



Independent Expert Scientific Committee
on Coal Seam Gas and Large Coal Mining Development

Information Guidelines Explanatory Note

Assessing groundwater-dependent ecosystems



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The Department acknowledges the traditional owners of country throughout Australia and their continuing connection to land, sea and community. We pay our respects to them and their cultures and to their elders both past and present.

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Images

Front and back cover: Flooded trees at the Hunter Wetlands Centre (Shortlands Wetland)

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Information Guidelines Explanatory Note

Assessing groundwater-dependent ecosystems





Waterbirds

Overview

The role of the IESC

The Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (the IESC) is a statutory body under the *Environment Protection and Biodiversity Conservation Act 1999* (Cth) (EPBC Act).

The IESC's key legislative functions are to:

- provide scientific advice to the Commonwealth Environment Minister and relevant state ministers on coal seam gas (CSG) and large coal mining development proposals that are likely to have a significant impact on water resources;
- provide scientific advice to the Commonwealth Environment Minister [on bioregional assessments \(CoA 2015a\)](#) of areas of CSG and large coal mining development;
- provide scientific advice to the Commonwealth Environment Minister on research priorities and projects;
- collect, analyse, interpret and publish scientific information about the impacts of CSG and large coal mining activities on water resources;
- publish information relating to the development of standards for protecting water resources from the impacts of CSG and large coal mining development and;
- provide scientific advice on other matters in response to a request from the Commonwealth or relevant state ministers.

Further information on the IESC's role is on the [IESC website](#) (CoA 2015b).

The purpose of the Explanatory Notes

One of the IESC's key legislative functions is to provide scientific advice to the Commonwealth Environment Minister and relevant state ministers in relation to coal seam gas and large coal mining development proposals that are likely to have a significant impact on water resources.

The IESC outlines its specific information requirements in the IESC Information Guidelines (IESC 2018). This information and data is requested to enable the Committee to formulate robust scientific advice for regulators on the potential water-related impacts from coal seam gas and large coal mining developments.

For some topics, Explanatory Notes have been written to supplement the IESC Information Guidelines, giving more detailed guidance to help the coal seam gas and large coal mining industry prepare environmental impact assessments. These topics are chosen based on the IESC's experience of providing advice on over 100 development proposals.

Explanatory Notes are intended to assist proponents in preparing environmental impact assessments. They provide tailored guidance and describe up-to-date robust scientific methodologies and tools for specific components of environmental impact assessments on coal seam gas and large coal mining developments. Case studies and practical examples of how to present certain information are also discussed.

Explanatory Notes provide guidance rather than mandatory requirements and proponents are encouraged to refer to issues of relevance to their particular project.

The tools and methods identified in this document are reviewed to help proponents understand the range of available approaches to assessing the potential risks to groundwater-dependent ecosystems from coal seam gas and large coal mine development and are designed to be utilised across a range of regulatory regimes. This Explanatory Note cannot address all risks to groundwater-dependent ecosystems and proponents are encouraged to refer to specialised literature and engage with their relevant state regulators.

The IESC recognises that approaches, methods, tools and software will continue to develop. The Information Guidelines and Explanatory Notes will be reviewed and updated as necessary to reflect these advances.

Legislative context

The *Environment Protection and Biodiversity Conservation Act 1999* (Cth) (EPBC Act) states that water resources in relation to coal seam gas and large coal mining developments are a matter of national environmental significance. This is known as the ‘water trigger’ and means that coal seam gas and large coal mining developments require Australian Government assessment and approval if they are likely to have a significant impact on a water resource. All groundwater-dependent ecosystems, even those that use groundwater occasionally, are considered as a water resource and must be assessed in an environmental impact assessment.

A water resource is defined by the *Water Act 2007* (Cth) (CoA 2007) as: ‘(i) surface water or groundwater; or (ii) a water course, lake, wetland or aquifer (whether or not it currently has water in it); and includes all aspects of the water resource (including water, organisms and other components and ecosystems that contribute to the physical state and environmental value of the resource)’.

Australian and state regulators who are signatories to the National Partnership Agreement seek the IESC’s advice under the *EPBC Act 1999* (Cth) at appropriate stages of the approvals process for a coal seam gas or large coal mining development that is likely to have a significant impact on water resources. The regulator determines what is considered to be a significant impact based on the Significant Impact Guidelines 1.3 (CoA 2013a).

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Executive summary

Groundwater-dependent ecosystems (GDEs) are ecosystems whose species and ecological processes rely on groundwater, either entirely or intermittently. Coal seam gas (CSG) and large coal mining (LCM) developments are important to Australia's economy yet pose potential risks to GDEs by altering groundwater regimes, groundwater quality or both.

This Explanatory Note describes the information required and tools available to assess the potential risks to GDEs from CSG and LCM development. It aims to help proponents prepare environmental impact assessments with sections specifically devoted to GDEs, and should be used in conjunction with the Independent Expert Scientific Committee's [*Information Guidelines for Proponents Preparing Coal Seam Gas and Large Coal Mining Development Proposals*](#) (IESC 2018) and relevant state guidelines (e.g. the Queensland Government's [*Information guideline for an environmental impact statement*](#) (2016) see EIS specific content for groundwater dependent ecosystems).

GDEs can be classified into three broad types:

- aquifer and cave ecosystems (subterranean GDEs)
- ecosystems dependent on the surface expression of groundwater (aquatic GDEs, including river baseflow systems, springs and swamps)
- ecosystems dependent on the subsurface presence of groundwater (terrestrial GDEs, including some riparian vegetation communities).

All three types of GDEs are likely to occur in areas where CSG and LCM developments are planned. They often support locally high biodiversity and provide valuable ecosystem services (e.g. nutrient cycling, groundwater filtration). Consequently, CSG and LCM developments should be designed to avoid or minimise impacts on GDEs, especially those deemed of high value.

In this Explanatory Note, a logical sequence of steps is proposed to help proponents prepare an appropriate environmental impact assessment for GDEs. These steps are:

1. Define the likely area of impact of the proposed project (including the disturbance footprint of surface infrastructure and the extent of groundwater depressurisation).
2. Use a desktop assessment of reports, maps, databases and other resources to list potential GDEs in the project impact area, and make a preliminary assessment of possible risks to these GDEs from each stage of the proposed project.
3. Apply conceptual models and other tools described in the Explanatory Note to assess the level of groundwater dependence for each GDE and the likely pathways (e.g. disruption of groundwater connections, reduction in groundwater quality) by which the project might impact on GDEs.
4. Determine baseline ecological condition and ecosystem value of each GDE, including GDEs to be used as control or reference sites to assess changes over time that are not associated with the project. Field surveys will be needed to obtain site-specific data that can be supplemented with information from remote sensing and other techniques.
5. Conduct a systematic risk assessment to estimate the likelihood and consequences of potential impacts on GDEs arising from the proposed project, including cumulative impacts. Tools such as the GDE Risk Matrix and the associated matrix of management options are useful here.
6. Using the risk assessment and other information from the preceding steps, specify options to avoid or mitigate impacts on GDEs and establish a monitoring plan to assess the effectiveness of mitigation. This monitoring plan

should include sampling variables that will provide ‘early warning’ of impending impacts on GDEs so that appropriate action can be taken to avoid or minimise harm.

The Explanatory Note includes a series of recommendations. The key ones are:

- Proponents should consider **all** GDEs that may be affected by the project. This includes GDEs that are only partially or occasionally dependent on groundwater as well as those that do not support any species listed in national or state legislation as threatened or endangered.
- Risk assessments will need data from desktop analyses and field surveys by qualified specialists who use appropriate methods, models and survey designs that include adequate reference sites and sufficient replication in space and time. Sampling should be more intensive in GDEs that are deemed of higher value (e.g. harbour rare or threatened species, provide valuable ecosystem services) and/or face greater risk of impacts. Ideally, GDE sampling sites should be located near groundwater monitoring bores so that concurrent hydrogeological and water quality data can be collected.
- Impacts on GDEs of particularly high value should be avoided. Where impacts cannot be avoided, mitigation strategies to minimise impacts are required and should be specified before operations commence. The choice of mitigation measures and their likely effectiveness should be justified in the environmental impact assessment. Targeted monitoring will be needed to confirm the effectiveness of these mitigation strategies, and alternative options proposed in case the strategies are ineffective.

1 Background

1.1 Purpose

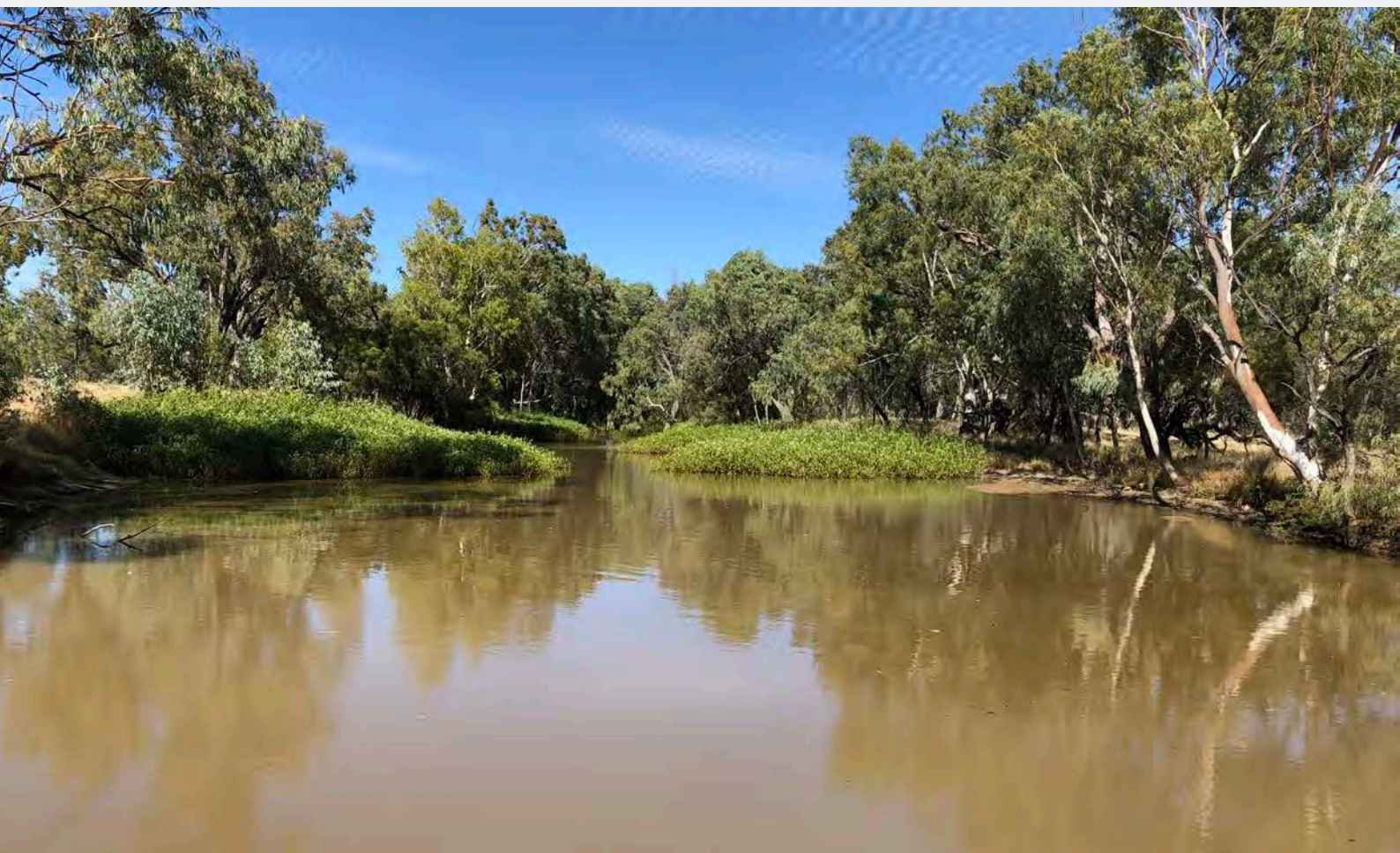
The purpose of this Explanatory Note is to describe the information required and tools available to assess the potential risks to groundwater-dependent ecosystems (GDEs) from coal seam gas (CSG) and large coal mining (LCM) developments. The refinement of policy and assessment protocols over the past decade has resulted in some inconsistencies in how impacts on GDEs are considered. This Explanatory Note outlines a logical sequence of activities to help a proponent who is required to prepare an environmental impact assessment (EIA) with a section specifically devoted to GDEs. These activities include:

1. identifying potential GDEs in the project impact area, coupled with a preliminary assessment of risks
2. assessing the level of GDE groundwater dependence and likely pathways of cause and effect of possible impacts
3. identifying the baseline ecological condition and ecosystem value of each GDE, including GDEs to be used as reference sites to assess changes over time that are not associated with the project
4. assessing the likelihood, frequency and magnitude of potential impacts on GDEs and characterising the risks related to the CSG or LCM operations
5. prioritising options to avoid or mitigate impacts on GDEs and establishing a monitoring plan to assess the effectiveness of mitigation.

Tools and methods for GDE assessments are reviewed to help proponents choose the most effective approaches. Where risks are higher and/or GDEs are of high value, more effort should be made to prevent decline in GDE condition due to potential impacts from CSG or LCM developments.



Moses Spring



Moray Anabranh, Queensland

2 Groundwater-dependent ecosystems

2.1 Groundwater and groundwater-dependent ecosystems

GDEs are complex and dynamic natural systems, defined by Richardson et al. (2011a) as:

ecosystems that require access to groundwater to meet all or some of their water requirements on a permanent or intermittent basis, so as to maintain their communities of plants and animals, ecosystem processes and ecosystem services.

The presence of diverse GDEs across a landscape is driven by temporal and spatial groundwater flow variability that is related to geology, climate and land use.

Groundwater is defined by the Water Act (CoA 2007) as:

- (a) water occurring naturally below ground level (whether in an aquifer or otherwise); or*
(b) water occurring at a place below ground that has been pumped, diverted or released to that place for the purpose of being stored there;
but does not include water held in underground tanks, pipes or other works.

For this Explanatory Note, groundwater includes water in the soil capillary zone (capillary fringe) but not the water held in the soil above this zone in the unsaturated or vadose zone (Figure 1). Within the saturated zone, pores are filled with water, whereas the capillary fringe and unsaturated zone increasingly have pores containing air as well as water (Figure 1). Water in caves that is sourced from groundwater is also included as groundwater, as are perched aquifers in the unsaturated zone (Figure 1).

GDEs have groundwater-related ecological water requirements associated with both quantity and quality (e.g. Kath et al. 2014, Boulton and Hancock 2006, Eamus et al. 2006). Quantity refers to aspects of the groundwater regime, such as the volumes, pressures, timing and variability of groundwater supply, that govern the location, timing, frequency and duration of groundwater connection to GDEs. Quality refers to physical and chemical characteristics of water, such as temperature, salinity, and concentrations of nutrients and dissolved organic matter. When investigating and monitoring GDEs, it is essential to understand the underlying geology and related aquifer and flow systems, trends in groundwater level, spatial and temporal variability in the GDE–groundwater connection, and ecosystem composition (e.g. vegetation types, stygofauna species). This is particularly important when GDEs are relying on perched (Figure 1) or highly localised groundwater systems that may not be adequately considered in regional groundwater models, and where existing data are limited.

GDEs occur in coastal and inland regions (Figure 2), and often interact with each other across the landscape. In this Explanatory Note, they have been classified into three broad types (based on Serov and Kuginis 2017, Richardson et al. 2011a and Eamus et al. 2006):

- aquifer and cave ecosystems (subterranean GDEs)
- ecosystems dependent on the surface expression of groundwater (aquatic GDEs)
 - river baseflow systems—aquatic and riparian ecosystems that exist in or adjacent to streams (including the hyporheic zone) which are fed by groundwater
 - wetlands—aquatic communities and fringing vegetation dependent on groundwater-fed lakes and wetlands. These include palustrine and lacustrine wetlands that receive groundwater discharge, and can include spring and swamp ecosystems

- ecosystems that rely on submarine discharge of groundwater for nutrients and/or physico-chemical attributes
- ecosystems dependent on the subsurface presence of groundwater (terrestrial GDEs).

The terms subterranean, aquatic and terrestrial GDEs are consistent with the classification system used in the [GDE Atlas](#) (CoA 2018a, Doody et al. 2017), where these GDE types are discussed in greater detail.

The Australian National Aquatic Ecosystem (ANAE) classification scheme (AETG 2012a) can also aid with classifying aquatic GDEs using scale, hydrological class (e.g. surface water, subterranean), system (e.g. floodplain in the surface water class) and habitat (e.g. water type, vegetation).

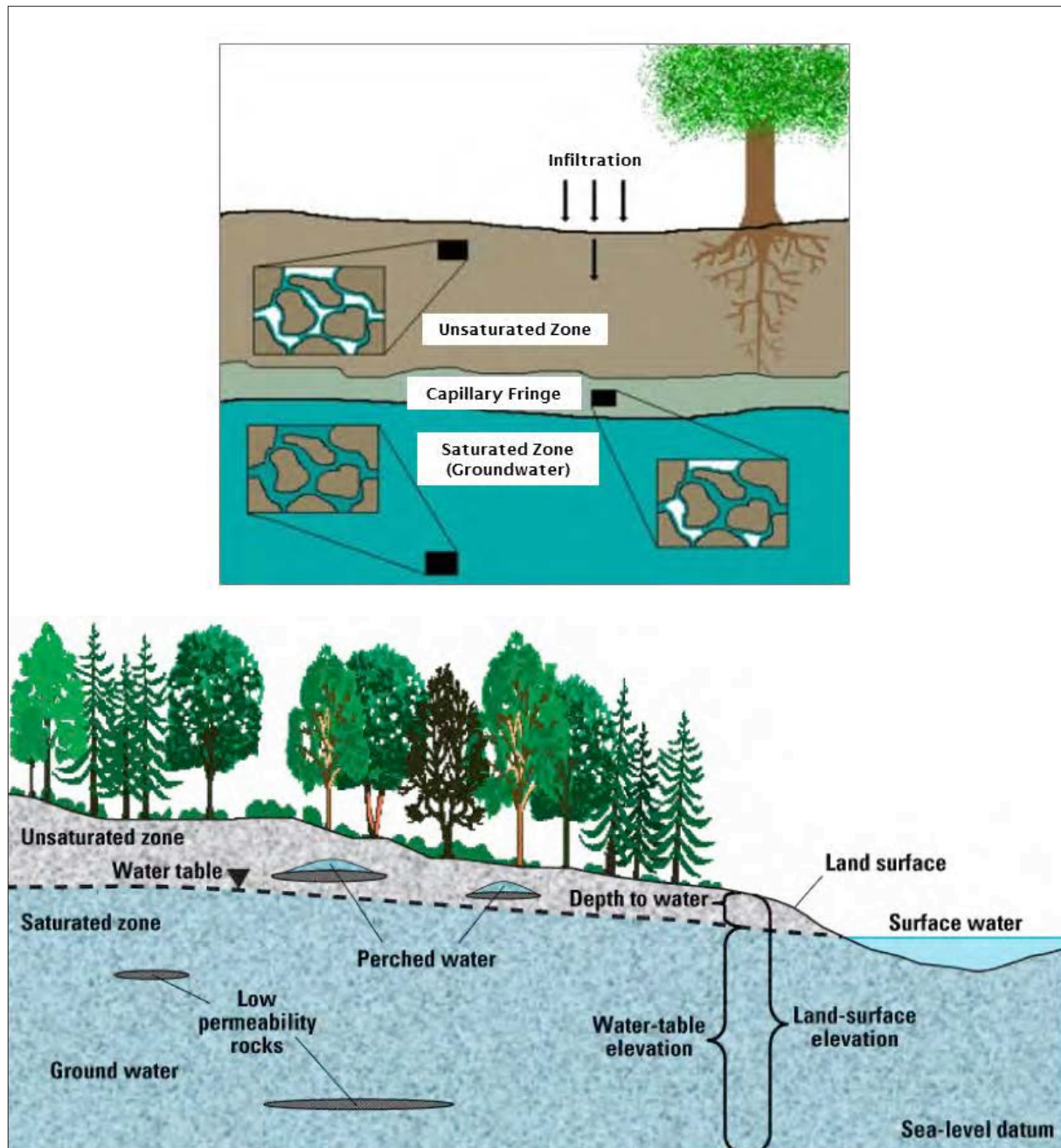


Figure 1. Top: difference in saturation among particles in the unsaturated zone, capillary fringe and saturated zone (Michigan State University 2018); bottom: perched aquifers in the unsaturated zone, which can be an important water source for some GDEs (Snyder 2008)

For in-depth tutorials on GDEs and wetlands, refer to the Queensland Government (2014a) education modules ([WetlandInfo](#)). These provide details on the different types of GDEs, their value and how they function. Refer to the [GDE Toolbox Pt 1](#) (Richardson et al. 2011a) for detailed descriptions of GDE types and case studies to demonstrate groundwater dependence within each type.

