned in the Bowen Basin.

One new coal project (Wandoan coal project, Xstrata) has investigated the feasibility of using CSG water for operational activities. Braeside Borefield at the confluence of Nebo and Denison Creeks supplies the most significant volumes of groundwater extraction in the Isaac-Connors accounting for nearly 60% of the total extraction estimates (2.9GL/year). The Braeside Borefield supplies water to coal mines and communities in the northern Bowen Basin. The total entitlement is 3.3 GL/year and the usage is on average 90% of the entitlement. Water balance modelling shows that current levels of extraction at the bore field will likely deplete the resource (Kaye et al, 2012).

4.2.6 Cumulative groundwater drawdown from the depressurization of coal seams

Queensland government established the Surat Cumulative Management Area (Surat CMA) in 2011 and Queensland Water Commission prepared the Underground Water Impact Report which reported the groundwater drawdown resulting from the development of the coal seam gas industry in the Surat CMA. Surat CMA encompasses Queensland parts of the Surat Basin and the southern parts of the Bowen Basin. Quantitative assessment of the cumulative impacts were based on the Surat CMA groundwater model developed by the Queensland Water Commission (QWC, 2012)

The target formations: the Bandanna formation in Bowen Basin and the Walloon Coal Measures in the Surat Basin, were predicted to have the biggest drawdown impacts. The long-term drawdown in the Walloon Coal Measures is expected to be less than 150 m (QWC, 2012). Similarly the long-term drawdown impact in the Bandanna formation is expected to be less than 200 m. The maximum drawdown impact in the Springbok Sandstone and Hutton Sandstone are predicted to be less than 20 m and 5 m respectively over most of the affected area. The predicted maximum drawdown in the Precipice Sandstone aquifer over most of the affected areas is less than 2 m and the same in Gubberamunda Sandstone is less than 3 m.

The maximum predicted drawdown for the Condamine Alluvium is about 1.2 m on the western edge of the alluvium with an average of about 0.5 m for most of the area. It is expected that an average of about 1100 ML/year of water would be lost from the Condamine Alluvium to the underlying Walloon Coal Measures over the 100 years as a result of the Coal Seam Gas water production.

It is noteworthy that the cumulative impact assessment using the Surat CMA groundwater model has not considered the impacts from the coal mines. CSIRO is currently working on incorporating the mine dewatering component to the cumulative impact assessment of the Maranoa-Balonne-Condamine subregion by considering the seven mines in this region. Regional scale cumulative impact assessment considering all the coal mines in the Bowen Basin has not been undertaken so far.

4.3 Hunter catchment

The Hunter region is known for the energy resource potential and has over 20 of the world's largest coal mines. Agriculture is another important industry in the Hunter valley. Coal Seam Gas activity in the Hunter region is only at the exploration stage. The geological Basins underlying the Hunter catchment is shown in Figure 6. A broad scale water account for the Hunter region is represented in Figure 7.

Figure 6: Map of the Hunter catchment showing the underlying Surat, Gunnedah and Sydney Basins

4.3.1 Water Resources

The Hunter River and its major tributaries including Goulburn, Paterson and William rivers and Wollombi Brook constitute the surface water resource in the region. The surface water storage facilities include Glenbawn Dam and Glennies Creek Dam with a total storage capacity of 1033 GL. The Hunter Valley Alluvial Aquifer and the Permian fractured rock aquifer are the major groundwater resources. Groundwater is also hosted by tertiary basalt formations along the north-west area of the Hunter Valley. There is a strong interaction between the surface water and groundwater systems in the Hunter. The alluvium has significant water storage, however, the groundwater extractions have impact on river flow (DWE, 2009). Similarly, extractions from a water hole in the river will access groundwater (Kaye et al., 2012). The groundwater resources within the alluvial aquifer may be under a higher risk of impact from further expansion of coal resource development in the Hunter Valley.