2.1.1 Examples of GDEs

Many GDEs are prominent in the landscape. They include groundwater-dependent plant communities, groundwater-fed lakes and swamps, and river baseflow systems along with their hyporheic and riparian zones. However, some GDEs are less obvious.

Stygofauna are often overlooked when considering GDEs. However, as subterranean animals that live in groundwater systems, they are often critical components of aquifer ecosystems that are themselves entirely dependent on groundwater. They inhabit the interstitial spaces of sedimentary aquifers, the cavities of karstic aquifers and the fissures of rock aquifers. The occurrence of stygofauna in an aquifer can be a useful indicator that the aquifer supports a broader ecological community that includes components such as bacteria and the roots of phreatophytic trees.

Other less known GDEs include vegetation communities on coastal sand dunes ([WetlandInfo](#), Queensland Government 2013a), springs and mound springs such as those in the Great Artesian Basin (Ponder 1986), mangroves (Lagomasino et al. 2015), hanging swamps and montane bogs and fens (Baird and Benson 2018).

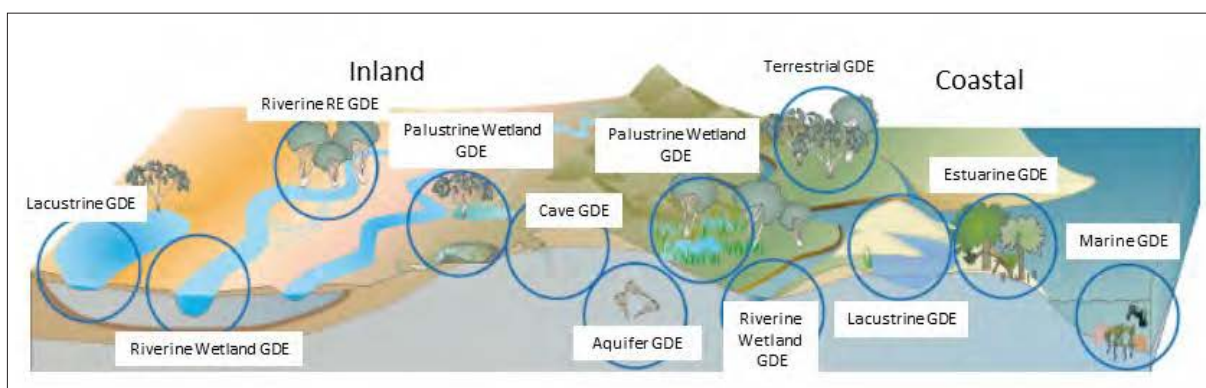


Figure 2. GDE types described in section 2.1 ([WetlandInfo](#), Queensland Government 2014a)

RECOMMENDATION:

Several helpful publications are mentioned throughout this Explanatory Note to aid proponents. Their use is recommended. Where possible, hyperlinks are given to open-access reports and relevant websites. However, some references include scientific journal papers that may need to be purchased at a low, one-off cost.

2.2 GDE values and ecosystem services

Definitions of ecosystem values and services are inconsistent between policies and jurisdictions. Proponents will need to adhere to what is meant by these terms in the policies and jurisdictions applicable to their sites of interest.

With respect to GDEs, the term ‘ecosystem value’ has been used to mean two distinctly different things: (i) the natural ecological processes occurring within ecosystems and the biodiversity of these systems (Richardson et al. 2011a), and (ii) the worth of the ecosystem so that it can be compared to other ecosystems and prioritised for conservation (Serov et al. 2012). The second definition is the more appropriate one because it specifies the **value** of the biodiversity and ecological processes that underpin the provision of ecosystem services by an ecosystem.

Ecosystem **value** differs from ecosystem **condition**. Ecosystem value is where an ecosystem is given a monetary or non-monetary value by society. A GDE may be deemed valuable if it is close to its pristine condition, contains threatened or endemic species, performs a critical ecosystem service and/or has some other aspect that is treasured by society. Ecological condition is the state of a GDE regardless of whether it contains any valuable assets (although GDEs that are in good ecological condition are often valued more highly than those that are not).

Assigning value/rank to prioritise GDEs is practical for management purposes, and forms part of state-based assessment criteria in Queensland (Department of Environment and Heritage Protection 2015) and New South Wales (AETG 2012b, Serov et al. 2012). A value can also be assigned through a combination of community consultation, expert knowledge and economic assessment (amenity, tourism, conservation, economic productivity) (Eamus et al. 2006). However, the intrinsic value of all GDEs in maintaining biodiversity and ecosystem function should be recognised, understanding there are still significant knowledge gaps about their vulnerability and resilience. Furthermore, it is critical that assessment of ecological water requirements is based on scientific information and is not influenced by management objectives or changes in value or priority (Richardson et al. 2011a).

Assigning ecosystem value based on expert knowledge requires information on biodiversity, rare and endangered species listed as threatened under national or state legislation, uniqueness (endemic species), ecological condition, services provided, the nature of groundwater dependence (e.g. obligate/facultative GDEs or frequency of dependence) and other special features (e.g. cultural or geological significance). Under Queensland state guidelines, environmental value is considered a function of the health or biodiversity of an ecosystem, the ecosystem’s natural state and biological integrity, the presence of unique features (which includes species and communities, as well as hydrological or geological features) and/or the natural interaction between ecosystems (Department of Environment and Heritage Protection 2015). In New South Wales, high ecological value aquatic ecosystems (HEVAE) are identified based on an understanding of diversity, distinctiveness, vital habitat, naturalness and representativeness (AETG 2012b, and section 6.6 below).



A Glossy Black Cockatoo

The term ‘ecosystem services’ refers to the benefits that people obtain from ecosystems. GDEs provide many such services (Griebler and Avramov 2015), and this aspect of GDEs should also be considered when determining their value. The range of ecosystem services provided by GDEs is yet to be fully realised, as this area of research is still developing. Noting that all GDEs have the potential to support endangered and threatened species and be biodiversity hotspots (Griebler and Avramov 2015, Mitsch et al. 2015), ecosystem services provided by one or more types of GDEs include:

- water purification and storage in good quality for decades to centuries
- active biodegradation of anthropogenic contaminants and inactivation and elimination of pathogens
- carbon sequestration
- nutrient cycling (e.g. transformation of nutrients in hyporheic zones and subsequent discharge to surface waters)
- provision of habitat for animals (e.g. timing of water availability, temperature regulation)
- timber or peat
- mitigation of flood (e.g. aquifers receive and retard large volumes of surface water), drought (e.g. groundwater discharge sustains surface waters) and storm damage (e.g. wetlands receive and retard large volumes of surface water)
- soil development
- hydraulic redistribution of deep water to shallow soil
- provision of pollinator habitat
- prevention of soil erosion
- support for recreational, educational and cultural uses.

2.3 Threats to GDEs from CSG and LCM activities

As GDEs rely on groundwater to sustain all or some of their water requirements, particularly in arid and semi-arid climates, they are at risk whenever there is a change in groundwater quantity and/or quality that exceeds natural background levels of variation.

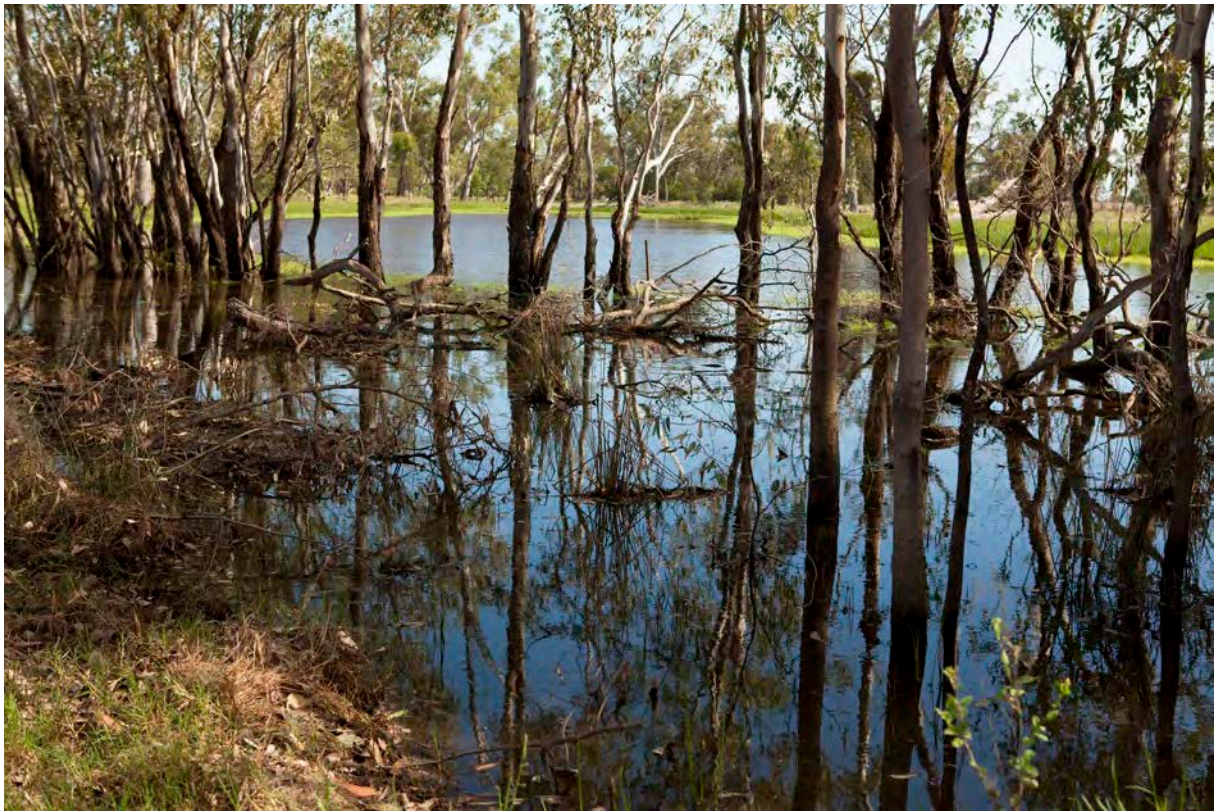
GDEs are vulnerable to CSG and LCM developments because of hydrological, hydrogeological and geological links between the development and adjacent GDEs. Surface water is also an essential component of water requirements for many GDEs, and any surface water regulation and/or change to its water quality can have a severe impact on the condition of GDEs.

Aquifers are the connecting features, and impacts from developments can be transferred to GDEs through changes in the structure of the aquifer and/or the water it contains. As a result, subterranean, aquatic and terrestrial GDEs are at risk of altered ecological condition. Estuarine and marine GDEs such as submarine discharge springs are not discussed in this Explanatory Note.

Currently many environmental impact assessments of CSG and LCM projects are limited to GDEs that rely on groundwater access on a permanent or near-permanent basis (such as spring communities), overlooking GDEs that use water episodically or opportunistically. Additionally, only protected or threatened ecological communities that have been listed tend to be considered. However, the legislative intent of the ‘water trigger’ is that potential impacts from CSG and LCM on all GDEs should be assessed. The next chapter discusses potential threats and impacts in more detail, along with their likely pathways of effect.

RECOMMENDATION:

All recommendations in this Explanatory Note apply to both greenfield projects and expansions of existing projects. Proponents need to consider all GDEs that are potentially affected by the project, including GDEs that are only partially or occasionally dependent on groundwater and/or do not support any listed species. Before development starts, all GDEs that are potentially impacted by the project or could be used as reference sites should be mapped and baseline data collected on their ecological condition. These baseline data, together with an assessment of each GDE's ecosystem value, can be used to prioritise GDEs for management.



Minor flooding occurring in a creek flowing through the Brigalow Nature Reserve in Goondiwindi

3 Potential impacts of CSG and LCM development on GDEs

Groundwater dependence of ecosystems is extremely variable through both space and time. Dependence by their biota can be continuous (e.g. stygofauna living in aquifers), episodic (e.g. riparian trees that use groundwater when soil moisture or surface water is not available) or strategically cued to critical life stages (e.g. fish using warm upwelling groundwater for spawning). In addition, the proportion of groundwater needed to sustain the ecosystem differs with GDE type. For example, aquifer ecosystems are 100% dependent on groundwater, whereas groundwater contributions in river baseflow systems may be volumetrically low compared to overland flow.

Although water is one of the main factors required by GDEs to function, it is often the accompanying nutrients, organic matter, dissolved minerals or other physico-chemical properties that are exploited by groundwater-dependent plants and animals. Such requirements for other groundwater components potentially make substitution with surface water (or water treated with reverse osmosis) an inadequate mitigation option for some GDEs.

Impacts of CSG and LCM activities occur over spatial scales that may extend beyond the immediate surface footprint of a project, and through temporal scales reaching decades or centuries beyond the period of operation. There are often long lag times between an action occurring and symptoms appearing in an ecosystem. This variability, coupled with the varying temporal and spatial nature of groundwater dependence, makes assessment of longer term impacts difficult. Assessments must use the best available data and leading practice to forecast potential impacts, focusing on both the period of CSG or LCM operations and beyond to a point when groundwater levels are modelled to return to pre-operation levels.

3.1 Causal impact pathways

Many activities associated with CSG and LCM exploration, development and operations have the potential to impact GDEs (App Table 1). The magnitudes and types of impact expected for a GDE are determined largely by the connection between the GDE and the CSG or LCM activities. This connection is referred to as the causal pathway of connection (a logical chain of events). It consists of four main conduits (Figure 3, defined in greater detail in Henderson et al. 2016):

- subsurface depressurisation and dewatering (A in Figure 3)
- subsurface physical flow paths (B in Figure 3)
- surface water drainage (C in Figure 3)
- operational water management (D in Figure 3).

Once the causal pathway has been established, each mechanism causing change (i.e. the impacting factor) needs to be considered. These mechanisms can be grouped into activities that:

- alter the hydrological connection between a GDE and the aquifer it depends on
- reduce groundwater quality
- cause direct disturbance to the ecosystem, such as the removal of groundwater-dependent vegetation or excavation of aquifer material
- result from cumulative impacts from multiple CSG and LCM operations and other activities, including reduced groundwater recharge.

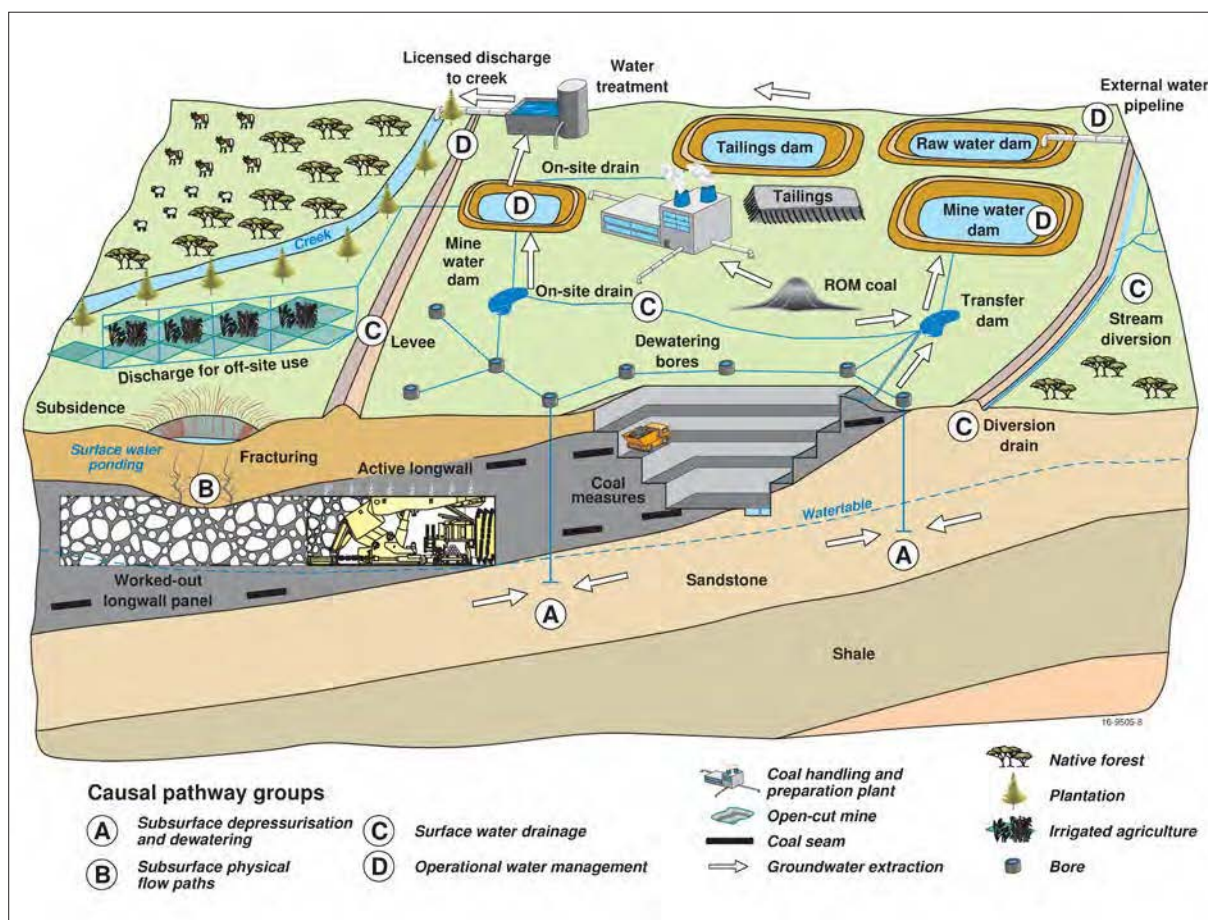


Figure 3. Causal pathways of LCM development (Herron et al. 2018). Some of these pathways also apply to CSG developments

Aquifer dewatering is a causal pathway that results in potentially widespread and severe impacts on GDEs (Figure 4) and is used here to demonstrate the concept of causal pathways. Details of the other causal pathways listed above are given in Henderson et al. (2016).

One impact of dewatering is the lowering of the groundwater level around groundwater-dependent terrestrial vegetation (terrestrial GDEs), which reduces the availability of water to established vegetation root networks, impairing the condition of the vegetation community. The response of vegetation to water stress may take years to become obvious, although some vegetation communities die back almost immediately (e.g. Banksia at Gngangara Mound—see CASE STUDY 5). Another impact is the lowering of the groundwater level in unconfined aquifers or depressurisation of confined aquifers that supply water to springs. This reduces groundwater discharge to the springs and the surrounding dependent vegetation (aquatic GDEs), reducing spring flow and affecting fringing vegetation condition.

A third impact is the lowering of groundwater levels near rivers, which can reduce groundwater discharge to rivers, changing surface water quality (e.g. temperature, salinity). There may also be reductions in surface water flow, particularly during low flow conditions. Cease-to-flow events may become more frequent than under natural conditions. When a permanently flowing river ceases to flow, this drastically changes its aquatic ecosystem and may lead to loss of some biota. Lowering groundwater levels near rivers also reduces the availability of water to surrounding groundwater-dependent riparian vegetation (aquatic GDEs) and may put these under water stress, impairing riparian vegetation condition (Doody et al. 2009). The direction of groundwater – surface water exchange can be reversed by lowering groundwater levels near rivers, changing the river from gaining to losing. This further

reduces surface water flow and changes water quality, which may make the river unsuitable habitat for native aquatic fauna but favourable habitat for exotic species.

The impacts of lowering groundwater levels near swamps and other standing-water wetlands resemble those listed above for rivers. However, there are several additional processes that may be disrupted by drawdown and loss of surface water which should be considered, such as potential exposure of acid sulfate soils resulting in water acidification (e.g. Sommer and Horwitz 2009) and reduced production of peat (e.g. Armandine Les Landes et al. 2014).

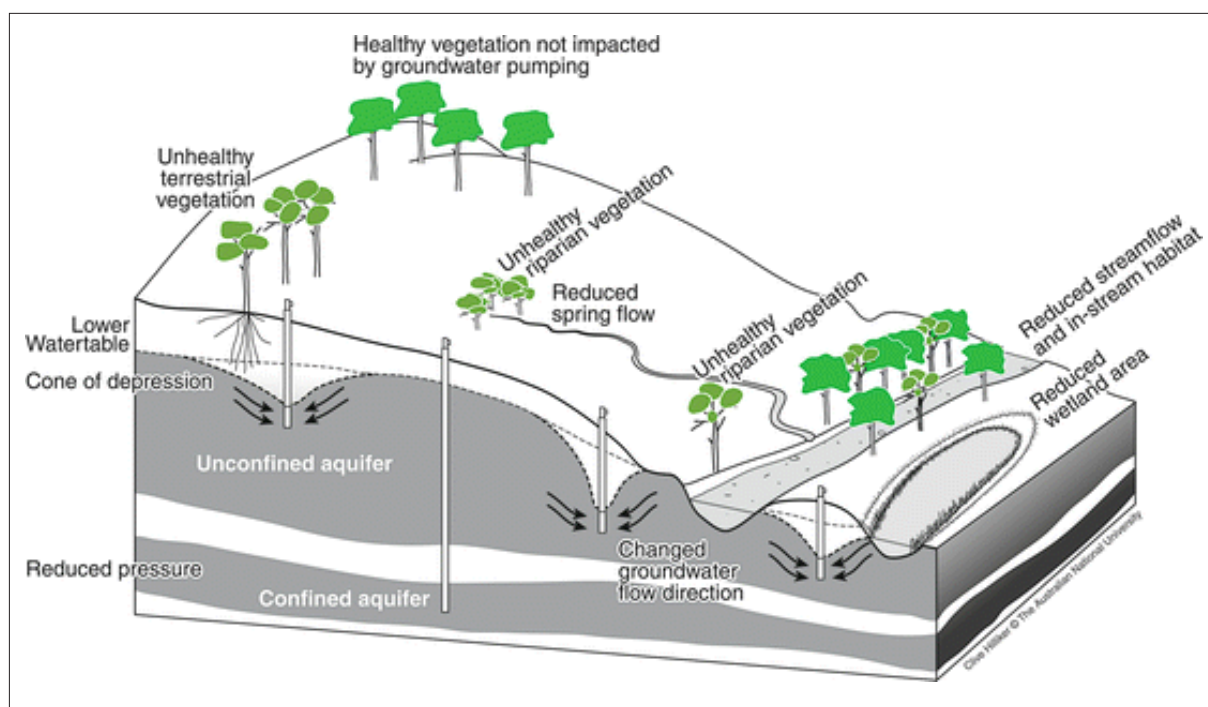


Figure 4. Some potential impacts on GDEs from aquifer dewatering (Causal pathway group A in Figure 3) (Eamus et al. 2016)

3.1.1 Altered connectivity

GDEs can decline in condition when the ecosystem becomes hydrologically isolated from the aquifer that it depends on or when it receives more groundwater than required (e.g. when an ephemeral stream becomes permanent). The change in groundwater connectivity may be permanent or temporary, but its occurrence at a critical point in the life history of a key organism can have a negative impact on GDE function. Frequent or sustained disconnection can irreversibly damage GDEs. For example, Kath et al. (2014) demonstrated a relationship between extended periods of groundwater disconnection and canopy condition decline, including instances of severe dieback in *Eucalyptus camaldulensis* (River Red Gum) and *E. populnea* (Poplar Box).

It is also important to consider changes in connectivity between aquifers and their recharge areas as there may be a gradual decline in the water table and altered groundwater physico-chemistry if connectivity is impaired. Alternatively, the water table may rise if connectivity is enhanced by activities that increase hydraulic conductivity, and this may impact on GDEs through, for example, waterlogging (terrestrial GDEs) or altered flow regimes (river baseflow GDEs). Factors on the land surface that alter groundwater recharge patterns include river diversion, construction of surface infrastructure, and changes in topography as mine pits progress or longwall panels collapse

(see CASE STUDY 1). As many GDEs also depend on surface water for part of the time, their biodiversity and ecological processes may be impacted if surface water flow and volume change.

CSG and LCM activities that can interrupt connectivity include:

- dewatering unconfined aquifers, which can lower the water table to a depth that is inaccessible to tree roots, river baseflow systems and wetlands. Aquifer dewatering can also alter the volume of saturated sediments available for habitation by stygofauna communities and lower the water table below a threshold where surface-derived organic matter and oxygen become limiting
- depressurisation of confined aquifers. Removing water and gas from confined aquifers may lead to a loss in hydraulic pressure, causing a reduction in the amount of water discharging to the surface at springs or into rivers
- changes to aquifer recharge patterns, potentially impacting hotspots of stygofauna diversity that occur in recharge areas. Reducing recharge, either through paving or compacting the land surface or through diverting run-off and river water, can impact aquifer ecosystems, reduce water levels in aquatic GDEs and isolate terrestrial GDEs. Changing recharge, through removal of surface strata (e.g. mining or earthworks) or clearing vegetation, can also impact GDEs as described earlier
- changes to subsurface flow paths (by pumping water from mines and production bores or when groundwater drains through the walls and floors of mines), which can alter the direction and velocity of groundwater flow. This can result in water moving away from GDEs and towards the extraction point
- fracturing of confining layers between aquifers. This may occur when less porous layers of rock that separate aquifers are penetrated or damaged during mining or drilling, or following longwall subsidence. This can redirect groundwater flows away from GDEs.



Upper Georges River, NSW
© Martin Krogh

CASE STUDY 1:

Impacts of longwall mining on groundwater-dependent upland peat swamps in the Sydney Basin

Subsidence impacts observed in multiple upland peat swamps in the Sydney Basin are detailed in CoA (2014). Key findings include:

- longwall mining beneath upland peat swamps has fractured the underlying bedrock and altered swamp water balances. The only strategy that has been proven to effectively mitigate the impacts of longwall mining is to change the mine layout to avoid upland peat swamps
- remediation strategies in regions affected by longwall mining are primarily designed to restore the hydrological regime. Remediation strategies have aimed to seal fractures on cracked stream beds but have not attempted to repair fractures beneath peat sediments. There were no examples of upland peat swamps impacted by longwall mining that were successfully remediated
- remediation to prevent vertical seepage beneath upland peat swamps was not attempted because proposed remediation techniques have not been proven and require destruction of the surface environment.

One example of a GDE impacted by longwall mining is the East Wolgan Swamp. The East Wolgan Swamp was undermined at a depth of 330 m in March 2006. By November 2006, rapid declines in groundwater level were observed due to interrupted connectivity. Saline mine effluent was discharged to the swamp for three years (commencing in 2008). In November 2009, it was discovered that water was entering a cavity and not resurfacing, and that flow (pre-mining: 1 ML/day) from the swamp had ceased. In 2011, an 'enforceable undertaking' was issued following an alleged breach of the EPBC Act. In 2012, remediation and restoration works were proposed but by this time there was already extensive degradation of peaty swamp soils, channelling, dieback of swamp vegetation and invasion by exotic species.

3.1.2 Reduced groundwater quality

A potential threat to groundwater quality is the leakage of groundwater from saline aquifers into fresh aquifers linked to GDEs. This can occur if CSG or LCM activities cause fracturing of less permeable rock layers (e.g. aquitards), either during drilling and mining or afterwards from subsidence. This can allow groundwater from aquifers with poorer water quality to enter aquifers which support GDEs. Another potential pathway for saline groundwater to impact GDEs occurs when saline water is pumped from a coal seam to allow resource extraction and is then stored in dams before treatment and disposal. Storage dams have the potential to leak, allowing water to escape into the underlying groundwater system or into surface waterways downslope. Storage dams also have the potential to overflow if there is a large rainfall event, releasing water into the environment.

Saline water from coal seams, including water extracted during CSG operations, is often treated with reverse osmosis to produce fresh water and a brine solution. Options for disposing of the brine solution are limited and mostly rely on transportation off-site. Before disposal, the risk of leakage or overflow from storage dams must be considered. Treated fresh water makes up the largest volume of the two products of reverse osmosis. Although it is more benign than the concentrated brine solution, there are still potential contaminant risks because treated water can be devoid of ions or elements, such as calcium and bromide, which are essential for biological processes.

Pits that extend below the water table and are left open after the completion of mining can fill with groundwater. Evapoconcentration and hydrogeochemical processes can cause the pit water to become acidic, with higher concentrations of dissolved metals, metalloids and sulfates compared to groundwater inflows (Bowell 2002). Seepage of water from the pit and into an aquifer could have long-term impacts on associated GDEs.

Other pollutants can have localised impacts if they enter groundwater flow paths. These pollutants include biocides used in water treatment or to prevent clogging of pipes and bores; drilling muds and lubricating fluids used in bore construction; petrochemicals stored on-site; sewage or waste water from mining or CSG extraction camps; and other toxicants. These impacts can generally be minimised or prevented by proper construction and maintenance of equipment.

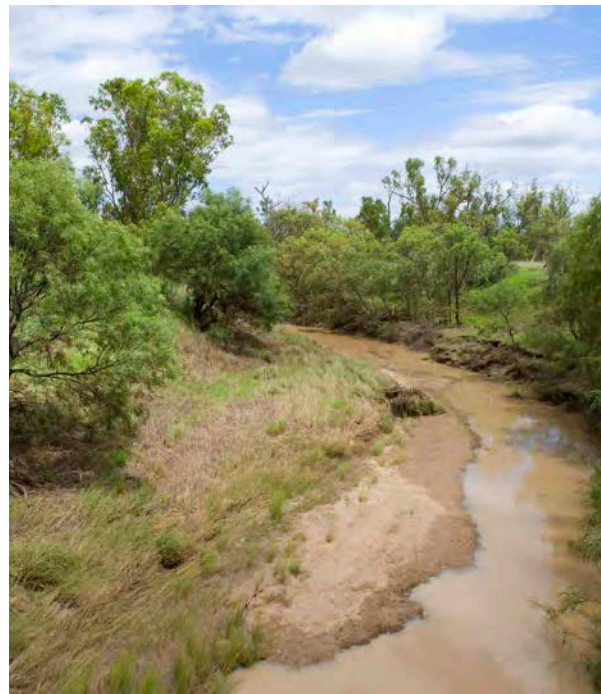
Another potential source of contamination to shallow groundwater is leachate from stockpiled coal and waste rock. State-based legislative requirements are designed to protect surface waterways and aquifers from contamination with leachate by specifying where stockpiles can occur and how they are bunded and managed (e.g. South Australian Environment Protection Authority 2017).

3.1.3 Direct disturbance

Risk assessments must consider activities that are not linked to groundwater but can also potentially impact GDEs. These include vegetation clearing, river realignment and wetland draining. Often the impacts from these will be considered in other EIA sections and not considered in the context of GDEs. This can lead to oversights in the mitigation or management of risks. For example, if terrestrial GDEs are cleared and offset against a similar vegetation type that is not groundwater dependent, then offsetting protects neither the GDE nor the crucial role the vegetation plays in providing organic matter (via roots) to aquifer food webs. Similarly, river diversions around a proposed mine pit may consist of an engineered channel that adequately connects upstream and downstream reaches, but does not mitigate the consequences of lost aquifer connectivity.



Riparian vegetation in the Galilee Basin



Brookstead in the Border Rivers-Condamine catchment area

3.1.4 Cumulative impacts

Cumulative impacts on GDEs need to be considered if there is a possible compounding effect from the proposed CSG or LCM activity with adjacent activities. This occurs when, for example, groundwater drawdown from one project intersects the cone of depression (extent of groundwater drawdown) from one or more nearby projects and amplifies drawdown near a GDE. Considering the potential impacts of two or more mines or CSG projects can be extremely difficult, particularly when they are at different stages of development and each project operator is considering several possible extraction options. These difficulties are exacerbated if the operators involved are hesitant to share monitoring data or development plans with each other, which can occur when there are perceived commercial confidentiality issues.

Plans for expansion should assess the cumulative impacts of the project as a whole, not just the expansion area. This can be achieved using regional groundwater models such as that for the Surat Basin (Janardhanaran et al. 2016).

Agriculture, urban water supply, power generation and other developments can also impair groundwater quality and interrupt connectivity. Where these occur near a mine or CSG development, the potential for cumulative impacts must be discussed and should be incorporated into impact modelling where possible.

As consequences of CSG or LCM activities potentially occur over decades or centuries, it is important that project impact assessments consider how GDEs will respond to or recover from these operations under modelled climate-change scenarios. Current forecasts for Australia are available from the Commonwealth Scientific and Industrial Research Organisation and the Bureau of Meteorology ([CSIRO and BOM](#) undated). Impacts on GDEs from CSG or LCM activities should be considered under these or newer forecasts as they are developed. Nugent et al. (2013) provide an example of a risk framework to manage GDEs under changing climatic conditions that may be useful for some projects.

4 Framework for assessing GDEs in an environmental impact assessment

GDEs potentially impacted by a CSG or LCM project can be identified and assessed using the logical framework developed in this Explanatory Note (Figure 5, modified from Serov et al. 2012). The steps of the framework include:

1. defining the project impact area (which includes the footprint of surface infrastructure and the extent of groundwater depressurisation)
2. undertaking a desktop study to identify potential GDEs and potential risks to GDEs in the project impact area
3. assessing the level of groundwater dependence for each GDE and the potential pathways of cause and effect of CSG or LCM activities
4. identifying the baseline ecological condition and value of each GDE
5. assessing the likelihood, frequency and magnitude of potential impacts on GDEs and determining the risks related to the CSG or LCM activity
6. prioritising options to avoid or mitigate impacts on GDEs and establishing a monitoring plan to test the effectiveness of mitigation strategies.

In 2011, the *Australian groundwater-dependent ecosystems toolbox part 2: Assessment tools*

([GDE Toolbox Pt 2](#), Richardson et al. 2011b) was published to guide assessment of GDEs. Various methods, or tools, were collated to aid identification and conceptualisation of how water may be used by a GDE (summarised in Table 2 and detailed in App Table 2). Additional methods are included in this Explanatory Note. Together these tools form the basis for the logical sequence of steps outlined in Figure 5. The next four chapters describe how to identify GDEs and their potential groundwater dependence (Chapter 5), how to survey GDEs to assess their baseline ecological condition and ecosystem value (Chapter 6), how to assess the risks of project-specific impacts on GDEs (Chapter 7) and what options exist for avoidance, mitigation and management of such risks (Chapter 8). These chapters follow the order of steps presented in Figure 5.



Ephemeral creek, Galilee Basin

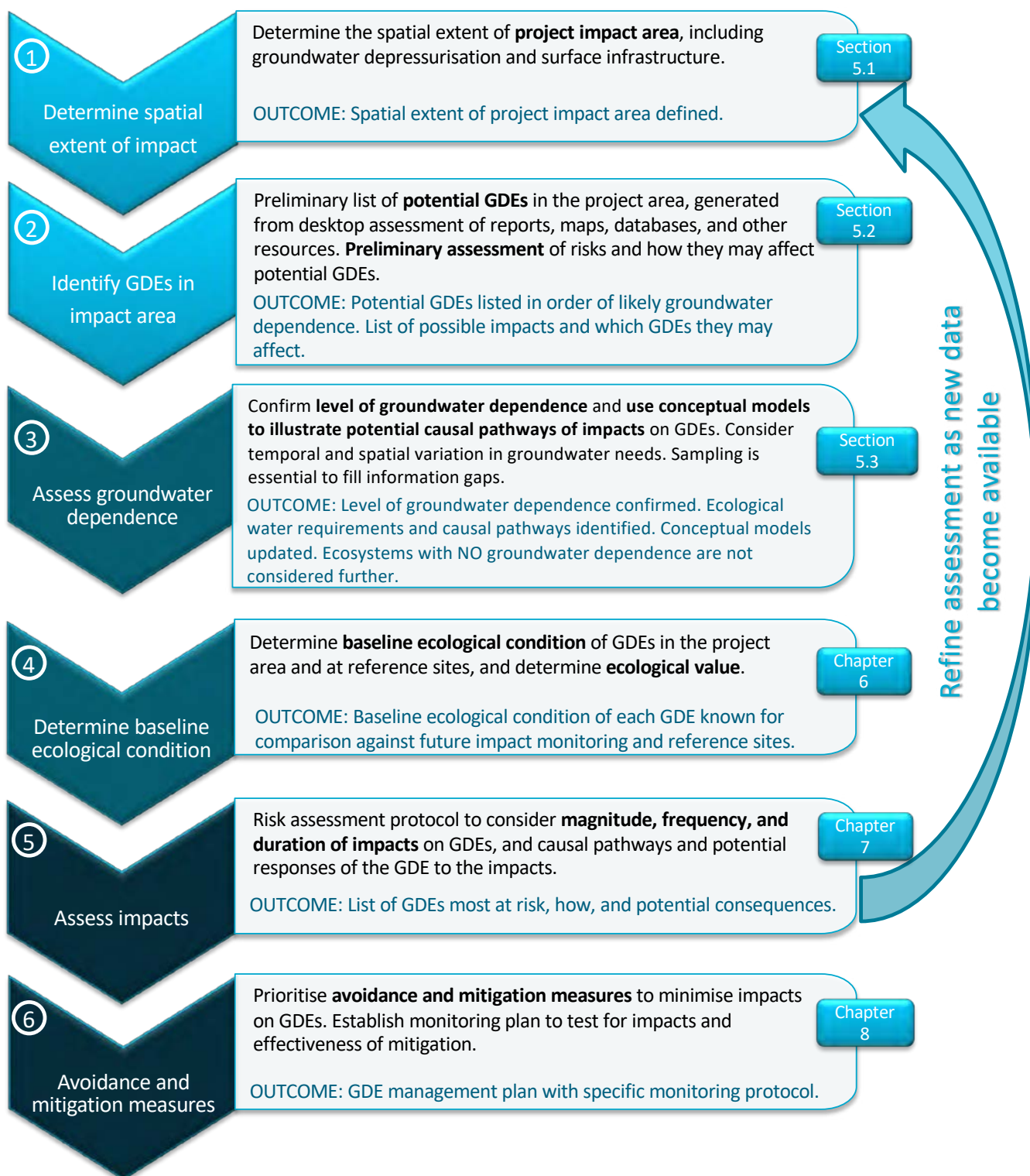


Figure 5. A logical framework to guide preparation of information for sections in an EIA that describe and assess potential impacts, risks and mitigation options of CSG and LCM activities on GDEs (modified from Serov et al. 2012)

5 Identifying GDEs potentially impacted by project activities

5.1 Identifying project area impact boundaries

The area of potential impact from CSG and LCM development is likely to extend beyond the immediate project boundary to include surrounding areas connected through the affected or adjacent aquifers. Critically, assessments need to consider all GDEs that are potentially affected by a project, regardless of whether they occur inside the lease boundary. As it is not always feasible to wait until the groundwater impact assessment provides a final boundary of potential groundwater impact (e.g. predicted contours of groundwater drawdown), proponents usually have only a rudimentary understanding of how far impacts are likely to spread when they begin their GDE assessment. Therefore, there should be consultation with hydrogeologists during the initial phase of an EIA to identify the maximum extent of possible drawdown. This estimate should be conservative so that the impact assessment does not miss any GDEs. This maximum ‘impact area’ will be refined as project plans develop, ecological and groundwater data are collected, and the groundwater impact assessment is completed (see arrow 1 in Figure 5).