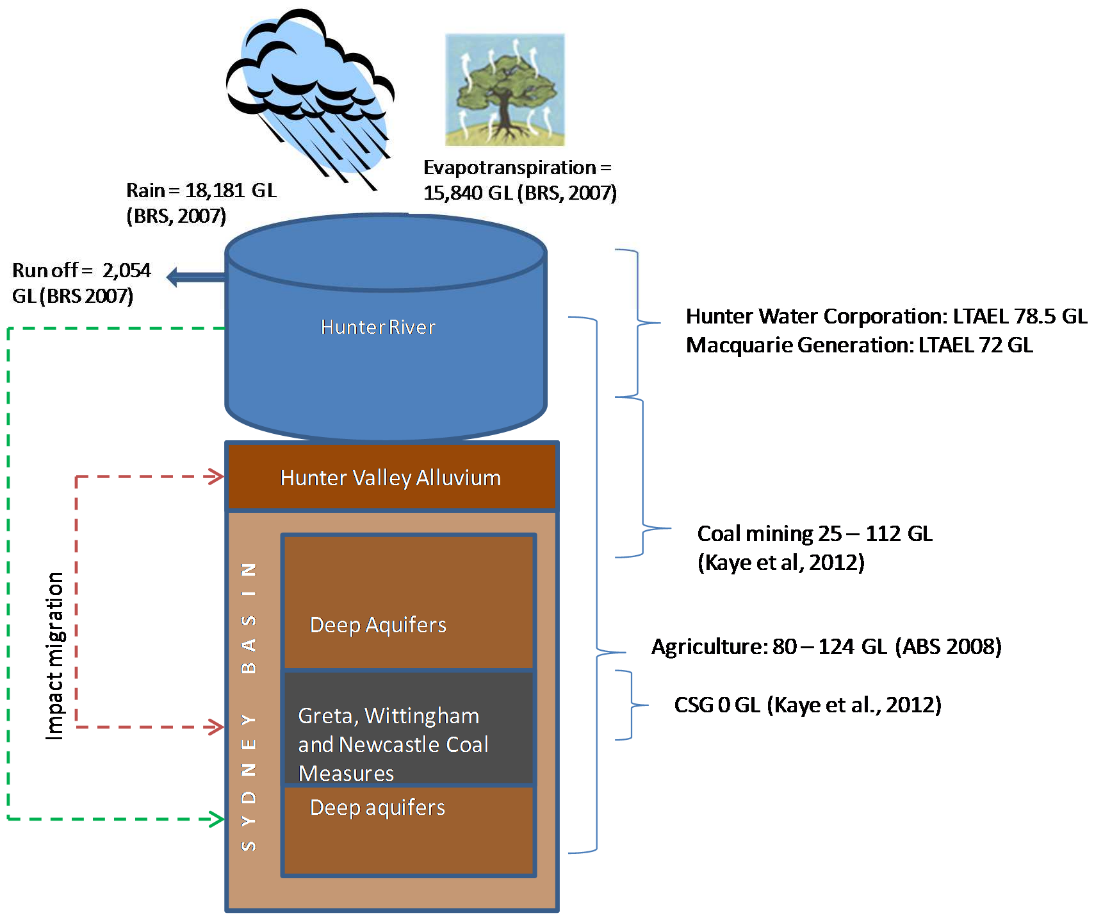


Figure 7 Water account for the Hunter region (modified from Kaye et al., 2012)

4.3.2 Non-CSG and non-mining water use

The major water users other than coal mines include the Hunter Water Corporation, urban water users, power generation and agriculture (NOW, 2012). Australian Bureau of Statistics (ABS, 2006) estimated the diversions for 2004/05 to be equal to 236.5 GL. The total long-term annual extraction limit (LTAEL) for all water sharing plans within the Hunter region is 307 GL/year.

Total water use for irrigation is estimated to be in the range 80 – 124 GL/year. It is estimated that 74% of this irrigation water use is derived from surface water sources and 23% from groundwater sources. It is estimated that 72% of the total groundwater use in the Hunter Valley is for agriculture.

The long-term average water requirement by power stations in the region is approximately 72 GL/yr. Hunter Water Corporation is a major user and holds a majority, approximately 72%, of the groundwater entitlement in the Tomago-Stockton-Tomaree Sandbeds, with a 3-yr average share of 29 GL/year.

4.3.3 Coal Seam Gas Water Production – Hunter Region

Coal Seam Gas industry is still at an exploration stage in the Hunter region. As of 2012, there are about 40 exploration wells drilled in the region. The Petroleum Exploration Licenses (PEL) 4 and 267 permits AGL to explore most of the Hunter region. Santos is also exploring on PEL 456 in the upper Hunter for the Gunnedah Basin project. AGL's Gloucester Gas Project lies directly adjacent to the northeast of the Hunter catchment and is expected to generate about 0.73 GL/year of CSG associated water. During 2009/10 approximately 12 ML of water was produced from CSG activities (Kaye et al., 2012).

4.3.4 Coal mining water use – Hunter Region

There are 26 operational coal mines in the Hunter region. There are eight new projects and several expansion projects proposed (Kaye et al., 2012). Coal mining water consumption in the Hunter region is estimated to be at 25.4 – 111.8 GL/year under the existing scenario (Kaye et al., 2012). With the new and expansion projects the water consumption is expected to increase by 1.5 times to 36.2 to 159.5 GL/year. Mine water demand account for about 25% of the groundwater allocation. Assessment of cumulative impacts on the groundwater resources resulting from coal seam gas development and coal mining activities have not been undertaken on a regional scale for the Hunter region. CSIRO is currently undertaking a regional groundwater modelling exercise as part of the Bioregional Assessment programme.