5.2 Identifying GDEs in project impact area

The next step is to establish where potential GDEs occur in the project impact area (see arrow 2 in Figure 5). The objective is to list and map ecosystems classified as subterranean, aquatic or terrestrial GDEs that have some potential reliance on groundwater. This is a ‘first pass’, designed to determine which GDEs may exist in the project impact area and therefore potentially be at risk.

A logical starting point for GDE assessments is the [GDE Atlas](#) (CoA 2018a). This should be supplemented with site-specific information where available to develop a conceptual understanding of the interactions between GDEs and groundwater (see section 5.3.1), and to determine potential causal pathways (section 3.1). Local-scale information is generally preferred to regional- or national-scale data. However, in the absence of sufficient local-scale information, regional and national databases are available to inform initial assessments (App Table 3 and App Table 4). One such dataset is the remote-sensing-derived ‘inflow dependence’ data available in the GDE Atlas at 25-m resolution, which identifies landscape areas where evaporative loss from the landscape exceeds rainfall. Areas with higher evaporative losses indicate additional but undefined water sources (see Doody et al. (2017) for more detailed information).

In this step a desktop assessment is undertaken using existing resources, which are generally indirect indicators of groundwater use (e.g. maps, vegetation and wetland assessments, geological reports, groundwater data, satellite imagery, ecological reports, and position in the landscape). Direct indicators are obtained from field studies such as those that measure plant water use (see section 5.3.2).

5.2.1 Indicators of GDE presence

Landscape indicators of GDE presence can be hydrological, geological, hydrogeological, climatic and/or biotic. Indicators include the presence of vegetation known to access shallow groundwater and associated vegetation communities that are likely to be GDEs (e.g. Froend and Drake 2006, Canadell et al. 1996). Eamus et al. (2006) pose a series of questions (Table 1) to help identify GDEs reliant on the surface expression of groundwater. If one or more of these questions have a positive answer it is likely that a GDE is present and will require further investigation. App Table 3 presents a suggested set of ancillary data which can be useful for answering the questions posed in Table 1.

Table 1. Questions to guide the identification of potential aquatic GDEs (Eamus et al. 2006), cross-referenced to GDE rule sets shown in App Table 5

Cross reference to App Table 5	Positive answers to one or more of the following questions suggest that an ecosystem may use groundwater:
1	Does a stream/river continue to flow all year, or a floodplain waterhole remain wet all year, despite prolonged periods of zero surface flows (that is, zero or very low rainfall)?
2	For estuarine systems, does the salinity drop below that of seawater in the absence of surface water inputs (e.g. tributaries or stormwater)?
3	Does the volume of flow in a stream/river increase downstream in the absence of inflow from a tributary?
4	Is the level of water in a wetland/swamp maintained during extended dry periods?
5	Is groundwater discharged to the surface for significant periods of time each year or at critical times during the lifetime of the dominant vegetation type (if such a resource is present, some species present are likely to be adapted to using it)?
6	Is the vegetation associated with the surface discharge of groundwater different (in terms of species composition, phenological pattern, leaf area index or vegetation structure) from vegetation that is close by but which is not accessing this groundwater?
7	Is the annual rate of water use by the vegetation significantly larger than annual rainfall at the site and the site is not a run-on site; e.g. low-lying paperbark (<i>Melaleuca</i> spp.) swamps in the Northern Territory receive surface and subsurface (lateral) flows of water)?
8	Are plant water relations (especially pre-dawn and midday leaf water potentials and transpiration rates) indicative of lower water stress (potentials closer to zero; transpiration rate larger) than for vegetation located nearby but not accessing the groundwater discharged at the surface (the best time to measure this is during rainless periods)?
9	Is occasional (or habitual) groundwater release at the surface associated with key developmental stages of the vegetation (such as flowering, germination, seedling establishment)?

There are some common decision rules of groundwater dependence that guide GDE identification. For example, vegetation associated with shallow groundwater (less than 10 m) is likely to be part of a GDE, as it can often quite easily reach and extract groundwater (Eamus et al. 2016, Canadell et al. 1996). App Table 5 provides a list of guiding rules used in the GDE Atlas. [WetlandInfo](#) (Queensland Government 2013b) contains rules developed in Queensland to assist with GDE identification at the catchment scale.

5.2.2 Ancillary datasets and expert knowledge

In a ‘first pass’ assessment of potential GDEs in the project impact area, datasets and information should be collated that can contribute to answering the questions in Table 1. Mapping the likely presence of GDEs at this stage is usually a process of overlaying spatial data in a geographic information system (GIS) and incorporating known GDE information to illustrate the locations of ecosystems that potentially use groundwater and their likely GDE type (App Table 2; Tool 1—Landscape mapping in the [GDE Toolbox Pt 2](#) (Richardson et al. 2011b)). Before overlaying spatial datasets on the GDE Atlas, it is important to ensure that they are not, in fact, the ones used to create the GDE Atlas maps in the first place; overlaid datasets must be independent to provide reliable results. A non-exhaustive list of example spatial data layers is given in App Table 3, with links to national and state datasets in App Table 4. Online resources, such as the GDE Atlas and Queensland’s [WetlandInfo](#) can also be used. The initial search must be more comprehensive than databases specific to GDEs because gaps currently exist in these databases, particularly for smaller ecosystems (<250 m²). An example of a database to complement searches of the GDE Atlas is the [Geomorphic Wetland Mapping](#) tool (Government of Western Australia 2018a) for Western Australia.

Known GDEs are GDEs identified from past field studies or desktop studies that have established a groundwater connection within a landscape (see CASE STUDY 2). Known GDEs in the project impact area can be identified using the GDE Atlas and reviewing literature including journal papers, reports and other EIAs.



A Glossy Ibis

5.2.3 Remotely sensed data

Increasingly, remotely sensed imagery is becoming easily accessible and free. [MODIS](#) imagery, for example, can be extracted via the ORNL DAAC website (undated) and includes many variations of analysis-ready products that suit identification of GDEs such as vegetation indices at 250–500-m pixel resolution every eight days. [Landsat](#), which has coarser temporal resolution (16-day return) but finer spatial resolution (30-m pixels), is also free from USGS (2018) but requires additional corrections before it is fit for purpose. The Australian Government is overcoming this constraint with the [Data Cube](#) (National Computational Infrastructure 2018), which is pursuing a user-friendly interface to download Landsat products that are user ready, similar to those of MODIS.

Remotely sensed data provides a way to assess the landscape across broad to fine scales. Its use is encouraged as a method to identify potential GDEs and their groundwater dependence before and after CSG and LCM operations. Landsat, for example, has a long archive of imagery that can reveal conditions before development. As these analytical methods progress, remote sensing will become an economical and valuable tool to indicate levels of groundwater dependence (section 5.3) in conjunction with other methods in a multiple-lines-of-evidence approach (Doody et al. 2017). Limitations occur in relation to spatial resolution (pixel size) as some wetlands, such as those smaller than 30 m across, cannot be easily identified using remote sensing unless imagery resolution is below 2 m.

5.2.4 Preliminary risk assessment

Once there is a list of potential GDEs in the project impact area, a list of potential impacts on those ecosystems can be developed. The impact list can be considered a preliminary risk assessment that aims to identify the main potential impacts. Conducting a preliminary risk assessment at this early stage can help focus field work on areas where impact is most likely or where there is uncertainty about the potential for impact. It can also identify areas where there are information gaps, what those gaps are and how they may be filled so that a more comprehensive risk assessment can be undertaken later (section 7).

OUTCOME:

This will yield a list and map of potential GDEs, including aquifers, wetlands, rivers, springs and vegetation communities, together with an indication of groundwater dependence for each potential GDE in the project's maximum area of impact. A preliminary assessment of the risks to GDEs will identify potential risks early and aid in prioritising future work.

CASE STUDY 2:

Integrated mapping of GDEs across Victoria

To identify threatened terrestrial GDEs across Victoria, a landscape mapping approach was undertaken (Dresel et al. 2010). Various data sources, including published field studies, were used to determine landscape settings of known GDEs and to identify potential GDEs.

Data sources included climatic zones to segregate a broad region; state ecological vegetation classes; remotely sensed Landsat greenness; MODIS photosynthetic activity; land use; groundwater depth; groundwater salinity; and surface geology.

Data overlaid in a GIS (Figure 6) provided an approach to identify potential GDEs. For example, vegetation that maintained a constant greenness over a dry period and was associated with a wetland ecosystem implied a high probability of GDE presence.

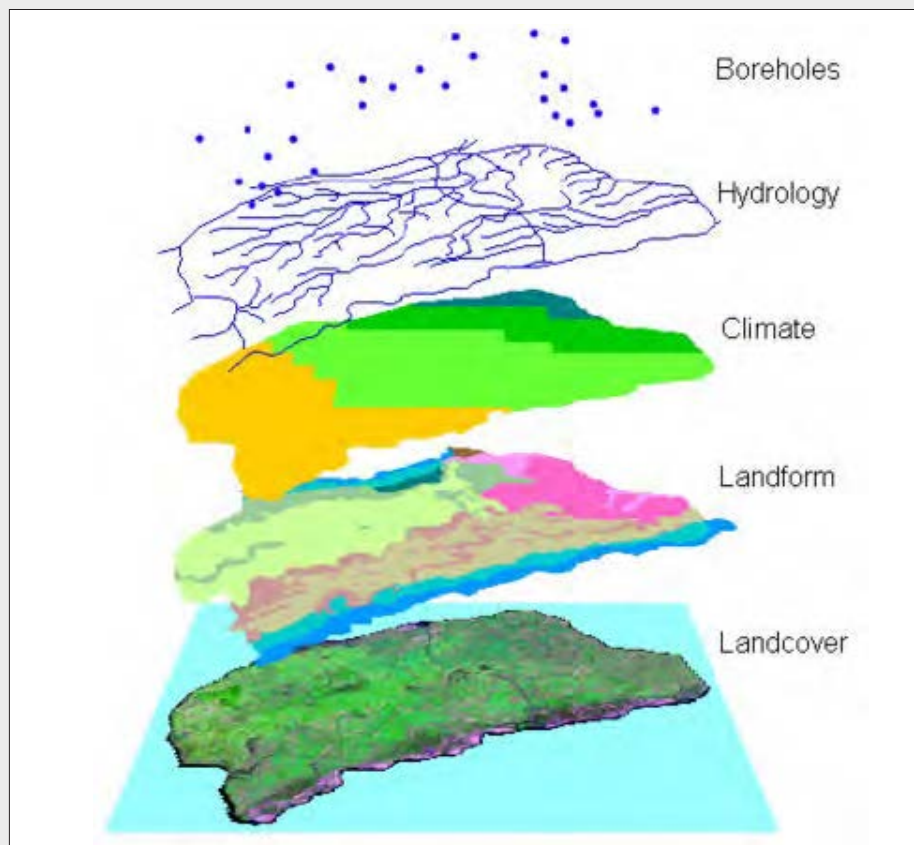


Figure 6. Example of some of the data sources that can be overlaid in a GIS to identify potential GDEs (Dresel et al. 2010)

5.3 Characterising the level of groundwater dependence

Once potential GDEs have been identified, proponents need to understand how each GDE interacts with aquifer(s) in the project impact area (see arrow 3 in Figure 5). Conceptual models (see section 5.3.1) improve this understanding by illustrating relationships of GDEs and groundwater, along with likely causal pathways of potential impacts (section 3.1). However, to assess the level of groundwater dependence, more information is needed on the specifics of the GDE–aquifer interaction, particularly the ecological water requirements of each GDE (section 5.3.2) and the likelihood of groundwater dependence (section 5.3.3). Details are deemed relevant if there are aspects of the groundwater regime or water quality that are likely to affect the GDE if changed (e.g. amount, location, timing or frequency of groundwater use).

5.3.1 Conceptualisation

Conceptual models, often presented as stylised diagrams, provide a way to visualise complex processes simply. They are useful in illustrating likely impacts and their causal pathways (section 3.1). Conceptual model development includes identifying and testing hypotheses that describe relationships between potential GDEs and groundwater such as the source aquifer, the frequency of groundwater use and the timing of this connectivity. It is critical that conceptual models show how each CSG or LCM activity could impact each GDE via all plausible causal pathways. This understanding of the type, mechanism and pathway of an impact can then be used to guide the development of an appropriate monitoring program (section 6), assess risks (section 7) and justify mitigation strategies (section 8).

Conceptual models are a suggested tool in the [GDE Toolbox Pt 2](#) (Tool 2—conceptual modelling (Richardson et al. 2011b; App Table 2)). Queensland's [WetlandInfo](#) site provides a step-by-step approach to their development (Queensland Government undated a).

RECOMMENDATION:

To create and update conceptual models as part of an integrated desktop study of likely groundwater dependence, guided by GDE rules, proponents should use the GDE Atlas; national-, state- and local-scale spatial data; remote sensing; expert knowledge; and scientific studies. The results of such a study will indicate potential GDE presence in and around the project's maximum area of impact (derived from a conservative initial estimate early in the EIA) and capture the relationships between potential GDEs and groundwater to enable a preliminary assessment of risks to GDEs.

5.3.2 Ecological water requirements of GDEs

Ecological water requirements of GDEs are those aspects of the natural groundwater regime that support the persistence of fundamental ecosystem characteristics (biodiversity and ecological structure) and processes (ecosystem function) (Richardson et al. 2011a). This section specifically focuses on the features of groundwater (flow, depth to water table, pressure and quality) that support ecosystems and need to be considered spatially and temporally. It is assumed that other hydrological requirements of GDEs (e.g. surface water) covered elsewhere in the EIA are also considered, but these are not discussed here.

Several methods exist for establishing the ecological water requirements and groundwater dependence of GDEs. These methods are detailed in App Table 2 and summarised in Table 2. Tools 5 to 8 aim to identify the sources of water used by vegetation, and Tools 9, 10 and 19 (see CASE STUDY 3) aim to identify whether vegetation uses more water than is likely to be available without access to groundwater. Remote-sensing techniques that are beginning to emerge improve our understanding of the relationship between groundwater regime and GDE dependence (Gow et al. 2016).

A multiple-lines-of-evidence approach is required to determine the level of groundwater dependence (high, medium, low, nil). Confidence in the level of dependence reflects the quality of data used (qualitative versus quantitative) and the number of lines of evidence (see Doody et al. 2017). The ‘precautionary principle’ (taking preventative action in the face of uncertainty) is applied when insufficient data exist to determine dependence.

Table 2. Summary of GDE assessment tools that incorporate field data (see App Table 2 for full details)

Code	Tool
5	Pre-dawn water potential
6	Plant water stable isotopes
7	Plant water use modelling
8	Plant rooting depth and morphology
9	Plant groundwater use field methods
10	Vegetation water balance
11	Stygofauna sampling
12	Evaluation of surface water – groundwater interactions
13	Environmental tracers
14	Introduced tracers
15	Genetic/DNA analysis
17	Long-term observation of ecosystem response to change
18	Numerical groundwater modelling
19	Remote sensing

Shallow alluvial aquifers inherently have a high likelihood of being GDEs and require sampling for stygofauna to investigate this (Tool 11). Recent advances in environmental DNA (eDNA) analysis provide a new approach to identify stygofauna habitats over larger scales (Gorički et al. 2017). While eDNA is still largely in the realm of research, it is likely to become more readily available as a tool for consultants in the next five years (see CASE STUDY 4). Tools 12 to 14 detail techniques for understanding how groundwater interacts with aquatic GDEs (e.g. rivers, wetlands, springs, swamps). In addition to these techniques, groundwater connection can be confirmed through the presence of stygofauna in the hyporheic zone (Hancock 2002).

The degree of groundwater dependence occurs over a continuum that varies over space and time. It is seldom possible to quantify how much groundwater all ecosystems use or exactly when. What is required at this stage of the EIA is an indication that the ecosystem uses groundwater, its likely level of dependence, and whether isolation of the potential GDE from the aquifer will result in significant change in ecosystem condition.

Initial investigations into the potential reliance of ecosystems on groundwater need to be supported by a longer term approach to understanding the ecological response to changes in groundwater regime. This can be achieved through targeted monitoring programs designed to sample along causal pathways (section 3.1) which test specific hypotheses of how different GDEs are affected by changes to the groundwater regime (e.g. Tools 17 and 18).

It is important to return to section 3.1 at this stage to ensure all causal pathways likely to impact on the GDEs are identified and documented. Conceptual models should also be updated if necessary.

RECOMMENDATION:

Proponents should assess ecological water requirements of GDEs and use this information to identify causal pathways that may create a change in GDE status through altered groundwater regimes. Multiple lines of evidence are to be used to determine groundwater dependence where possible.



A Green And Golden Bell Frog

CASE STUDY 3:

Landsat remote sensing delineation of GDEs

Remote sensing provides a broad-scale, fine-resolution ability to map GDEs over time. Landsat imagery is especially suitable, with a long, freely accessible global archive and a spatial resolution of 30 m. Multi-spectral indices such as NDVI (Normalised Difference Vegetation Index) and NDWI (Normalised Difference Wetness Index) are ideal to track changes in vegetation greenness and wetness, respectively. In combination, they can be used to map terrestrial GDEs by showing vegetation status over prolonged dry periods. Terrestrial GDEs are expected to maintain higher greenness over extended dry periods as well as higher surface water content related to increased water availability in comparison to dryland, rainfall-dependent xeric vegetation.

Using NDVI and NDWI, a study undertaken in the south-west of Western Australia identified GDEs (Barron et al. 2012) in a Mediterranean climate with hot, dry summers. From field assessments, a number of GDEs were known to be associated with groundwater, diffuse discharge zones and riparian vegetation. The study was founded on the assumption that after limited rainfall over a six- to seven-month period, soil moisture stores would be depleted and areas that maintained constant greenness and high surface moisture (wetness) were indicators that vegetation was likely to have access to groundwater. The research identified two land cover classes (CLs) of GDEs, two classes of non-GDEs and a class which identified open water bodies. In Figure 7, CL1 contains GDEs with permanent access to water (high greenness and wetness); CL2 contains GDEs that have reduced access to groundwater but remain green over a long dry period (slow-drying GDEs); CL3 contains ecosystems that have no groundwater connection and hence are not GDEs in a fast-drying landscape; CL4 represents open water bodies (GDEs) where wetness is high but greenness is low; and CL5 shows areas of low greenness which are not GDEs. The mapping agreed well with field data where GDEs were associated with springs, riparian vegetation along perennial rivers, break-of-slope seepage zones and terrestrial vegetation with access to shallow groundwater.