5 Threats of mining and CSG activities to the groundwater environment and stygofauna

Key points

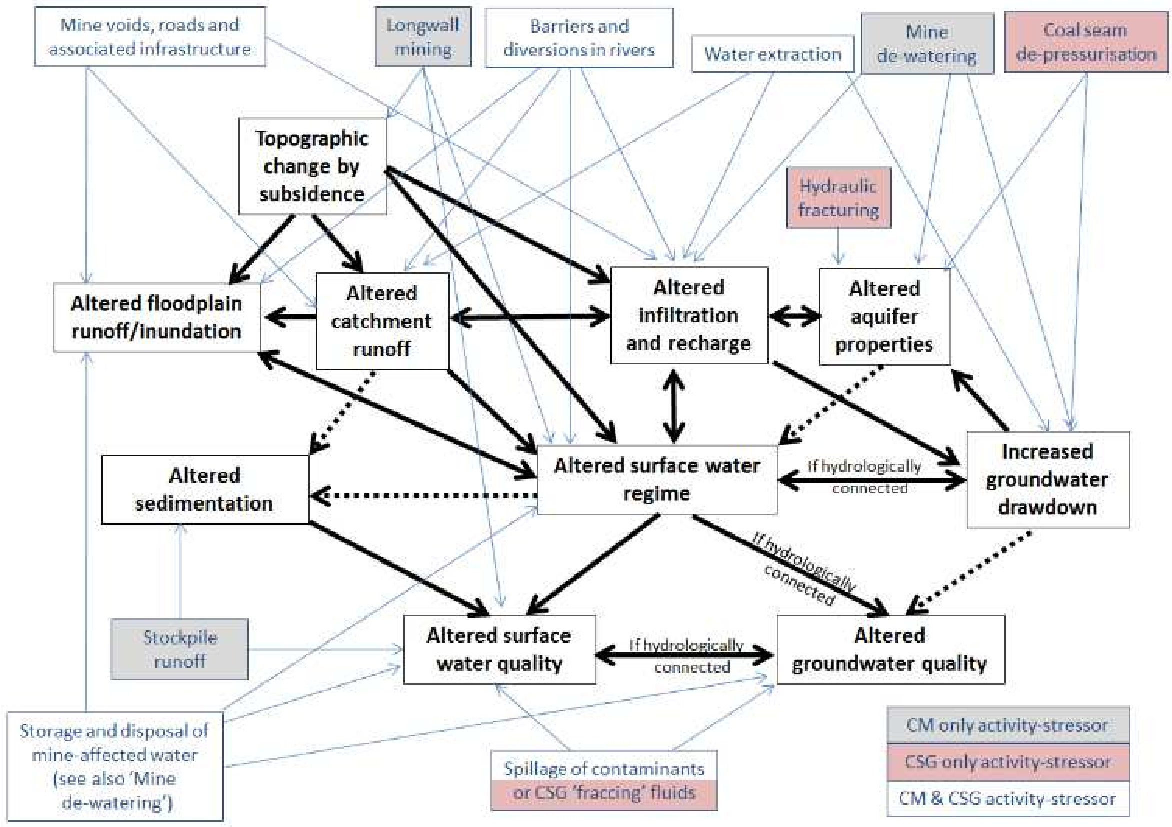
- Coal mining and CSG developments affect aquifers at different depths. Coal mining intersects shallow aquifers that are most likely to contain stygofauna whereas CSG activities target aquifers at depths that are generally greater than those at which stygofauna are commonly found.
- Both coal mining and CSG may cause changes to the groundwater environment within the target aquifer and in aquifers above and below.
- Threats to stygofauna arise from changes to the groundwater environment, particularly those associated with change in groundwater levels or hydraulic pressure, groundwater quality or changes in aquifer pore dimensions (e.g. due to subsidence).
- Stygofauna are particularly sensitive to groundwater environment disturbance because they are adapted to a steady conditions and have very narrow spatial distributions.
- Stygofauna assemblages have limited capacity to recover from disturbance because they have low mobility and low reproductive rates meaning recolonisation is slow.
- Under groundwater drawdown stygofauna can be stranded and have limited ability to survive in unsaturated conditions.
- Stygofauna are potentially sensitive to changes in aquifer pressure, but no research has been conducted to date.
- Stygofauna are sensitive to changes in water quality that deviate from the natural background conditions. This related to changes in both physico-chemical water quality (temperature, level of oxygenation or salinity) and pollution of the groundwater environment.

5.1 Background

The stressors arising from coal mining and coal seam gas developments have been identified as part of activities associated with Bioregional Assessments of coal mining and coal seam gas impacts (Figure 8, Commonwealth of Australia (2015)). The various activities associated with these developments can lead to three major changes in groundwater conditions, which can be describe as stressors that directly threaten the integrity of groundwater ecosystems. These stressors are:

- spatial and temporal changes in water level (groundwater drawdown);
- altered groundwater quality; and
- altered aquifer properties (including aquifer porosity and depressurisation).

Such changes in the physico-chemical conditions individually or cumulatively are likely to affect the occurrence and/or the distribution of stygofauna in an aquifer. In this section we examine the evidence for impacts of these stressors on groundwater ecosystems broadly and stygofauna in particular.



Note. Interactions among stressors (bold black type) from coal seam gas extraction and coal mining (blue type); dashed lines represent possible linkages.

Figure 8 Hydrological stressors/impacts from coal seam gas extraction and coal mining. Source: Commonwealth of Australia (2015)

The effects mining and CSG developments occur in addition to other stressors in the landscape, such as agricultural groundwater use or climate change. This means that the responses of groundwater ecosystems can be associated with cumulative impacts from the multiple stressors (CoA 2015) and, as such, understanding or predicting the effects of coal mining or CSG developments cannot be considered in isolation from other activities in the landscape.

The potential risks to stygofauna depend on the nature of the mining operations, such as the mining method (e.g. longwall vs open cut), groundwater management strategy, water quality controls and the attributes of the aquifer(s) affected. There are a number of activities that may lead to changes in the groundwater environment (Figure 8). The response of the stygofauna to these changes depends on the duration of the changes, the spatial extent of the changes relevant to the aquifer size, depth and mining area, and the intensity or rate of the changes.

Mining and CSG activities may affect stygofauna directly or indirectly. Direct effects on stygofauna include:

- groundwater contamination or anoxia can cause acute (rapid) mortality of stygofauna and be manifested quickly as a loss or decline in population abundance; and
- chronic (long-term) exposure to stressors such as low-level water quality changes or changes to food availability that affect long-term health and fitness of stygofauna. When stygofauna are stressed in this way they may spend more energy on maintaining their health and fitness and less energy and resources on reproduction or growth. This may lead to a reduction in reproduction and gradual population decline which may take a long time to become evident because of the naturally slow growth and low metabolic and reproductive rates of stygofauna.

The indirect effects of mining or CSG development on stygofauna are those that cause changes to conditions in the aquifer that favour the introduction of exotic or surface taxa (increased abundance of stygoxenes) that outcompete stygofauna, leading to their extinction through competition.

As a group, stygofauna may be particularly sensitive to environmental changes because:

- they are adapted to relatively stable environmental conditions and are thus vulnerable to changes in those conditions;
- they have limited ability to disperse through aquifers, and recolonise following disturbance;
- they often have a high degree of endemism with species often restricted to small geographic areas (short-range endemics) that maybe much smaller than basin; and
- they have slow rates of reproduction and low dispersal abilities which means that recovery of populations, if possible, will be slow.

In general, there are few data on the response of stygofauna to environmental changes. Here we describe, in general terms, the likely effects of mining and CSG activities on stygofauna, but recommend that risk assessments consider the local environment, including the stratigraphy, local hydrogeology and mine operating conditions in order to assess the likely extent of stressors and their affects.

5.2 Spatial and temporal changes in water level

Changes to groundwater depth is perhaps the most recognisable, direct effect of mining on groundwater environments. Changes in depth to groundwater can occur as a result of changes to diffuse (rain water infiltration) and localised recharge from surface waters, loss of water to adjoining aquifers with changes in groundwater pressure or fracturing of adjoining aquitards (Fig 8). Mining activities that intersect aquifers commonly lead to a substantial drawdown as a result of mine dewatering. Increases in water tables as a result of hydrogeological changes can also occur (e.g. as a result of groundwater reinjection), but groundwater drawdown is considered the most common and significant effect.

The potential effects of lowered groundwater tables on stygofauna are two-fold:

1. The lowering of water levels may leave stygofauna stranded above the water table.

2. Declining water levels may reduce available habitat as strata become unsaturated.

Stygofauna have limited mobility and may not be able to move with water tables as they drop. Stumpp and Hose (2012) demonstrated that stygofauna became stranded when water tables receded by either 2.6 m/day or 1.0 m/day. While the majority of syncarids were found below the water table, 25% of stygofauna were stranded above the water table, including 19% that were stranded in the unsaturated area above the capillary fringe. Relatively fewer copepods (12-16%) were stranded above the water table, with 6-7% stranded in the unsaturated zone. The rates of drawdown applied in those experiments may be faster than those likely to occur as a result of mining activity. It is possible that with slower rates (<1 m /day) the stranding of fauna would be less, but this remains untested.

The effect of drawdown may also be different for various species. Tomlinson (2008) tested the response of copepods to water drawdown and observed downward movement of the animals with the water table and some stranding. In contrast, there was no downward movement by amphipods as the water table declined, with the majority of animals tested being stranded in the area of the original water table depth.

Both Tomlinson (2008) and Stumpp and Hose (2012) examined the fate of stygofauna in drying sediments. Both studies showed that stygofauna (copepods, amphipods and syncarids) stranded in unsaturated sediments have limited survival beyond 48 hours, and that survival decreased with decreasing sediment saturation. Both amphipods and syncarids were more tolerant to drying conditions than the copepods, which may be due to their greater ability to migrate (by walking) in the drying sediments compared to copepods who move more my swimming.

The decline of groundwater tables may be problematic for stygofauna when the water table drops below areas of suitable habitat, such that the habitat is no longer accessible to fauna or is no longer saturated. Importantly, capillary forces will ensure that some areas of the aquifer matrix above the water table remain saturated, but the degree to which this occurs is likely to be small (<1 m), and influenced by the aquifer geology and pore size. It is also possible that areas of habitat above the water table may retain water and remain partly saturated (due to hydrostatic forces) but isolated. These areas may provide a temporary refuge for fauna but the longer-term survival of stygofauna in such areas will require the return of groundwater levels to replenish nutrients in the water and allow stygofauna to migrate.