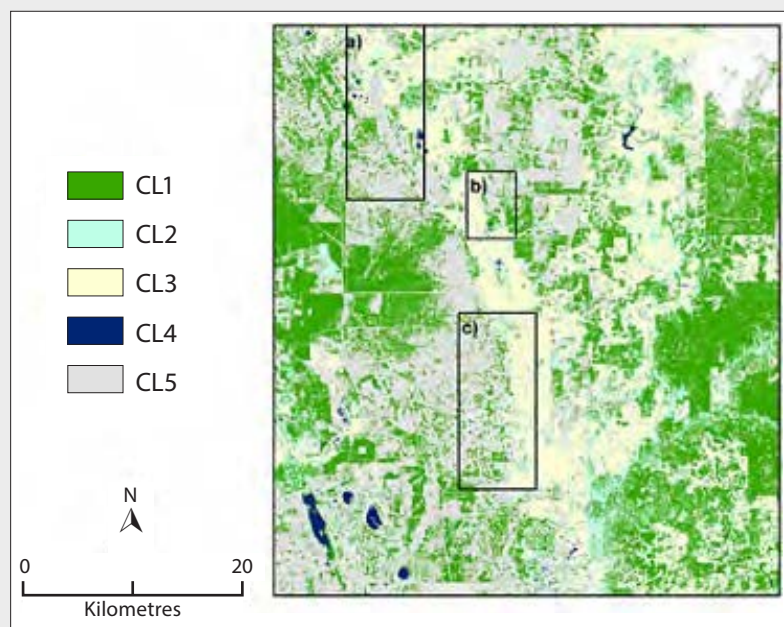


Figure 7. Map of the study area depicting the identified land cover classes (Barron et al. 2012)

CASE STUDY 4:

Environmental DNA (eDNA)

Environmental DNA (eDNA) is the DNA released by organisms as they move through the environment. The DNA of a range of aquatic organisms can be detected in water and sediment samples at very low concentrations. In aquatic environments, eDNA is diluted and distributed in water, where it can persist for one to three weeks; however, once trapped in sediments, the DNA can be preserved for thousands of years.

Large-scale assessment of subterranean GDEs has typically been based on determining the presence of groundwater invertebrates (stygoфаuna). However, these represent a very small portion of the ecosystem diversity, and the microbial component of the aquifer ecosystem is responsible for many of the key ecosystem functions relating to water quality. Using eDNA provides an opportunity to rapidly identify a more representative suite of micro-organisms that exist within an aquifer than traditional stygoфаuna sampling approaches. Taberlet et al. (2018) provides a recent overview of the use of eDNA.

Advances in eDNA processing will continue to improve the capacity to identify the presence of a range of micro-organisms within an aquifer, and to map and monitor the distribution of endangered, rare (e.g. Gorički et al. 2017) and invasive species. For example, the olm (*Proteus anguinus*) is a large endangered cave-dwelling aquatic salamander (endemic to Bosnia and Herzegovina) whose habitat is largely inaccessible to humans and therefore its distribution was poorly understood. eDNA was used to detect the presence of olms in water samples collected from karst springs, wells and caves, enhancing knowledge about its distribution (Gorički et al. 2017).

In standing waters such as lakes and ponds, eDNA has been used to estimate population abundance of target species. However, assessing the spatial and temporal distribution of eDNA in flowing waters is more complicated and requires more research (e.g. Shogren et al. 2017). A powerful application of this technology may be to examine changes in community diversity over time.

5.3.3 Determining the likelihood of groundwater dependence

In the early stages of impact assessment, likelihood of accessing groundwater may be used as a proxy for groundwater dependence. Without detailed field surveys, it is difficult to quantify the likelihood, so it can be reported qualitatively as 'high', 'medium', 'low' and 'nil'. For terrestrial GDEs, the likelihood of groundwater dependence can be determined initially by the species of tree (for those species with a known dependence on groundwater) or groundwater depth as reported by preferably local or regional monitoring data. For example, a stand of River Red Gum on a floodplain where the water table is less than 5 m deep will have a high likelihood of accessing groundwater, based on published records.

Rivers are assigned a high likelihood of groundwater dependence (aquatic GDEs) if groundwater levels near the river channel are shallow and the water table intersects or runs just below the lowest point in the river cross-section. All subterranean waters in alluvial aquifers are likely to be GDEs and are assigned a high likelihood of groundwater dependence (subterranean GDEs). Groundwater dependence of other GDEs will be medium or low. If the ecosystem does not access groundwater (i.e. has a likelihood of nil), it is not a GDE.

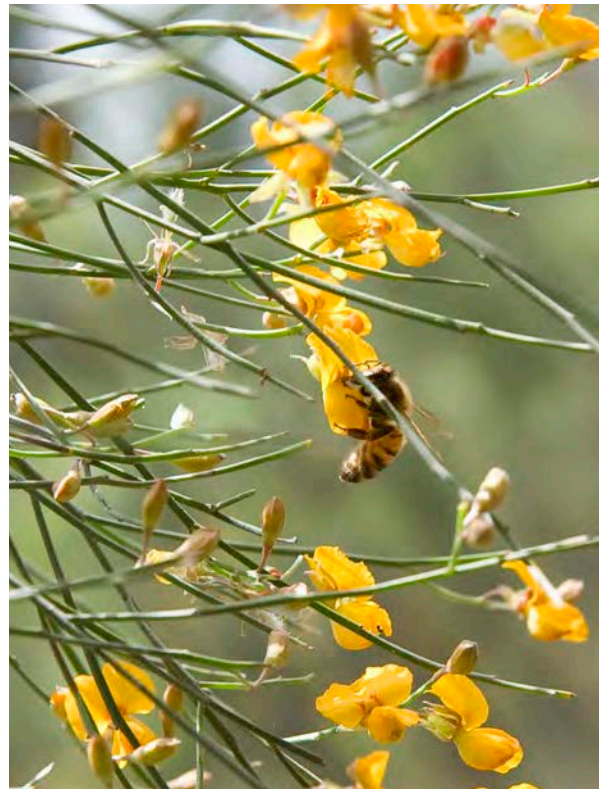
Determining the likelihood of groundwater dependence requires further targeted desktop studies once potential GDEs have been identified (Kuginis et al. 2016). The guiding questions provided by Eamus et al. (2006) (Table 1) aid assessment of likelihood. A positive answer to any one question implies groundwater dependence. To answer these questions, additional data and analysis (e.g. of streamflow or groundwater regime) are required. Vegetation dependence on groundwater can be predicted from literature reviews and species information. Additional remote-sensing analysis such as that undertaken by Barron et al. (2012) (see CASE STUDY 3) and Gow et al. (2016) to

highlight the characteristics of groundwater connection (e.g. seasonal connection) can highlight relationships to groundwater, which help to reveal likely groundwater dependence (Eamus et al. 2015a).

Using desktop analysis and integration of three indirect data sources (vegetation community mapping, groundwater level data and remotely sensed greenness), Kuginis et al. (2016) demonstrate a model to identify vegetation with high, medium and low potential for groundwater dependence. Frequency matrices for each GDE type (vegetation, wetland, etc.) are created where classifications of one, two, three and four correspond to 'high', 'medium', 'low' and 'no' potential (or likelihood) to extract groundwater, respectively (Table 3). In this study, remote sensing was used to identify how many times in a 10-year period greenness of woody vegetation exceeded a threshold that implied it had an additional water source. For example, a likelihood of one (high) was assigned when vegetation greenness remained above the threshold almost every year (nine to 10 times) over groundwater depths of 0-8 m (Table 3). Likelihood declined when the threshold was exceeded only one to four times in ten years (Table 3). As groundwater depth increases (>20 m), the greenness threshold is exceeded less frequently, which indicates a low (three) or no (four) likelihood of groundwater dependence.



Waxy Cabbage Palm



*Remnant bushland between Millmerran and Goondiwindi
in the Border Rivers-Condamine catchment area*

Table 3. Groundwater depth (m) and number of times in a 10-year period when greenness remained above a determined threshold to indicate groundwater use by woody vegetation: 1 = high, 2 = medium, 3 = low, 4 = no potential (or likelihood) to use groundwater (see Kuginis et al. 2016 for full methods)

Groundwater depth (m)	1–4 times	5–8 times	9–10 times
0–8	3	2	1
8–12	3	2	2
12–16	3	3	2
16–20	4	3	3
>20	4	4	3

OUTCOME:

The proponent will have assessed the likely level of groundwater dependence of potential GDEs in the project impact area as high, medium, low or nil using a multiple-lines-of-evidence approach. Temporal and spatial groundwater needs will be documented, and causal impact pathways identified. Where possible, conceptual models will have been updated with new information.

6 Field survey requirements for assessing baseline ecological condition and ecosystem value of GDEs

The baseline ecological condition of a GDE is the state of the ecosystem before the commencement of any CSG or LCM activities for the project being considered. Where the GDE occurs in an agricultural or other modified landscape, there may already be some pre-existing influences on the ecosystem that have altered it from a pristine condition. These should be considered. In an EIA the main purpose of determining the baseline ecological condition of each GDE is to establish the 'starting point' of the ecosystem before development. This becomes a benchmark against which to compare results from future monitoring.

6.1 Baseline conditions

Before operations commence, baseline ecological and hydrological conditions of potentially impacted GDEs within, and reference GDEs outside, the project impact area must be established to ensure that changes due to CSG or LCM activities can be distinguished from those due to natural variability and climate change. Detailed guidelines for determining baseline condition exist for aquifer communities (subterranean GDEs) in Western Australia and Queensland (Queensland Government 2018a, Government of Western Australia 2016, Queensland Government 2015), and use the stygofauna community as the main biological indicator to assess ecological condition. Other potential indicators of aquifer ecological condition include bacterial activity, water chemistry, and environmental indicators (Korbel and Hose 2017 and 2011, Stein et al. 2010). There are no detailed guidelines for assessing the baseline condition of other types of GDEs. For these, a combination of the approaches and databases described in section 5 will be useful, supplemented with field surveys in the project impact area and at reference GDEs where no impact is predicted. There are also several standard methods and associated indices that are used for assessing current ecological condition (e.g. BioCondition (Eyre et al. 2015) for vegetation; AUSRIVAS (Australian River Assessment System undated) for aquatic ecosystems) at national or state levels. These may be useful for assessing the baseline condition of relevant GDEs.

6.2 Sampling groundwater quality

Groundwater quality often governs the biological composition and condition of GDEs (section 5). Reduction in groundwater quality is one of the causal pathways by which CSG and LCM activities can affect GDEs (section 3.1.2). Therefore, groundwater quality should be sampled and these data matched with ecological data from associated GDEs. There are detailed instructions on groundwater sampling in Sundaram et al. (2009) and AS/NZS 5667.11:1998 (1998, revised in 2016) as well as various state-level guides (e.g. for Queensland, Queensland Government 2018a and DSITI 2017; for Victoria, EPA 2000). *Guidelines for groundwater quality protection in Australia* (CoA 2013b) describes data requirements and processes for undertaking risk assessments of likely changes in groundwater quality and is another very useful reference.

Most groundwater sampling is done from bores, wells or piezometers, and requires special equipment such as pumps, syringes and bailers. The different methods and their various advantages and disadvantages are described in Sundaram et al. (2009). Although bailers are inexpensive and portable, they have many disadvantages (e.g. time-consuming to use, may aerate samples during collection) and should be used only as a last resort. It is crucial that groundwater

samples contain water representative of the aquifer as opposed, for example, to potentially stagnant water in the bore column. Therefore, it is usually necessary to purge bores before sampling for water quality. Pumps are more efficient than bailers for purging bores, which is another advantage to their use over bailers.

Special precautions may be needed to prevent changes in the quality of groundwater samples when they are being collected and, in some cases, filtered. For example, exposure to atmospheric components such as oxygen can oxidise compounds (e.g. ferrous ions) naturally present in the reduced form and alter the water chemistry of the sample. Changes in temperature during sampling can increase the volatilisation of dissolved constituents (Queensland Government 2018a). Similarly, the transport and storage of samples for laboratory analysis should be tailored to the analytes of interest, especially when sampling locations are remote from the laboratory.

Appropriate procedures are needed to avoid cross-contamination among sampling points and, of course, among samples. This is also important for samples collected for microbial analysis and molecular (omics) tools (see CASE STUDY 4), which are becoming more feasible for routine analysis of groundwater quality. Finally, consistently robust quality assurance and quality control measures (Sundaram et al. 2009) are essential to ensure high-quality data. Whenever groundwater samples are collected, details on the sampling, storage and analysis methods must be recorded in case these methods affect detection or measurement of different water quality parameters.

The choice of which parameters to measure and how often is determined by the goals of the study, the risks and causal pathways predicted from conceptual modelling of the project, and any legislative requirements for groundwater or GDE protection. Common choices include salinity (often measured as electrical conductivity); water temperature; pH; dissolved oxygen; redox potential; and concentrations of nutrients, metals such as arsenic, lead, copper, nickel, chromium and zinc, organic compounds such as phenols and cresols, and other potential contaminants associated with CSG and LCM activities (section 2). Sometimes these analyses of groundwater quality are supplemented with ecotoxicity tests using biota (e.g. fungi, stygofauna) representative of non-impacted GDEs, but this is usually reserved for situations where the GDEs are of particularly high value and/or there is a very high risk of impact (section 7).

6.3 Requirements for GDE field surveys

Field surveys of GDEs are required for two key purposes. The first is to confirm the presence of each potential GDE in the project impact area (ground truthing), test hypotheses derived from the conceptual model of groundwater–ecosystem relationships, select reference sites outside the project impact area (where possible), and assess the baseline condition of each GDE. The second is to identify a representative subset of each GDE type to use for detecting impacts associated with CSG or LCM activities and monitoring the effectiveness of mitigation strategies.

When establishing a field survey protocol during the impact assessment phase, it is important that the proponent consider how the sites, protocols and sampling regimes will be used throughout the project, including after CSG and LCM activities cease. This saves time and is likely to improve impact assessment efficiency. GDE data collection sites and protocols can be consistently used to (i) establish whether the ecosystem is groundwater dependent; (ii) determine baseline condition and ecosystem value; (iii) monitor for impacts during and after CSG or LCM activities; and (iv) where applicable, assess GDE recovery after operations cease.

Site location should be considered carefully before the start of surveys. Ideally, surveys should be set up with a before–after control–impact (BACI) design (Downes et al. 2002). This allows the condition of GDEs in impact areas to be compared with both their pre-impact condition and that of similar GDEs outside the impact area. While there may be difficulties in establishing and monitoring reference sites (or ‘control’ sites) located beyond the project boundaries, having these sites can help the proponent account for natural variations in GDE condition such as changes in species composition or a decline in vegetation health caused by factors (e.g. drought, abnormally wet periods) not associated with the CSG or LCM activities.

Given the uniqueness of many GDEs, it can be difficult to find enough reference or control sites for statistical comparisons using a BACI design. Where this is the case, the best option is to measure GDE condition through time, with sufficient sampling events before the commencement of development to both determine the baseline ecological condition and estimate the likely natural variability of GDE condition over time. This should be followed up by regular monitoring during the operational phase of the CSG or LCM project to compare the ecological condition of each GDE with pre-development baseline data.

6.4 Field surveys and monitoring

As mentioned in section 5.3, field surveys for GDE assessment are important to confirm that each potential GDE identified in the desktop study is groundwater dependent and to assess the nature of that dependency (section 5.3.2). This allows ecosystems not dependent on groundwater to be eliminated from further assessment. The focus here is to confirm either that there is a connection between the ecosystem and an aquifer (terrestrial and aquatic GDEs) or that stygofauna are present (subterranean GDEs). Field-based tools are summarised in Table 2 and App Table 2.

The second purpose of pre-development field surveys is to establish the baseline condition and ecosystem value of the ecosystem once it has been confirmed as a GDE. Taberlet et al. (2018), Korbel and Hose (2017), Korbel et al. (2017) and Korbel and Hose (2011) all provide examples of the application of tools for assessing the condition of subterranean GDEs that could be useful for proponents. Example approaches to assess terrestrial and aquatic GDE condition were discussed in section 6.1. If the ecosystem is listed as threatened under state or federal legislation or if it contains species or populations that are listed, then its value is considered high. Other benchmarks for value include biodiversity, how common the ecosystem type is throughout the landscape, its spatial extent, the ecosystem services it provides and whether it contains endemic species (Serov et al. 2012; see section 2.2).



The Namoi River



Giant Dragonfly, Marrangaroo Swamp
© Martin Krogh

Sufficient understanding of baseline conditions is essential so that reliable benchmarks can be set for future comparisons once CSG or LCM activities commence. Groundwater dependence changes spatially and temporally. Therefore, to estimate natural variability, baseline sampling needs to be sufficiently replicated within an ecosystem type (e.g. at several locations in a vegetation community, wetland system or aquifer), and data should be collected more than once, with at least one survey occurring at or near the time of optimal groundwater dependence (e.g. dry season, drought). Baseline data collected over long periods of time will give a better indication of natural variability than data collected over short periods. Where no previous records or data exist, survey periods of at least two years are recommended for GDEs to assess their potential variability. Of course, some indicators of GDE condition change slowly and will not be adequately assessed within two years, but a compromise is sought between reliable determination of GDE condition and realistic lead times for a CSG or LCM development.

Proponents should also, where possible, establish and sample reference GDEs outside the expected project impact area if there are comparable GDEs available in the region. Reference sites should be as similar as possible to the 'impact' sites in their species composition, environmental setting and use of groundwater. Data from reference sites will indicate whether changes observed in GDEs in the project impact area exceed changes in the GDEs in the broader region that may be explained by climate or other sources of variability.

A key consideration for sampling during the impact assessment phase of a project is how sites, sampling protocols and data will be used to inform monitoring during the operational and post-operational phases. The type of data and how, when and where they are collected during the initial stages of a monitoring program will need to be compatible with future surveys designed to detect impacts of the operations. During the impact assessment phase, preference should be given to choosing sites that can be included in subsequent monitoring programs throughout the life of a project. Substantial savings of time and money can be made if the proponent samples GDEs intensively during the early stages of field surveying to identify redundant sites and variables, because these can then be removed to provide a reliably representative subset of sites and variables for efficient long-term monitoring.

A final task in the impact assessment phase is to develop hypotheses (e.g. predicted changes) that will guide future monitoring programs. These hypotheses should be robust and testable, and relate to variables sensitive to change in groundwater quality or availability. It is likely more than one variable (e.g. species composition, NDVI cover) will be required for each GDE. The variables should not all be biological, because these may not show signs of stress until it is too late. Groundwater level is one variable that should be included in all GDE monitoring, as it can be monitored remotely, is relatively easy to determine benchmarks for (given enough baseline data) and can be used to indicate that impacts are imminent rather than already occurring. The [Australian and New Zealand guidelines for fresh and marine water quality website](#) (ANZG 2018) provides advice on determining appropriate guideline values using existing biological, physical, and chemical data. These could be referred to when setting levels of acceptable change in GDEs.

6.5 Site selection

To assess the condition and value of GDEs during the early phase of an EIA, sites need to be selected that are representative of the GDE types that exist in the project impact area. For example, sampling locations for aquifer ecosystems should initially focus on areas where stygofauna are most likely and attempt to cover as much of this GDE as possible. However, stygofauna surveys usually rely on access to an already existing bore network, which limits where samples can be collected and the number of suitable bores available for each aquifer type (App Table 6).

Preferably, GDE survey sites should be located close to existing groundwater monitoring bores, as groundwater data are critical to understanding the specific nature of the GDE–groundwater interaction. If no monitoring bores are near a GDE, especially a high-value one, they should be installed and monitored in conjunction with the GDE.

If sites are selected for the purpose of detecting a potential impact (such as water table drawdown), then sampling points should be within the region where the impact is likely to occur but also include suitable equivalent reference sites outside the likely project impact area.