The impacts of drawdown may be influenced by the nature of the aquifer matrix. For example, changes in the groundwater level in a coarse alluvium that is free draining will provide adequate vertical migration opportunities for fauna to move with declining water levels (Nevill et al., 2010). Here also, isolated pockets of groundwater are less likely to occur. In finer matrices, or those with lenses of fine material, the vertical migration pathways for fauna may be limited, resulting in a high degree of stranding as water levels decline. However, fine matrices may be more likely to retain isolated, saturated areas as temporary habitat above the water table (Nevill et al., 2010).

The intensity of the water table drawdown effect on stygofauna habitat is likely to be site specific. However, the maximum drawdown for some regions (see section 4) of up to 20 m (such as in the sandstone aquifers of the Condamine catchment) are likely to impact on stygofauna where present.

Habitat loss due to drawdown will depend on the depth of suitable habitat within the geological strata and whether that habitat becomes unsaturated. Given the likely heterogeneity of habitat within an aquifer, potentially at small scales, the effects of drawdown are difficult to predict, and effects will be dependent on the relationship between the water table and the aquifer thickness. Furthermore, a drop in water table may isolate areas of habitat within an aquifer, which unless reconnected over time, may lead to localised loss of fauna. Declining water tables in caves of the Leeuwin Naturaliste Ridge, WA led to changes in the stygobitic invertebrates associated with tree roots. The unique assemblages threatened by water levels declined dramatically as water levels declined and root mat habitats dried out (Eberhard and Davies 2011; Chilcott 2013).

There have been few field-based studies of the effects of water table changes on stygofauna. Current research in the UK has shown significant changes in groundwater invertebrate and microbial assemblages following greater than usual recharge and rising water tables associated with large, natural rain events (Anne Robertson, University of Roehampton, pers. Comm.).

Hancock (2009) monitored changes in stygofauna assemblages in the Hunter Valley, NSW, during and after drought in which groundwater levels in the shallow alluvium varied. Significant recharge of the aquifer associated with drought-breaking rains raised water tables by up to 3 m, and coincided with an increase in the abundance of stygobitic amphipods, syncarids, beetles and copepods. In the calcrete aquifers of the Yilgarn, major recharge events have been associated with reproduction in beetles and amphipods (Dillon et al., 2009). Similar responses have been observed in chalk aquifers of the UK (A Robertson pers. comm.), but such increases in reproduction and abundance of fauna may be associated with the increase in nutrients that accompanies recharge events rather than being a result of water level change per se.

A critical consequence of water table drawdown is the increased thickness of unsaturated zone. This can lead to reduction in groundwater recharge and nutrient removal from infiltrating water by soil microbes, with their concentrations in infiltrating water decreasing with depth. The effect of this is that the nutrient concentrations entering deeper groundwater may be less than those reaching shallower water (see Pabich et al., 2001; Datry et al., 2005). For example, shallow aquifers with depth to groundwater (vadose zone thickness) <1.25 m had dissolved organic carbon concentrations up 23 mg C/L whereas aquifers below 5 m had concentrations below 2 mg C/L (Pabich et al., 2001), which implies that groundwater level changes of several metres can alter infiltrating groundwater quality.

More research into the impact of water level declines on stygofauna is needed, in particular, laboratory and field studies of groundwater drawdown, and its impact on the behaviour and health of stygofauna. Such studies should be multi-disciplinary in nature and should link water levels to habitat suitability, local groundwater hydrology and both microbial and stygofauna assemblages.

5.3 Altered groundwater quality

Stygofauna are generally adapted to stable environmental conditions, including water quality. Changes to water quality that are beyond the range of conditions normally experienced by stygofauna pose a threat to their survival. Changes in groundwater quality may occur when mining activities increase linkages with aquifers of poor water quality, or through other means such as seepage of acids or heavy metals from overburden, or infiltration of produced water from storage facilities or via recharge of aquifers from rivers where produced water is discharged.

5.3.1 Nutrients and physico-chemical conditions

Dissolved oxygen is considered limiting for fauna, with Hahn (2006) suggesting that 0.5 mg/L was the lower limit for stygofauna in studies in Europe. Studies in Australia have found similarly, with fauna collected at sites above 0.23 mg/L (Hancock and Boulton 2008) and above 0.31 mg/L (Leijs and Mitchell unpub. data in Dillon et al., 2009). Data presented in Table 1 indicate stygofauna were found in the Hunter catchment at and above 0.5 mg/L and in other coal production basins at above 0.93 mg/L. While dissolved oxygen concentrations may be limiting below around 0.2-0.5 mg/L, higher DO concentrations are generally not related to greater stygofauna richness and diversity.

Dissolved organic carbon is a key energy source for groundwater ecosystems, but is often present in only low concentrations. Slightly elevated nutrient concentrations can stimulate stygofauna abundance (Boulton et al., 2008, Hallam et al., 2008, Simon and Buikema 1997), but stygofauna that are adapted to low energy conditions are often outcompeted by surface fauna in cases where aquifers become heavily nutrient enriched (Hallam et al., 2008). Dissolved organic carbon concentrations for undisturbed aquifers are typically below 4 mg/L (Korbel and Hose 2011). Deep groundwater is often free of DOC. Although dissolved organic carbon is an important component of groundwater ecosystems, only a small proportion of the total organic matter dissolved in groundwater is readily bioavailable, so total dissolved organic carbon is rarely correlated with the diversity and abundance of stygofauna (e.g. Korbel et al., 2015).

Produced water from mining and CSG activities is often saline (Commonwealth of Australia 2014d) and large volumes are often produced (Tables 3,5). Changes to the salinity of groundwater can occur a result of leaching of produced water from surface storage, infiltration from rivers in the case of surface discharges, or leakage of saline water from adjoining aquifers. Field studies of stygofauna distribution suggest that the salinity tolerance of most stygofauna is limited to salinity level (measured by water electrical conductivity) less than 5000 µS/cm (Hancock and Boulton 2008). It might be expected then that changes to salinity of groundwater above 5000 µS/cm may by toxic to stygofauna. However, this threshold does not indicate the sensitivity of stygofauna to changes in salinity; those inhabiting and adapted to relatively fresh groundwater will be potentially sensitive to changes well below this level. It is likely that stygofauna are adapted to local conditions so that changes from background salinity could be deleterious.

The effects of salinity to stygofauna arise through its action first as an osmotic stressor. Second, the dissolved ions that make up saline water can impose a direct toxic action (see below), with some ions being more toxic than others. Consequently, treating salinity without understanding the ionic composition of the salinity is not recommended (Lincoln Smith et al., 2010). Understanding the effects of mining associated salinity requires identification of the ionic composition of the saline water causing the change, and subsequently assessing the direct toxicity of that water to stygofauna.

Stygofauna are most commonly associated with groundwater that has a pH close to neutral, although are found in water with varying pH (Table 1). The pH of groundwater is strongly influenced by the geology, with stygofauna found in carbonate-dominated waters of caves which have a high pH and waters of the fractured sandstones of Sydney which can have an acidic pH close to 5 (Hose unpub. data). Importantly, it is changes to pH away from the typical background level that are likely to be problematic for stygofauna, as they are for other freshwater invertebrates (e.g. Haines 1981, Haddaway et al., 2013) thus requiring understanding the local conditions in order to assess the risks associated with changed in water quality. However, we are not aware of experimental studies of pH changes on stygofauna per se.

5.3.2 Toxicants

Contamination of groundwater by mining and associated activities can occur accidentally by infiltration of contaminants from the surface via spills, lack of containment or leaching from surface storages or overburden and spoil or by contamination from injected materials that contaminate target (i.e., coal seams) and non-target aquifers. There is a large variety of chemicals used and produced in coal mining and CSG process which have the potential to cause changes in water quality (CoA 2014) and consequently effects to stygofauna.

Produced water from coal mining and CSG operations (e.g. Tables 3, 5) has an ionic composition, and hence toxicity that is very different from the sodium chloride or carbonate dominated salinities in most undisturbed aquifers (Mount et al. 1997; CoA 2014). Despite large amounts of data available on the toxicity of saline waters, including produced water, on surface aquatic biota (e.g. Mount et al. 1997; Kefford et al., 2003, Lincoln Smith et al., 2010), there are currently no data available on the toxicity of such waters to stygofauna.

The few toxicity data available for stygofauna are unequivocal in identifying whether they are more sensitive or less sensitive to toxicants than related surface water species. Certainly there is evidence of stygofauna being more sensitive than surface water species (e.g. Hose 2007, Hose et al., in review). Indeed, the physiology of stygofauna can be very different from surface species which means that stygofauna populations are likely to respond differently to toxicants compared to populations of surface taxa (Hose 2005, 2007). At the community level, the truncated diversity of groundwater ecosystems (i.e. the dominance of crustaceans, lack of plants and vertebrates) makes groundwater communities particularly vulnerable to toxicants such as pesticides that target invertebrates but potentially less vulnerable to toxicants such as herbicides compared to surface water communities (Hose 2005). Accordingly, ANZECC and ARMCANZ (2000) state that groundwater ecosystems should be given the highest possible protection, and hence there is a great need for toxicity data for stygofauna for both toxicants and physico-chemical stressors such as pH, nutrients and temperature.

5.4 Altered aquifer properties and water regime

The removal of the aquifer matrix, either through coal extraction (in the case of coal seam aquifers) or the removal of overlying material that is a part of aquifers, is a clear and present threat to stygofauna. Mine dewatering resulting in loss of habitat (described above) and depressurisation all lead to changes in aquifer properties.