The short time over which EIA data are usually collected limits adequate assessment of GDE temporal variability. These data are seldom sufficient for establishing reliable baseline conditions against which future monitoring will be compared. To address this problem, reference sites need to be established. These should be located in areas where impacts from CSG or LCM activities (which include the project under assessment as well as existing and likely future operations) are negligible but where the ecosystems are still subject to changes not caused by CSG or LCM activities. In a landscape where the GDE is already subject to pressures of irrigated agriculture or other modifications, reference sites should experience similar pressures so that impacts due to CSG or LCM activities can be successfully distinguished. Ideally, the survey design should include relevant GDEs in undisturbed sites as well as disturbed reference sites. However, it is often challenging to find appropriate undisturbed sites where access is feasible.

Each GDE should have multiple sampling sites with enough replication to differentiate natural variation in the ecosystem for species that are sensitive to groundwater regime change. The question of how much replication is required will be determined by the size of the GDE, how homogenous it is in the characteristics being sampled, how accessible it is to sample, and how many GDEs of a particular type are available to sample. At least three locations per GDE are likely to be required for an adequate assessment of variability. Where the GDE is large or highly variable, more survey sites will probably be required.

Depending on the location of GDEs with respect to predicted water table drawdown, it may be necessary to stratify sampling to account for the impacts of different levels of drawdown. For example, terrestrial GDEs might suffer more where the predicted drawdown is 10 m than in a location further from a bore or mine where drawdown will only be 2 m or 3 m (assuming there is not a threshold depth to water table shallower than 2 m where major impacts abruptly occur).



Monitoring bore, Queensland

RECOMMENDATION:

Prioritise site selection and suitable replication during the pre-development stage so that a representative subset of sites can be included in subsequent monitoring to track changes during CSG or LCM operations. GDE monitoring sites should be located near groundwater monitoring bores. Monitor comparable GDEs from outside the predicted area of impact, where possible, to provide reference points against which to assess hydrological and ecological changes over time.

6.6 Assessing ecosystem value

The purpose of assigning an ecosystem value to a GDE during impact assessment is to assess what might be lost as a result of development, so that management decisions can be fully informed. It also helps prioritise avoidance and mitigation strategies and guide the investment of sampling effort in monitoring programs. A useful tool for assessing the value of GDEs is outlined in AETG (2012b). These guidelines help identify high ecological value aquatic ecosystems (HEVAE) based on the following criteria, and could be extended to encompass non-aquatic GDEs:

- **Diversity** of species, habitats, ecological processes and abiotic features such as geomorphology
- **Distinctiveness** of the ecosystem itself, of the species/communities it contains, and of the geomorphic features present. This also includes whether it supports rare/threatened/endemic species or communities
- Whether it provides **vital habitat** for native plants and native/migratory animals
- How **natural** the ecosystem is, and how close it is to a state not adversely impacted by human activity
- **Representativeness** of the ecosystem, and whether it is an outstanding example of an ecosystem class within a drainage division.

Further details on HEVAE methods, as well as case studies, are available in AETG (2012b).

When assessing the ecosystem value of a GDE (see section 2.2), a proponent must consider the criteria that exist for the state or territory in which they work (Appendix D). As ecosystem value is closely associated with ecological condition, the condition of each GDE under current and historical land management must be assessed together with how this differs from its likely condition before any impact from CSG or LCM activities, and the potential for the GDE to return to its pre-impact condition with and without mitigation measures. The process of establishing ecological condition, and the thresholds used to determine whether the ecosystem is in good, moderate or poor condition, will vary for each GDE and relate to its regional significance. Usually field surveys are required to fill information gaps. Guidance on field assessment of ecosystem condition or value for subterranean fauna is detailed in Appendix G and App Table 6 and App Table 7.

Eamus et al. (2006; see section 2.2) recommend that value be assigned to GDEs through a combination of community consultation, expert knowledge and economic assessment (amenity, tourism, conservation, economic productivity), and that where value, threat (vulnerability) and uncertainty are the greatest, GDEs should be prioritised using the precautionary principle. Guidance on community consultation and economic assessment is outside the scope of this document.

Serov et al. (2012) provide a comprehensive guide to attributing low, moderate or high value to GDEs, including consideration of:

- the sensitivity of GDE communities to changes in groundwater (*high value*—GDEs for which only slight changes in groundwater level will result in loss of biota and/or services; *moderate value*—GDEs that require a moderate change in groundwater to cause changes in their distribution, biota, services and/or condition)
- location of GDEs (*high value*—GDEs in state reserves)

- condition (*high value*—GDEs that are relatively unaltered and in good condition; *low value*—GDEs that are highly modified from their natural state and declining in ecosystem condition)
- uniqueness (*high value*—GDEs that contain endemic, relictual, rare or endangered species; moderate value—GDEs that contain vulnerable or threatened biota)
- services (*high value*—GDEs that provide multiple ecosystem services).

6.7 Data requirements

The [GDE Toolbox Pt 2](#) (Richardson et al. 2011b) contains a list of different methods available for sampling GDEs (App Table 2). Pragmatically, the sampling regime must fit within the time constraints allowed for preparing the EIA, which means that collecting adequate long-term data will not be feasible for most parameters.

Each GDE in a project impact area should be surveyed before operations start. Levels of detail and sampling intensity are guided by GDE condition and ecosystem value (section 2.2), level of groundwater dependence and vulnerability (section 7.2). Greater survey effort should be allocated to GDEs that have high ecosystem value and/or are potentially at higher risk.

Remotely sensed data offer an opportunity to cover broad areas quickly and economically (see section 5.2.3), and can be used to demonstrate changes through time in aquatic and terrestrial GDEs such as river baseflow systems, springs and vegetation communities. However, for many GDEs, field surveys are required to determine baseline condition. Before conducting field surveys, proponents need to consider the type of data required. These data must sufficiently fill any gaps identified in the desktop phase of the assessment (section 5), be useful for indicating ecological condition and ecosystem value, and establish whether the ecosystem has a connection to an underlying aquifer (see Eamus et al. (2006) and Table 1 for criteria to determine the likelihood of groundwater connection).

Critically, ecological data need to be paired with groundwater data (see section 6.5) so that the link between GDE condition and groundwater level and water quality can be determined and monitored. However, consideration should be given to lag effects (e.g. River Red Gum tree decline may take six months to become obvious after groundwater lowering) and antecedent conditions that might influence current ecological state (e.g. the health of a GDE might be declining before operations start). The interaction between a patch of vegetation and the groundwater that it depends on can be better understood (and, later, better managed) if groundwater data come from as near the GDE as possible. Once a high-value GDE has been identified, one or more bores should be installed nearby to monitor local groundwater levels and other ecologically relevant data (e.g. electrical conductivity, pH, dissolved oxygen concentration, dissolved organic carbon and nutrient concentrations).

Sampling frequency will vary between different GDE types. Canopy cover of riparian vegetation, for example, will often change in relation to season and water availability. If water is scarce or its extraction is energy-limited, native eucalypts will drop leaves and reduce water use to compensate (Doody et al. 2015 and 2009). To assess the seasonal trends related to vegetation dynamics, sampling at least quarterly is advised. This quarterly sampling can be supplemented with remote sensing of greenness to establish a long-term baseline of seasonal canopy response trends. Variables that potentially serve as early warning indicators of groundwater change, such as groundwater levels, should be sampled more frequently.

All non-spatial data (e.g. water quality, ecological condition, groundwater level) should be linked to a known point in the landscape, such as a GPS point, for inclusion in spatial databases. Maps are often the main means of displaying GDE location and condition, so an ability to overlay data on these maps can be important for illustrating interactions between groundwater regime and ecosystem condition (see Figure 8).

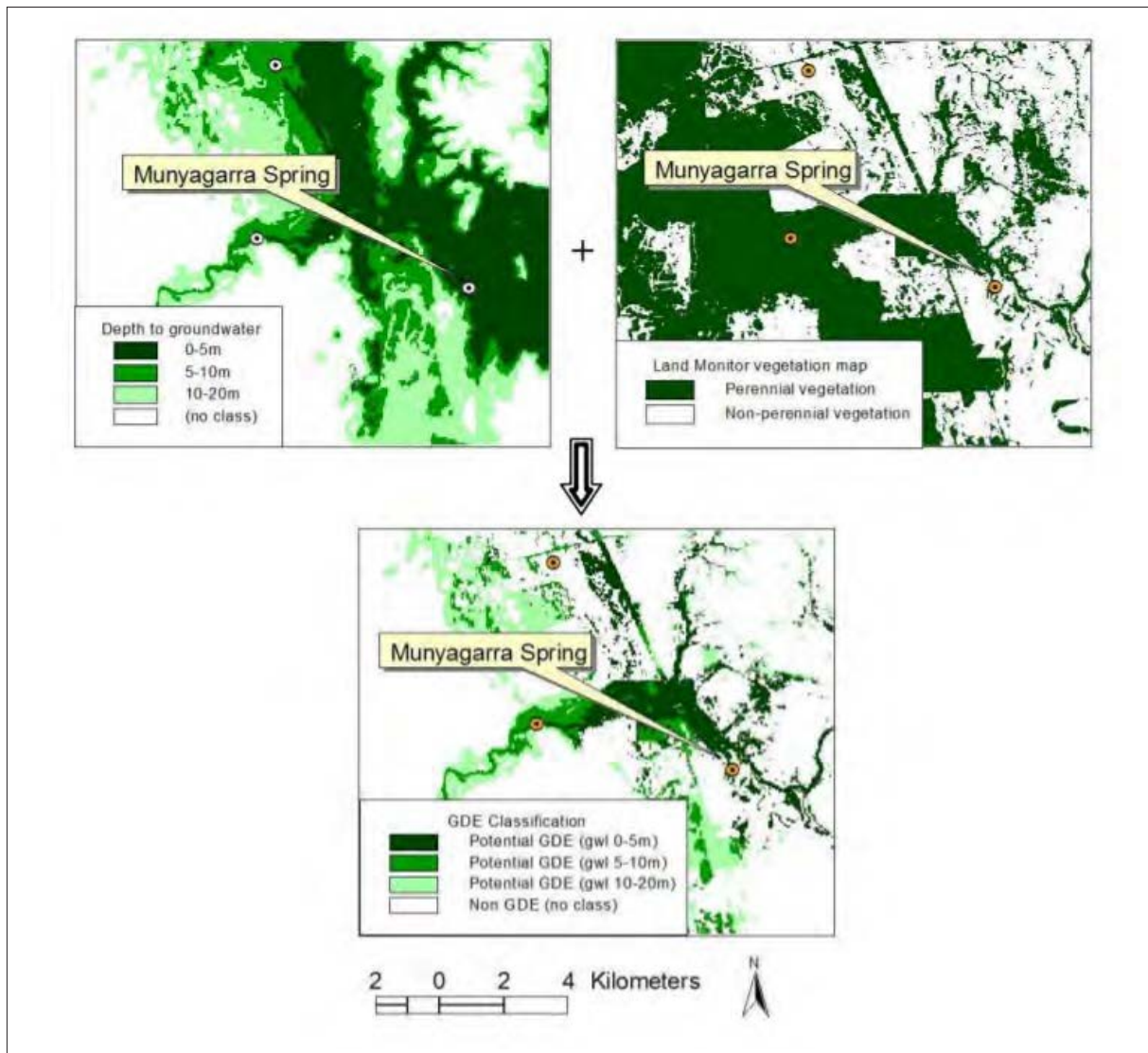


Figure 8. Mapping example demonstrating the combination of overlaying maps of depth to groundwater (top left) and vegetation (top right) to reveal potential GDEs from the intersection between the two (bottom) in three classes where groundwater depth is 0–5 m, 5–10 m and 10–20 m near Hill River in the northern Perth Basin, Western Australia (vegetation is not considered a GDE when groundwater depth is greater than 20 m in this example) (Rutherford et al. 2005)

It may also be possible to use the data collected for other sections of an EIA. Most EIA documents include a chapter assessing vegetation communities (including riverine vegetation), which can be used to describe the condition and value (e.g. biodiversity, presence of threatened species or communities) of communities that are also groundwater dependent.

6.8 Survey level of detail

Generally, each GDE should be sampled with enough replication over space and time to indicate their degree of groundwater dependence, ecological condition and ecosystem value. Greater detail is needed if threatened species or other significant components are present that may be impacted by changes to the groundwater regime or groundwater quality. For example, if a floristics survey finds a threatened orchid that is reliant on the hydraulic redistribution of water by a patch of terrestrial GDEs, the population of orchids in the patch of terrestrial GDEs should be mapped so that changes through time are evident. Greater detail and sampling effort are also required when the material risk to a GDE is potentially greater. This should be explicit in monitoring programs and management strategies to avoid or mitigate impacts.

Surveys need to adequately consider:

- the spatial extent of a GDE, ensuring there are enough data points to represent a GDE's characteristics across a gradient of depth to groundwater (for example) and that there are enough suitable bores nearby so that ecological condition can be paired with groundwater data (e.g. water level and water quality)
- the number of surveys needed at each site to describe temporal patterns (e.g. seasonal or occasional water use) in each GDE
- variables and level of detail needed to adequately assess GDE ecological condition and ecosystem value across space and over time in the project impact area and nearby reference sites
- sampling frequency, especially where responses may be rapid or provide early indications of impending severe impacts
- matching data with the causal pathways in the conceptual models of the GDEs to justify in the EIA and management plans why particular variables (and their sampling regimes) were chosen to detect and monitor impacts on GDEs.

RECOMMENDATION:

Proponents should, where possible, identify a suitable number of reference sites outside the project impact area that are representative of GDEs in the project impact area. The sampling regime (number of sites and frequency of sampling) and selected variables need to reflect ecological condition and ecosystem value, level of groundwater dependence and level of risk to the GDE. Their choice must be justified in the EIA.

6.9 Data analysis and management

Data analysis should allow for an indication of an acceptable level of change in a critical variable (e.g. species diversity, pre-dawn leaf water potential). This requires past data from sufficient sites for each GDE to assess the background variability in each variable. For most GDE types, data on ecological condition will be sparse or non-existent before the initiation of EIA studies, so an understanding of natural variability will be limited. Management plans developed during the EIA phase must acknowledge this and set realistic monitoring goals that are adaptable to new data. Furthermore, impacts on GDEs may not be immediate, requiring an additional period for data collection if the project is approved. Some estimate of these time lags should be made; this could be guided by conceptual models of causal impacts and groundwater dependence (section 5.3.1).

An acceptable level of change can be determined through either comparisons between impact and reference sites or comparisons with patterns published in the scientific literature or reports about similar projects.

Ideally, all data collected during GDE assessments for EIAs should be stored in a central repository, such as the GDE Atlas, so that they are available for use by other proponents or researchers wishing to increase our understanding of

the interactions between GDEs and aquifers. For this to be achieved, proponents will require clear instructions on the content and format of data. There will also need to be a data-review process to ensure data are suitable. There are several state-based resources where GDE datasets are stored (e.g. WetlandInfo and the Subterranean Aquatic Fauna Database in Queensland).

Whether or not data are stored in a central repository, proponents must take responsibility for managing and storing data collected from the project area. This is because throughout the life of a project the consultant collecting data for the EIA and the consultant conducting the monitoring during the operational phase may be different people or entities. Unless the proponent requests raw data from the consultant and stores them appropriately, data are likely to be lost and the only information available will be that presented in reports. Without access to pre-impact data, it can be difficult to detect whether GDE changes have occurred.

OUTCOME:

The proponent will have assessed the baseline condition of GDEs within and outside the project impact area, recognising the need to incorporate appropriate field survey and monitoring methods that consider factors such as site selection, level of survey detail required, sampling methods to determine level of groundwater dependence, ecological condition and ecosystem value, suitable methods for data analysis and storage, and well-justified management options. The collected information will describe the natural variability in each GDE and inform decisions to determine an acceptable level of change, with consideration of the ecosystem value of each GDE. Monitoring programs should state the goals of monitoring, what is to be measured and where and how often, how each variable relates to potential impacts and GDE responses, and how the data will be stored, analysed and presented. The proponent should retain all raw data collected for the project.



Wetland vegetation in the Galilee

7 Assessing risks of project-specific impacts on GDEs

Once baseline assessment of ecological condition has been undertaken for each GDE and its ecosystem value has been established, potential project-specific impacts must be addressed in a risk assessment protocol that considers the magnitude, frequency and duration of each impact (see arrow 5 in Figure 5).

7.1 Assessment of impacts

State-based guidelines for assessing impacts on GDEs exist in New South Wales (Serov et al. 2012) and Queensland (Queensland Government 2016). Both of these states provide instructions to proponents on how to identify GDEs in the project impact area and how to determine which activities are likely to result in impacts.

In New South Wales, the steps involved in the assessment process (once GDEs in a project impact area have been identified and their ecological condition and ecosystem value determined) are:

- determine the impact of the activity on all GDEs, including the aquifer community
- determine magnitude of risk to all GDEs
- apply the GDE Risk Matrix (App Table 8; Serov et al. 2012)
- develop a management plan consistent with the outcomes of the risk category determined in the GDE Risk Matrix.

The GDE Risk Matrix (App Table 8) consists of a vertical axis that represents three levels of ecosystem value (termed 'ecological value') and a horizontal axis that represents three levels of risk of an activity. The three categories for both variables are high, moderate and low. The resulting matrix has nine possible outcomes, labelled A (high value; low risk) to I (low value, high risk) (App Table 8).



Bedrock channel, Gang Gang Swamp

For each of these nine possible outcomes, the GDE Risk Matrix management action table (App Table 9) identifies both the management action required and a time frame (short, medium or long term) in which this action needs to be implemented (action priority) for each GDE. Management actions are aligned with ecological value and do not vary with changes in risk (e.g. the rules for the management of high-ecological-value GDEs are the same whether the risk is high or low). However, the time frame for management actions varies in response to the risk level.

These two risk matrices can be used to assess project-specific impacts and associated risks to GDEs in the project impact area. Both the Queensland and New South Wales guidelines require an assessment of ecosystem value (ecological value), magnitude of impact and significance of impacts at regional and state levels. The Queensland guidelines are not as prescriptive as the New South Wales guidelines in defining management actions based on the combination of ecosystem value and the risks posed by the activity.

7.1.1 Ecological responses by GDEs to changes in groundwater

Ecological responses by GDEs to changes in groundwater (e.g. change in regime such as magnitude of fluctuation, discussed in Richardson et al. 2011a) are best described using demonstrated relationships. However, as these are seldom available, pictorial conceptual models (section 5.3.1) and causal pathways (section 3.1) can be developed and used to illustrate and justify predicted responses. Predicted GDE responses to changes in groundwater can then be validated by data.

Tools to help determine ecological function in relation to change in groundwater regime (e.g. leaf water potential, isotope and water use studies—Table 2 and App Table 2) may need to be applied spatially and temporally as demonstrated in CASE STUDY 5 to understand the interaction between a GDE and its groundwater connection.

In general, changes in groundwater availability have been found to impair growth, reproduction, recruitment and survival of groundwater-dependent biota and to alter the structure and function of GDEs (Kath et al. 2014, Eamus et al. 2006). Data collected from monitoring programs can be used to derive and revise conceptual and predictive models to further test hypotheses of how ecosystems may change if impacted by threatening groundwater-related processes. For example, field data collected after conceptual model development confirmed that riparian River Red Gum trees will access groundwater when other water sources are not easily available (Doody et al. 2009), further informing the processes displayed in the conceptual model. This may lead to a new hypothesis that groundwater alteration in riparian areas supporting River Red Gums will have significant impacts during times of extended drought when rainfall is below average and surface water flows are substantially reduced.