Large volumes of water abstracted as part of coal mining and CSG operations (Section 4) can lead to changes in groundwater pressure, but the effects of depressurisation on stygofauna are unknown. Janse (1981) showed that the orientation behaviour of freshwater snails changed under increasing water pressure at ~100 KPa (10 m depth), causing them to move toward the surface to areas of lower pressure. The snails moved downward (deeper) when pressure was subsequently reduced (Janse 1981). Similar patterns of behaviour have been observed in crustaceans (which dominate the stygofauna) and other invertebrates (Lincoln 1971; Morgan 1984) following changes in hydrostatic pressure as little as 3 mbar (Forward and Wellins 1989), which in an unconfined aquifer equates to water level changes of only 0.03 m.

It might be expected that decreasing water pressure associated with dewatering will encourage stygofauna to move deeper in the aquifer, as reported for other crustaceans (Morgan 1984). With nutrient and oxygen concentrations in groundwater typically decreasing with water depth (Pabich et al., 2001), fauna would be moving to potentially poorer quality habitat as a result. In unconfined aquifers, changes in pressure will be associated with changes in water levels, but in confined aquifers in which groundwater may be already under pressure, decreases in pressure may occur without water level changes, and the potential effects of such changes on stygofauna are unknown. Although changes stygofauna are generally less common in confined than unconfined, an overall greater understanding of the effects of changes in aquifer pressure on stygofauna is needed.

A key step in the hydraulic fracturing of coal seams is the injection of fracking fluids under high pressure, creating a spike of pressure in the aquifer. Injection of fracking fluids into deep shale beds in the United States occurs at pressures up to 69,000 KPa (PADEP 2011). While coal seams require lower pressures because of shallower depths and softer geologies, the spike of pressure associated with fluid injection could well exceed the levels fatal for many invertebrates (marine crustacean 1 h LP50 range 12000-89000 KPa, Brown and Thatje 2015).

Infiltrating rainfall or water from creeks or rivers can recharge aquifers and in doing so replenish organic matter and oxygen in the groundwater. Changing surface topography can change the timing, location, and intensity of groundwater recharge and the replenishment of nutrients. Similarly, changes to land surfaces with impervious surfaces or compaction of soil may change infiltration.

Changes to groundwater flow, due either to changes in aquifer pressure, flow direction or level, will influence the transport and distribution of nutrients within the aquifer. Such changes may cause disruption to foodwebs as the baseline concentration of energy in the system may change.

It is uncertain whether the physical processes of mining, including blasting and removal of material causes changes to the physical structure of aquifer matrices in areas beyond the footprint of the development. Changes to the aquifer matrix through sedimentation or disruption of the integrity of strata leading to clogging of interstitial spaces can reduce available habitat for stygofauna (Hancock and Boulton 2005). Habitat change can be caused by clogging of pore spaces by compaction, artificial filling, changes to recharge, fine sediment mobilization, changes in pressure and temperature etc. all of which can occur with mining operations. Subsidence triggered by mining operations can cause major changes in the drainage pattern and local groundwater flow regimes which can affect the stygofauna habitat.

Groundwater abstraction can increase the groundwater flow velocity in the area surrounding the abstraction bore. The effect of the groundwater abstraction would be to remove stygofauna with the groundwater, in the same way that stygofauna are collected through groundwater pumping (e.g. Hancock and Boulton 2009; Hose and Lategan 2012). The effect of the increased flow velocity on stygofauna is unclear and would depend on the magnitude of the increase and the capacity of stygofauna to move within the aquifer under the higher flow regime.

6 Knowledge gaps and research needs

The dearth of knowledge surrounding the diversity, distribution and ecology of stygofauna in Australia creates considerable uncertainty in the assessment of ecological risks associated with coal mining and CSG activities. In the previous sections we have summarised current knowledge of stygofauna diversity and distribution in Australia (section 2), the factors that influence the occurrence of stygofauna (section 3), the changes to the water balance associated with mining operations in key production regions (section 4), and the threats that these changes to water balance, and other aspects of mining operations pose to stygofauna (section 5). In this section we consider the key knowledge gaps that limit the application of robust risk assessments for groundwater ecosystems, and list these as areas for further research.

The sampling and taxonomy of stygofauna remains difficult and unknown

Much of the stygofauna of Australia remain undescribed (Guzik et al., 2010) and the taxonomic expertise to complete this task is limited. A lack of suitable, detailed taxonomy limits the knowledge of the distribution of fauna, particularly the understanding of the spatial extent of a species with respect to a development area, and whether populations of that species are present at sites remote from the development. Molecular (DNA-based) analysis of stygofauna is recommended to address this issue. Further, the results of molecular analyses of stygofauna should be geo-referenced and lodged with an on-line genomics database.

The conclusions drawn from one-off stygofauna surveys are often constrained by the heterogeneous distributions of stygofauna, and usually more than a single survey is recommended to have confidence of the presence or absence of stygofauna in an area. Difficulties in surveying rare fauna in surface waters have prompted the use of molecular analysis of water and sediment which targets latent DNA of those rare species (e.g. Thomsen and Willerslev 2015), i.e. detection of target DNA in these sediments and water can be evidence of presence or absence of fauna in an area, without the need to physically collect those organisms. We are not aware of these approaches being applied in aquifers, but they represent a potential means of improving the accuracy and reliability of surveys and reducing the resources required.

The effects of water level drawdown on stygofauna

While some information is available on the effects of water level drawdown, these studies have to date been laboratory based and over a small-scale with limited, homogeneous matrices. Field-based studies of drawdown are needed, in combination with laboratory studies using matrices of different composition. Such studies should also examine a range of different drawdown rates and also examine the capacity of fauna to return to an area once water levels have been restored.

Key to understanding water-level drawdown is knowing the habitat preferences of stygofauna. Understanding the habitat thresholds for different species in terms of sediment particle size or pore size will inform whether changes in water level do limit habitat availability.

As water levels decline, the tolerance of stygofauna to drying will dictate their survival. Further work on the effects of drying, the suitability of the capillary fringe as habitat, and the mobility of stygofauna to seek saturated areas is needed to predict their response.

Changes to water levels has the capacity to change nutrient availability as nutrients are lost from infiltrating groundwater as it seeps through the unsaturated zone. Research on how nutrient concentrations change with incremental water level changes will indicate the relative importance of this aspect of water level change to ecosystem functioning.

The role of coal seams as stygofauna habitat

There is some evidence that stygofauna occur in coal seams despite the depth and water quality conditions in coal seam aquifers being potentially sub-optimal for stygofauna. Previous studies have only reported a small number of individuals in coal seams, and generally only in those aquifers closely linked alluvium.

Further surveys of coal seams are needed to provide stronger evidence of the association between stygofauna and coal seams. This is clearly relevant to both the coal mining and CSG industries since these are the target aquifers. It is important to establish whether there are species or types of stygofauna specific to these aquifers.

Water quality tolerance of stygofauna – toxicants and physico-chemical stressors

Knowledge of the response of stygofauna to changes in groundwater quality is limited. While there is a large database of effects of water quality changes to surface-dwelling taxa, the applicability of these data as a proxy for stygofauna is uncertain. To address this knowledge gap, there is a need for studies on water quality effects on stygofauna. The results of such studies should be compared to those from surface species to establish whether (and under which situations) the use of toxicity data for surface species can be used.

Priority water quality attributes that require research are;

- **Salinity**, with a particular focus on the ionic composition of the saline waters. There is a need to examine the sodium chloride and carbonate tolerance of stygofauna to understand how natural salinity gradients influence the distribution of stygofauna. There is also a need to examine the toxicity of key ions present in produced water, acknowledging that produced water is a complex mixture which may affect stygofauna if infiltration of produced water into aquifers should occur.
- **Organic compounds** used in coal processing and production. These may include flocculants and oils, and may affect aquifers as a result of infiltration of accidental spillage or leaking from onsite water storages. There are currently no data available on the toxicity of these or similar compounds to stygofauna.

Groundwater foodwebs and cascading effects

As described in this report, mining activities can potentially affect stygofauna directly (such as mortality) or indirectly (such as changes in nutrients/food supply). Changes to nutrients are likely to affect stygofauna by way of changes to microbial assemblages and thus food supply, but the links within groundwater foodwebs are poorly known and largely speculative. There is a need for greater understanding of groundwater foodwebs to understand how changes in one aspect of the ecosystem may cascade and affect other parts, leading to an overall change in ecosystem condition. Studies of carbon and nitrogen isotopes have been used effectively to understand food web interactions in a variety of ecosystems and provide great potential for use in groundwater as well (e.g. Hartland et al., 2011).

Prediction of impacts of mining and CSG induced hydrological changes on stygofauna

Assessment of changes to the groundwater level and flow conditions owing to the development of coal seam gas and coal mining are often conducted on regional scales. Regional scale groundwater models are often used to predict the groundwater pressure and level changes in aquifers associated with mining and CSG production. Such modelling efforts focus on predicting the long term impacts caused by the stresses on the deep aquifer systems and often are limited in scope to explore the spatial and temporal dynamics of water level and flow changes in the alluvial aquifers and spring complexes. Given that stygofauna presence is most likely in shallow aquifer systems, springs and other areas where surface water – groundwater interaction occurs, modelling efforts for the prediction of impacts on stygofauna should focus on accurately predicting the local-scale surface water – groundwater interaction and the spatial and temporal dynamics of the flow and water level changes caused by mining and CSG operations.

Modelling of coal mine effects on stygofauna should consider local changes in groundwater level and connectivity among aquifers above and below the target coal seams. For underground mines, this includes understanding how subsidence might interfere with the hydrology of overlying aquifers. For CSG activities, which occur at greater depths, detailed knowledge on the connectivity among aquifers, their integrity and the risk of fracturing, and the role and transmissivity of aquitards is greatly needed. For both mining and CSG activities, considering the prediction of hydrological variables together with the prediction of ecological response of the fauna to changes in hydrological variables will be key in quantifying the potential impacts.

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