Assessing GDE responses to changes in groundwater must include spatial and temporal consideration of:

- how the GDE (or one of its components) is likely to respond to changes in groundwater regime and water quality
- the natural range of hydrological conditions under which the GDE persists
- hydrological thresholds that represent the limits of ecosystem persistence and resilience or vulnerability.

As uncertainty in determining thresholds of relationships between groundwater regimes and ecological responses can be high, particularly during the early years of CSG and LCM development, New South Wales and Queensland have integrated risk assessments into their protocols for determining threats to GDEs (section 7.2). This aims to minimise impacts on the most valuable and vulnerable GDEs (Rohde et al. 2017) until their ecological water requirements are better understood through long-term monitoring of ecological responses to changes in groundwater regime (Tool 17, long-term observation of ecosystem response to change, Table 2 and App Table 2) and modelling ecosystem response to potential threats to groundwater (Tool 18, numerical groundwater modelling, Table 2 and App Table 2).

CASE STUDY 5:

Long-term monitoring of ecosystem response to changes in groundwater condition: Gngangara Mound, Western Australia

Gngangara Mound is a shallow unconfined aquifer that is used to supply potable water to the Perth metropolitan area. Surface water, groundwater and vegetation have been monitored around Gngangara Mound over the last four decades. The amplitude of seasonal fluctuation in groundwater level is about 2.5 m. Only two years after groundwater extraction (for potable water supply) commenced, groundwater levels declined by an additional 2.2 m during summer. The decline in water table, coupled with lower-than-average annual rainfall and a period of high summer temperatures, resulted in extensive dieback of *Banksia* species (a loss of 20–80% of adults of overstorey species and up to 64% of adults of understorey species) within 200 m of the production bore. No significant overstorey or understorey dieback occurred at the reference site over the same period (Groom et al. 2000). Subsequent studies, summarised in Eamus et al. (2015b), have examined the vulnerability of *Banksia* species to changes in the depth to the water table by using a number of techniques for assessing vegetation water stress (including xylem embolism vulnerability, leaf water potential, Huber values (the ratio of sapwood to leaf area), leaf-specific hydraulic conductivity, and root growth).

Key findings included:

- two of the species of facultative phreatophytes were more resistant to xylem embolism at the upper slope (greater depth to groundwater) than at the lower slope (Canham et al. 2009)
- vegetation species, in order of increasing sensitivity to groundwater level decline, were *B. menziesii*, *B. attenuata*, *B. ilicifolia* and *Melaleuca preissiana* (Froend and Drake 2006)
- critical leaf water potentials below which dieback would be likely to occur (Froend and Drake 2006)
- at the surface, root growth responded to seasonality and microclimate, whereas at depth, root growth continued all year and was dependent on soil aeration (e.g. rapid root elongation following the declining water table and dieback when groundwater levels rose) (Canham et al. 2012)
- groundwater level declines of 50 cm/year resulted in mass dieback of both mesic and xeric species, whereas at the reference site, groundwater level declines of 9 cm/year reduced the abundance of both mesic and xeric species but did not cause the replacement of mesic with xeric species (Sommer and Froend 2010)
- reduced groundwater levels have caused incidents of reduced groundwater quality, with salt water intrusion occurring in some coastal and estuarine parts of Gngangara Mound
- lowered groundwater levels have contributed to acidification of some wetlands due to the exposure of acid sulfate soils. Artificial watering of the wetlands has reduced the impacts of acidification on macroinvertebrate communities (Sommer and Horwitz 2009).

7.2 Risk assessment

Risk assessments provide a mechanism to make an indicative evaluation, via a threat analysis, of how the current GDEs might change if groundwater conditions change (Richardson et al. 2011a). To assess the risk of CSG and LCM activities affecting GDEs, risk assessments need to define relationships for each threat between (i) the consequences to the GDE, spatially and temporally, as a function of the severity of the threat; (ii) the likelihood of the threat affecting each GDE; and (iii) the significance of impacts in a regional/state/national context.

Serov et al. (2012) present a risk assessment approach that:

- identifies GDE types and their inferred degree of dependence on groundwater
- determines ecological value of the aquifer and its associated GDEs
- determines likely impacts of each activity on the aquifer and/or associated GDEs
- determines the level of potential risk from each activity
- develops management strategies for each activity through a risk matrix approach (App Table 8 and App Table 9).

By assessing the value of each GDE in the project impact area and the vulnerability of each GDE to activities affecting groundwater, GDEs that have high ecological value and/or are subject to high risk can be identified so that management actions can be prioritised to minimise risk while data from monitoring programs are gathered to reduce uncertainty (Rohde et al. 2017; App Table 9). Monitoring programs may take years to produce sufficient data to reduce uncertainty about how dependent GDEs are on groundwater or to quantify the relevant thresholds of change in groundwater condition that will affect GDEs. Incorporating risk assessment into an adaptive management framework can help prioritise work, reduce risk and avoid adverse impacts on GDEs despite the uncertainties (Rohde et al. 2017). However, it is likely that more targeted investigations using more advanced methods (e.g. Table 2 and App Table 2; Rohde et al. 2017) will still be required to better understand the relationships between ecosystem condition and groundwater availability.

RECOMMENDATION:

A risk assessment must be undertaken in all EIAs to identify GDEs that have high or medium ecological value and/or are at high or medium risk of impacts from CSG and LCM activities, so that management actions can be prioritised. Impacts on GDEs should be avoided where possible and, if unavoidable, followed by appropriate mitigation strategies.



A group of Little Egrets

7.3 Gaps in current GDE assessments

The inclusion of GDEs in impact assessments has been a requirement in Queensland and New South Wales for less than a decade, so there is still some uncertainty among consultants about how GDE assessments should be undertaken. This has led to gaps in the assessment process, and these in turn potentially result in underestimating impacts of CSG and LCM activities on GDEs in the project impact area. These gaps include:

- use of online databases only instead of incorporating information from tailored field surveys and detailed desktop studies
- assessments carried out by non-GDE specialists who miss critical information or interpret findings incorrectly
- information gaps in ecology, taxonomy and distribution of many groundwater-dependent species and their degree of groundwater dependence
- failure to use the best-practice tool or model for a task
- assessments that focus on only the area proposed for development, rather than the cumulative impact of the whole operation and adjacent activities
- omission of sufficient reference sites in nearby areas where impacts of CSG and LCM activities are not predicted
- gaps in assessment requirements
- uncertainty of proponents about what is required for adequate GDE assessments.

RECOMMENDATION:

GDE impact assessments must not rely solely on online databases but should be followed up with desktop and field surveys by qualified specialists who use appropriate methods, models and survey designs that include adequate reference sites.



Water level monitoring site in a swamp

7.3.1 Information sharing between consultants during the EIA process

For a single (or multiple adjacent) CSG or LCM projects, GDE impact assessments are often completed in conjunction with other impact assessments of vegetation and aquatic ecology. During the EIA process, a vast amount of information is gathered about a region, often by different consultants. Some of this information, while not collected specifically for GDEs, can be highly relevant to GDE assessments. It is important that this relevant information be shared freely between consultants where possible through direct communication, via a facilitating party or through the company undertaking the CSG or LCM activities. This will prevent needless repetition of work and allow a more holistic assessment of potential impacts.

RECOMMENDATION:

Project consultants should share information during all stages of EIA development to provide a full assessment of potential impacts on GDEs.

OUTCOME:

The proponent, after defining the baseline condition and ecosystem value of each GDE within the area of potential impact, will have identified how the GDEs and the services they provide are likely to respond to changes in groundwater regime and water quality, which processes are likely to threaten GDEs as a result of CSG and LCM activities, and which GDEs are most at risk, and the likely consequences at regional, state and national levels. This risk assessment will use transparent and repeatable approaches (e.g. the GDE Risk Management matrix) and, where possible, use all GDE data collected by different consultants in the project area.

8 Avoidance, mitigation and management options

Once the locations, ecological condition and ecosystem values of GDEs in the project impact area are known, the key management goal is to protect them from impacts of CSG and LCM activities that may reduce their ecosystem value, whether the impacts occur in the pre-construction, construction, operational or post-operational phase (including rehabilitation). This requires strategic planning to either avoid the impacts or, where impacts are unavoidable or unforeseen, mitigate them (see arrow 6 in Figure 5). A GDE management plan is needed that details:

1. the ecological components and water requirements of each GDE
2. their ecological condition and ecosystem value
3. the legislative status under which they might be protected
4. the causal pathways and risks of each potential impact
5. the measures that will be used to avoid or mitigate each impact
6. the monitoring regime that will detect the effectiveness of these measures
7. any proposed adaptive management measures that could be implemented in response to monitoring results indicating that management measures have not been as effective as expected.

8.1 Management plans

A management plan will draw on information from all the steps described in the previous sections of this Explanatory Note. The plan should present the causal impact pathways (section 3.1) illustrated in appropriate conceptual models, and use information from desktop analyses and field surveys (sections 5 and 6) to identify likely GDEs, their ecological water requirements, baseline condition and ecosystem values. From this information, potential threats and risks are assessed (section 7) so that options to avoid or mitigate impacts can be presented and justified.

Monitoring is fundamental to inform the management plan and develop sampling regimes that effectively assess GDEs against baseline conditions and reference sites (section 6). For all phases of operation, management control measures must be described for each GDE against impacts that might arise or change as a result of CSG or LCM activities, such as groundwater drawdown or contamination. The plan must establish a monitoring protocol with sampling at a suitable frequency to detect change in condition of taxa such as threatened flora species (section 6.3), and from locations that would signal imminent threats (section 6.4).

If some change to condition occurs or is predicted, mitigation measures must be detailed for each GDE, outlining what a trigger for corrective action might be (e.g. drawdown in the vicinity of a spring complex exceeding an acceptable level of change that has been determined through research and monitoring). The corrective action should be described in full and involve some form of adaptive management. For example, monitoring could be repeated immediately and, if non-compliant results recur, there could be an incident report and an investigation that leads to implementation of suitable corrective action identified in the mitigation strategy. The effectiveness of this corrective action would then be monitored to confirm its success.



Swift Parrot
© Chris Tzaros

8.1.1 Objectives and indicators of management plans

The key objective of a management plan is to present actions and procedures that need to be followed during all phases of CSG or LCM activities to avoid or mitigate adverse impacts on GDEs. Performance indicators guide the management and protection of GDEs and are likely to be specific to each development. Examples of indicators of performance include ensuring that impacts on GDEs do not cause unacceptable or unapproved loss of biodiversity values and, for aquatic GDEs, downstream flow changes remain within natural ranges of fluctuation .

8.1.2 Avoidance

Avoidance is the preferred option for preventing significant impact to all GDEs, especially high-value ones. Avoidance involves comprehensive planning to select access routes and development sites that will avoid impacts on GDEs. This might include altering a road, rail or pipeline alignment to avoid removing a vegetation GDE, or revising mine location or aspect to reduce impact area or magnitude. Mine dewatering plans might require alteration to avoid impacts related to timing, extent or magnitude of dewatering that may impair hydrological links to GDEs.

If significant impacts can be avoided, the need for mitigation and offsets to provide environmental benefits to counterbalance the impacts can also be avoided. Monitoring is required to ensure that these measures are successful and no impacts on GDEs occur.

RECOMMENDATION:

Avoidance of impacts on GDEs is the preferred option for preventing significant impacts from CSG and LCM activities.

8.1.3 Mitigation

Mitigation is the reduction of all unavoidable impacts as much as possible (see CASE STUDY 6 for an example). While avoidance is the preferred management option, usually CSG and LCM activities will have some impacts on GDEs that can only be reduced through mitigation measures.

Where it is determined that loss or mortality of groundwater-dependent vegetation and fauna is likely to occur, it is critical to actively manage and, if possible, enhance the ecosystem values that characterise the project impact area and surrounding landscape before and during operations to reduce the overall impact on biodiversity values.

Mitigation actions can include supplementing reduced hydrological connectivity to aquatic GDEs with treated water recovered during CSG and LCM activities, removing weeds and pests, and controlling sediment erosion.

Mitigation strategies must be supported by:

- scientific literature and case studies that describe where the strategy has been successful
- justification of why and how the proposed mitigation measures will be successful in the project impact area, using the causal pathways shown in conceptual modelling
- a plan to monitor the effectiveness of the mitigation by targeted monitoring of GDEs
- a statement of how to determine whether a mitigation measure is a success or a failure, highlighting how to detect early signs of failure or benchmarks against which success is determined (e.g. no decline compared with reference sites outside the impact zone)
- a statement of the management options available if mitigation fails.

Rehabilitation may be considered. However, investigation is required to ensure that pre-impact groundwater regimes and water quality can be established, and that the cumulative impacts over decades do not completely degrade the GDE. Under the New South Wales Aquifer Interference Policy (DPI Office of Water 2012), proponents are required to provide a security deposit to be held by the New South Wales Government to ‘cover the costs of remediation works for unforeseen impacts or ongoing post-closure activities’. Queensland has similar financial assurance provisions. The amount deposited is to reflect the level of risk to the aquifer or its dependent ecosystems, and is determined separately for each case.

RECOMMENDATION:

Mitigation strategies to minimise impacts on GDEs are needed when avoidance is not possible. These strategies are required before operations commence. Targeted monitoring is needed to confirm the effectiveness of these mitigation strategies.



Weeli Wolli Creek © Garry Davies

CASE STUDY 6:

Mitigation strategy for reduced spring flow—Weeli Wolli Creek

The Weeli Wolli Creek system in the Pilbara, north Western Australia, is a source of permanent water in a dry landscape. The creek system, including a spring and pools, is considered a high-priority ecosystem because it supports a unique community of vegetation and fauna, some species of which are endemic to the spring. In 2009, the spring was nominated for listing as a Threatened Ecological Community at the state level on the basis of floristic communities as well as the diverse aquatic invertebrate and significant stygofauna communities (van Leeuwen 2009). Furthermore, Weeli Wolli Creek has considerable spiritual and cultural value to the Traditional Owners. There are a number of active iron ore mines in the Weeli Wolli catchment.

Under natural conditions, most creeks in the Pilbara are ephemeral, with flow only occurring after occasional intense rainfall events. However, groundwater discharge from Weeli Wolli Spring maintains perennial creek flow for approximately 2 km; after this streamflow becomes ephemeral. Permanent pools are also present in the creek near the spring. The perennial spring discharge is episodically swamped by peak storm-derived creek flow.

Weeli Wolli Spring woodland includes known obligate (*Melaleuca argentea*) and facultative (*E. camaldulensis* and *E. victrix*) groundwater-dependent trees and a unique understorey for the area (including sedge and herbfield communities) that fringe many of the pools. The extent of these vegetation types is regularly disturbed by intense rainfall and flooding, which is also likely to instigate regeneration.

The Weeli Wolli Creek catchment is rich in stygofauna, with 56 species recorded, most of which were around Weeli Wolli Spring (Bennelongia Environmental Consultants 2015). Several creek-line and hyporheic species of conservation and/or scientific value have been identified (Wetland Research and Management 2015):

- hyporheic species: *Vestenula* n. sp. (new species of ostracod), *Chydaekata* sp., *Paramelitidae* sp., *Maarrka weeliwolli* (stygol paramelitid amphipods—short-range endemic) and *Pygolabis weeliwolli* (stygol isopod—short-range endemic)
- macroinvertebrate species: *Hemicordulia koomina* (Pilbara Emerald Dragonfly—IUCN near threatened), *Eurysticta coolawanyah* (Pilbara Pin Damselfly—IUCN near threatened), *Ictinogomphus dobsoni* (Pilbara Tiger Dragonfly—Pilbara endemic, restricted distribution), *Aspidiobates pilbara* and *Wandesia* sp. (water mites—Pilbara endemic, restricted distribution).

Mine dewatering and discharge of surplus water were processes identified that could potentially threaten the Weeli Wolli Creek system. An irrigation system was designed to counter the impacts of groundwater drawdown, such as reduced spring flow which could cause groundwater levels to drop out of reach of phreatophytic vegetation. Surplus water of a suitable quality is discharged by the mine at several locations in the creek-line to maintain baseflow and permanent pools in the vicinity of the spring. This water also supports a shallow groundwater system, riparian vegetation and some phreatophytic vegetation that requires additional irrigation. Watering will continue for the duration of the dewatering operations and until natural spring flow resumes.

Ten years after dewatering and irrigation commenced, natural spring flow has ceased and there have been some changes in vegetation. Although the overall ecosystem of the spring and creek appears to be functioning, supported by artificial spring discharge (Government of Western Australia 2018b), the impact of groundwater dewatering and artificial watering at Weeli Wolli Spring on stygofauna and hyporheic and aquatic macroinvertebrate species has not yet been described in currently available literature.

Concern remains that discharge of surplus water into the creek-line, which extends the perennially flowing portion of Weeli Wolli Creek for several more kilometres downstream, could cause adverse impacts due to the long-term increase in average water levels.

8.1.4 Environmental offsets

An environmental offset is defined as an activity undertaken to counterbalance the residual impact of a prescribed activity on a prescribed environmental matter ([Environmental Offsets Act 2014 \(QLD\)](#) (Queensland Government 2014b)) or measures to compensate for the residual adverse impacts (unavoidable impacts) of an action on the environment. Offsets are intended to counterbalance the impacts that remain after avoidance and mitigation measures have been applied. They are required if residual impacts are significant. Where GDEs have endemic species or a spring complex has a rare or unique combination of species, offsetting is unlikely to be a viable option if residual impacts are significant. Therefore, other options require investigation.

Offsets can create a net positive or, at least, should aim for no net overall loss of ecological value. Examples of offsetting GDEs are currently rare. However, a proposal has been made in the GDE Management Plan for Carmichael Coal Mine to offset 4 ha of groundwater-dependent waxy cabbage palm (GHD 2014). The proposal claims there are 2744 ha of suitable waxy cabbage palm habitat available outside the project impact area, so direct offsetting may be feasible in this case. Indirect offsetting was also proposed, through measures including seed collection and planting along upstream reaches of the Carmichael River, relocation of plants, contributing to research to understand range, water dependence and thresholds of processes threatening to waxy cabbage palms, and conservation activities in waxy cabbage palm habitat outside of the project impact area.

8.1.5 Monitoring

Monitoring is essential to measure the effectiveness of mitigation practices. Monitoring programs need to be project specific and should include monitoring for changes in the groundwater regime (e.g. declines in water level) as well as changes to GDE condition (e.g. vegetation stress, major changes in stygofauna assemblage composition). Monitoring networks should be designed to test specific hypotheses generated during the development of monitoring plans. In establishing a monitoring program to assess the effectiveness of mitigation practices:

- each of the variables measured should have a clearly justified purpose and be explicitly linked to the mitigation measure(s) it aims to test
- the level of detail (number of replicates, number of sites, survey timing, precision of measurement of variables) should be sufficient to detect the level of change that indicates an impact
- ecological data should have associated groundwater data
- data should be analysed soon after collection to facilitate prompt adaptive management actions and the mitigation of unforeseen impacts.



View of Lee's Reserve on the McIntyre River near Goondiwindi in the Border Rivers-Condamine catchment area

Variables that show changes in the condition of the aquifer (rather than the GDE) and that can provide real-time data should be used as early indicators of imminent impacts on a GDE. Real-time sources for groundwater data include telemetered loggers that measure groundwater level and salinity, and satellite imagery. If groundwater data show that site-specific guidance values are likely to be exceeded, field surveys (section 6) can be used to assess the level of ecosystem stress, and the results can prompt changes to management strategies.

There are very few biological or ecological variables that can be used as reliable early-warning signs of impact from CSG or LCM activities. Impacts on GDEs are usually evident as a loss in condition or visible signs of stress in individual ecosystem components, but these symptoms often appear at the surface only after the impact has taken hold. At this point it may be too late for successful mitigation. Hence, real-time groundwater data are important to GDE monitoring programs so that mitigation actions can be as effective as possible.

RECOMMENDATION:

Proponents will need to identify hydrological variables that can be used as early warning indicators of groundwater change to draw attention to imminent impacts on GDEs. Data need to be analysed soon after collection so that adaptive management to avoid or mitigate impacts can begin promptly.

OUTCOME:

The proponent will have a management plan which prioritises avoiding impacts on GDEs and justifies mitigation measures to reduce unavoidable impacts. The management plan will include specific monitoring protocols to assess the effectiveness of mitigation strategies or identify unexpected impacts.

9 Concluding statements and recommendations

Proposals for new CSG and LCM projects and expansions of existing developments are required by Australian legislation to consider impacts on GDEs. State-based policies aimed at protecting GDEs have been evolving since 2002, as have guidelines and tools to assist in the proper consideration of GDEs in impact assessment. The refinement of policy and assessment protocols over the past decade as new information became available has resulted in some inconsistencies in how impacts on GDEs are considered. This Explanatory Note provides an assessment framework that is consistent with requirements in New South Wales and Queensland and can be applied to other states and territories as necessary.

There are still many uncertainties in our understanding of how different types of GDEs use groundwater and how they are then affected when the groundwater regime or water quality is altered. Little is also known about how best to manage GDEs when impacts are imminent, or how to restore impacted GDEs. All GDE assessments need to take these uncertainties into account and should be adapted to consider new knowledge that becomes available.

Online spatial and non-spatial databases are critical components of improving GDE assessment. However, many GDEs are currently unmapped, so impact assessments should not rely solely on searches of online databases. Where there are potential GDEs in the project impact area, field-based assessments must be conducted to determine their ecological condition and ecosystem value, and the nature of their reliance on groundwater. The power and accuracy of online databases would be substantially improved if the different databases were coordinated, curated and updated regularly with data gathered during impact assessments, and if proponents were encouraged to share their raw data on GDEs.



A Giant Barred Frog (female)

Many of the options for mitigating impacts on GDEs have largely gone untested and deserve further research. Proposed mitigation measures should be carefully considered and justified. Proponents should identify clear and testable criteria that can be used to determine the success of the proposed mitigation strategies. Options should also be given for responding to failure.

9.1 Summary of recommendations made throughout the Explanatory Note

All recommendations apply to both CSG and LCM developments, and to expansions of existing projects as well as to new projects.

- Several helpful publications are mentioned throughout this Explanatory Note to aid proponents. Their use is recommended. Where possible, hyperlinks are given to open-access reports and relevant websites. However, some references include scientific journal papers that may need to be purchased at a low, one-off cost.
- All recommendations apply to both greenfield projects and expansions of existing projects. Proponents need to consider all GDEs that are potentially affected by the project, including GDEs that are only partially or occasionally dependent on groundwater and/or do not support any listed species. Before development starts, all GDEs should be mapped and baseline data collected on their ecological condition. These baseline data, together with an assessment of each GDE's ecosystem value, can be used to prioritise GDEs for management.
- To create and update conceptual models as part of an integrated desktop study of likely groundwater dependence, guided by GDE rules, proponents should use the GDE Atlas; national-, state- and local-scale spatial data; remote sensing; expert knowledge; and scientific studies. The results of such a study will indicate potential GDE presence in and around the project's maximum area of impact (derived from a conservative initial estimate early in the EIA) and capture the relationships between potential GDEs and groundwater to enable a preliminary assessment of risks to GDEs.
- Proponents should assess ecological water requirements of GDEs and use this information to identify causal pathways that may create a change in GDE status through altered groundwater regimes. Multiple lines of evidence are to be used to determine groundwater dependence where possible.
- Prioritise site selection and suitable replication during the pre-development stage so that a representative subset of sites can be included in subsequent monitoring to track changes during CSG or LCM operations. GDE monitoring sites should be located near groundwater monitoring bores. Monitor comparable GDEs from outside the predicted area of impact, where possible, to provide reference points against which to assess hydrological and ecological changes over time.
- Proponents should, where possible, identify a suitable number of reference sites outside the project impact area that are representative of GDEs in the project impact area. The sampling regime (number of sites and frequency of sampling) and selected variables need to reflect ecological condition and ecosystem value, level of groundwater dependence and level of risk to the GDE. Their choice must be justified in the EIA.
- A risk assessment must be undertaken in all EIAs to identify GDEs that have high or medium ecological value and/or are at high or medium risk of impacts from CSG and LCM activities, so that management actions can be prioritised. Impacts on GDEs should be avoided where possible and, if unavoidable, followed by appropriate mitigation strategies.
- GDE impact assessments must not rely solely on online databases but should be followed up with desktop and field surveys by qualified specialists who use appropriate methods, models and survey designs that include adequate reference sites.

- Project consultants should share information during all stages of EIA development to provide a full assessment of potential impacts on GDEs.
- Avoidance of impacts on GDEs is the preferred option for preventing significant impacts from CSG and LCM activities.
- Mitigation strategies to minimise impacts on GDEs are needed when avoidance is not possible. These strategies are required before operations commence. Targeted monitoring is needed to confirm the effectiveness of these mitigation strategies.
- Proponents will need to identify hydrological variables that can be used as early warning indicators of groundwater change to draw attention to potential imminent impacts on GDEs. Data need to be analysed soon after collection so that adaptive management to avoid or mitigate impacts can begin promptly.

10 Acknowledgements

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11 Abbreviations and acronyms

SHORT FORM	MEANING
ACLUMP	Australian Collaborative Land Use and Management Program
ANAE	Australian National Aquatic Ecosystem classification framework
BOM	Bureau of Meteorology
CSG	Coal seam gas
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DAWR	Department of Agriculture and Water Resources
DEM	Digital elevation model
DPI	Department of Primary Industries
DSITI	Department of Science, Information Technology and Innovation
EC	Electrical conductivity
eDNA	environmental DNA
EIA	Environmental impact assessment
EIS	Environmental impact statement
EPA	Environment Protection Agency
EPBC Act	<i>Environment Protection and Biodiversity Conservation Act 1999</i>
ET	Evapotranspiration
GA	Geoscience Australia
GDE	Groundwater-dependent ecosystem
HEV	High ecological value
HEVAE	High ecological value aquatic ecosystems
IDE	Inflow-dependent ecosystem
IUCN	International Union for Conservation of Nature
IESC	Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development
LCM	Large coal mining
LEV	Low ecological value
MEV	Moderate ecological value
MODIS	Moderate Resolution Imaging Spectroradiometer
NDVI	Normalised difference vegetation index
NDWI	Normalised difference wetness index
NVIS	Native Vegetation Information System
PAR	Photosynthetically active radiation
SEA	Sensitive environmental area
SEED	Sharing and enabling environmental data portal
SRTM	Shuttle Radar Topography Mission

12 Glossary

TERM	DESCRIPTION
Acceptable level of change	The degree to which a stated variable (e.g. species diversity, groundwater level, NDVI) can be affected by LCM or CSG activities without being considered a significant impact. Where past data or data from reference sites are available, it may be possible to determine the acceptable level of change as that which lies within the natural range of variability.
Bioregional assessment	A scientific analysis of the ecology, hydrology, geology and hydrogeology of a bioregion, with explicit assessment of the potential direct, indirect and cumulative impacts of CSG extraction and coal mining development on water resources. The central purpose of bioregional assessments is to inform the understanding of impacts on and risks to water-dependent assets that arise in response to current and future pathways of coal seam gas and large coal mining development.
Coal seam gas development	Defined under the <i>EPBC Act 1999 (Cth)</i> as any activity involving CSG extraction that has, or is likely to have, a significant impact on water resources (including any impacts of associated salt production and/or salinity), in its own right or when considered with other developments, whether past, present or reasonably foreseeable developments.
Conceptual model	A descriptive and/or schematic hydrological, hydrogeological and ecological representation of the site showing the stores, flows and uses of water, which illustrates the geological formations, water resources and water-dependent assets and provides the basis for developing water and salt balances and inferring water-related ecological responses to changes in hydrology, hydrogeology and water quality.
Cumulative impact	Defined as the total impact of a CSG and/or LCM development on water resources when all past, present and/or reasonably foreseeable actions that are likely to impact on water resources are considered.
Ecological processes	Part of the components that contribute to the physical state and environmental value of a water resource. They can include processes such as nutrient cycling, eutrophication and carbon metabolism.
Facultative	When used with reference to GDEs, refers to those that use groundwater optionally or opportunistically rather than solely (see 'obligate').
Groundwater-dependent ecosystems (GDEs)	Ecosystems that require access to groundwater on a permanent (obligate) or intermittent (facultative) basis to meet all or some of their water requirements so as to maintain their communities of plants and animals, ecological processes and ecosystem services. GDEs include terrestrial vegetation, wetlands (swamps, lakes and rivers) and ecosystems in aquifers and caves.
Groundwater regime	The prevailing pattern of groundwater behaviour in an aquifer over time. The regime considers the magnitude, duration and frequency of water level fluctuations, as well as the direction of water movement through the three-dimensional space of an aquifer.

TERM	DESCRIPTION
Hyporheic zone	The region beneath and alongside a stream or river where there is mixing of shallow groundwater and surface water.
Inflow-dependent ecosystem	A GDE Atlas term that describes ecosystems that are likely to be using another source of water in addition to rainfall. IDEs include groundwater-dependent ecosystems as well as ecosystems that use sources of water other than rainfall (e.g. surface water, water stored in the unsaturated zone, irrigation).
Known GDEs	GDEs that have previously been identified using field studies or desktop studies.
Large coal mining development	Defined under the <i>EPBC Act 1999 (Cth)</i> as any coal mining activity that has, or is likely to have, a significant impact on water resources (including any impacts of associated salt production and/or salinity), in its own right or when considered with other developments, whether past, present or reasonably foreseeable developments.
Obligate	When used with reference to GDEs, refers to those that are entirely dependent on groundwater (see 'facultative').
Phreatophytes	Plants that habitually obtain their water from groundwater, via the zone of saturation, either directly or through the capillary fringe above the water table.
Piezometer	A specially designed bore with a short intake screen to monitor groundwater levels at a specific point in an aquifer.
Project impact area	The likely area of impact from CSG or LCM activity.
Riparian vegetation	Vegetation on the banks of streams and rivers. Its distribution is often governed by permanent or occasional access to groundwater.
Significant impact	Defined by the Significant Impact Guidelines (CoA 2013a) as an impact that is important, notable or of consequence, having regard to its context or intensity. Whether or not an action is likely to have a significant impact depends upon the sensitivity, value and quality of the water resource which is impacted, and upon the intensity, duration, magnitude and geographic extent of the impacts.
Water balance	A mathematical expression of water flows and exchanges, described as inputs, outputs and changes in storage. Surface water, groundwater and atmospheric components should be included.

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Appendix A: Impacts

App Table 1. Examples of activities in CSG and LCM development that potentially impact on GDEs, including by reducing native species numbers and altering species composition within GDE communities; disrupting ecological processes that deliver ecosystem services; damaging aquifer geologic structure; increasing risk of exotic species invasion; removing GDE habitat; altering groundwater quality; and changing timing, duration, pressure and flow conditions of groundwater

Impacting activity	Type of impact	Type of GDE affected	When does this impact need to be considered in EIA?	Factors to consider during impact assessment
Aquifer dewatering	Water table lowering; change in timing and magnitude of groundwater level fluctuations	All	When an aquifer connects to a surface GDE; when an aquifer (alluvial, karstic, calcrete) is likely to have stygofauna that experience dewatering at a rate, magnitude and duration outside natural variability	Magnitude, duration, rate, frequency, and timing of dewatering; how these compare to pre-impact conditions and/or at reference sites
				Initial water table depth; water level fluctuation range over annual and supra-annual timescales, amplitude and rate of change
				Water table lowering (e.g. will it convert gaining streams or wetlands to losing ones?)
Aquifer depressurisation	Loss of artesian pressure	Springs	When depressurisation is of an aquifer connected to a spring	Lost pressure; alteration of discharge flow rate to spring
				Flow rate changes affect water level, permanence and spring water quality, with potential impacts on spring biota
Excavation of overburden	Removal of upper aquifer	All	When the overburden is an aquifer that supports GDEs	Water table depth in overburden; aquifer porosity
				Alteration of subsurface flow paths with excavation

Impacting activity	Type of impact	Type of GDE affected	When does this impact need to be considered in EIA?	Factors to consider during impact assessment
Surface topography changes	Alteration of groundwater recharge patterns	Vegetation; wetlands; river baseflow GDEs; aquifer GDEs	When there are major landscape changes such as excavation of mine pits or subsidence of longwall panels	Alteration of channelling of water to or from aquifer recharge zones; availability of groundwater modelling
				Potential flow changes considered in groundwater modelling
				Whether GDEs have some level of reliance on surface water
River diversion	Disconnection between river and aquifer	River baseflow GDEs; aquifer GDEs	When connection exists between channel and aquifer	Whether the diverted reach is dependent on groundwater, either locally or upstream
Leakage of saline or contaminated water from surface storage or through fractures between aquifers	Increase in aquifer salinity; decline in water quality	All	When a pressurised lower aquifer of poor water quality occurs beneath an aquifer with better quality water that supports GDEs	Whether dilution of saline water will occur; whether there is a risk of contamination of adjacent aquifers or transfer of contaminants to GDEs
			When overflow or leakage from storage dams and water infiltrates aquifers	Rate of dispersal of saline or contaminated water
			When hydraulic fracturing is planned and there is potential for a confining layer to be ruptured.	Chemistry of saline or contaminated water compared to that in the receiving aquifer
Construction and operation of surface infrastructure (buildings, roads, rail, pipelines, stockpile areas)	Permeable surface compaction; pollution from effluents, petrochemicals, explosives and other on-site chemicals	All	When infrastructure is located upslope of aquifer recharge areas (including coal and rock stockpiling areas)	Footprint of disturbance area; proximity to GDEs, especially high-value ones
Leachates from coal or rock stockpiles	Potential groundwater pollution from saline or acid drainage	Aquifer GDEs	When there is potentially toxic stockpile leachate	Geochemical characteristics of the stockpiled rock; process of stockpile draining

Impacting activity	Type of impact	Type of GDE affected	When does this impact need to be considered in EIA?	Factors to consider during impact assessment
Vegetation clearing	Direct impact on groundwater-dependent vegetation; removal of organic matter source for aquifer communities	Vegetation; aquifer GDEs	When large areas of vegetation are removed	Frequency of vegetation groundwater extraction; location and type of vegetation
Construction and operation of an open pit lake	Aquifer impact through poor water quality	Aquifer GDEs; river baseflow GDEs; wetlands	When there is potential for pit lakes to leak into aquifers supporting GDEs	Potential to release water into the surrounding aquifer through seepage; water quality of pit lake
				Geochemical rock characteristics; chemical changes in pit water once mining ceases
				Flow rate and direction of groundwater drainage

Appendix B: Tools to identify GDEs

App Table 2. Summary of tools for assessing GDEs (adapted from the [GDE Toolbox Pt 2](#) (Richardson et al. 2011b) with inclusion of recent methods such as eDNA)

Tool code	Tool	Brief description	Further information
1	Landscape mapping	Locating and identifying ecosystems that are potentially groundwater dependent, based on biophysical parameters such as depth to water table, soils and vegetation type. Assessing primary productivity, water relations and/or condition of vegetation communities using remotely sensed images to infer use of groundwater	GDE Toolbox
2	Conceptual modelling	Documentation of a conceptual understanding of the location of GDEs, interactions between ecosystems and groundwater, and potential cause–effect pathways of impacts	GDE Toolbox
3	GDE Atlas	A web-based national dataset of Australian GDEs. It includes a national inflow-dependent landscapes layer, derived from remotely sensed data, which indicates the likelihood that a landscape is using water in addition to rainfall	GDE Atlas CoA (2018a)
4	ANAE classification	The Australian National Aquatic Ecosystem (ANAE) classification framework is a nationally consistent process for classifying aquatic ecosystem and habitat types within a regional and landscape setting	ANAE AETG (2012a)
5	Pre-dawn leaf water potential	Identification of groundwater uptake by components of vegetation on the basis of pre-dawn measurements of leaf water potential	GDE Toolbox
6	Plant water stable isotopes	Use of naturally occurring stable isotopes of water to identify sources of water used for plant transpiration	GDE Toolbox
7	Plant water use modelling	Identification of sources and volumes of water used for plant transpiration, through mathematical simulations of plant function	GDE Toolbox
8	Plant rooting depth and morphology	Comparison of the depth and morphology of plant root systems with measured or estimated depth to the water table to assess the potential for groundwater uptake	GDE Toolbox

Tool code*	Tool	Brief description	Further information
9	Plant groundwater use determination	Measures of leaf area index and climatic data are used to estimate groundwater discharge from terrestrial ecosystems that have access to groundwater	GDE Toolbox
10	Water balance—vegetation	Use of water-balance measurements and/or calculations to determine whether and to what extent plant water use is dependent on groundwater uptake	GDE Toolbox
11	Stygofauna sampling	Techniques available to collect groundwater fauna	GDE Toolbox
12	Evaluation of surface water – groundwater interactions	Analysis of the hydraulics of surface water – groundwater interactions. The processes by which groundwater discharge into surface water systems provides insight into the nature of groundwater dependency in wetlands and baseflow river ecosystems	GDE Toolbox
13	Environmental tracers	Environmental tracers are a naturally occurring physical or chemical property of water that can be used to trace its flow path. Analysis and interpretation of these properties of surface water and groundwater can be used to identify groundwater contribution to dependent ecosystems	GDE Toolbox
14	Introduced tracers	Analysis of deliberately introduced hydrochemical tracers to identify water sources and surface water – groundwater mixing relationships	GDE Toolbox
15	Genetic/DNA analysis	Analysis of environmental DNA (eDNA) or DNA collected from captured stygofauna to identify species present in an aquifer	
16	Literature	Review existing journal articles and reports. Look up conservation status and endemism of GDEs. Access information on species composition and ecosystem function for different GDEs	
17	Long-term observation of ecosystem response to change	Long-term observations of GDEs and the hydrologic environment they exist within to establish ecosystem responses to changes in water regime due to climatic and/or anthropogenic influences	GDE Toolbox

Tool code*	Tool	Brief description	Further information
18	Numerical groundwater modelling	Construction of mathematical models to simulate groundwater flow systems	GDE Toolbox
19	Remote sensing	Use of vegetation greenness, wetness, and land surface temperature to discriminate GDEs. Use of wetness index to delineate water bodies	

* tool code is a numerical identifier adopted for this Explanatory Note

Appendix C: Resources useful for identifying GDEs, including national data availability

App Table 3. Landscape and ecosystem datasets that are useful to help identify GDEs. This list should be used as a starting place because it is not an exhaustive list

Ancillary data	Data types	Dataset link and source
<i>Landscape datasets</i>		
DEM / surface elevation	Aerial photographs, satellite imagery	1 second SRTM DEM (GA 2011a) GEODATA 9 second DEM (GA 2008)
Groundwater depth	Maps, reports, observation bore records	National groundwater information system (CoA 2018b) Australian groundwater explorer (CoA 2018c)
Groundwater flow systems and elevations; hydrogeology	Maps, reports, observation bore records, DEM	Australian groundwater flow systems (DAWR ABARES 2000)
Surface water level	Maps, reports, observation bore records, river gauge data	Water data online (CoA undated a)
Surface water (rivers, wetlands, springs) mapping	Aerial photographs, satellite imagery, Google Earth	National flow direction grid (GA undated a) Geofabric (CoA 2018d) Water observations from space (GA undated b) Interactive maps —water (GA undated c)
River connectivity/classification map Groundwater—surface water connectivity	Geological and hydrogeological mapping	River classification report (Kennard et al. undated)

Ancillary data	Data types	Dataset link and source
Underlying geology and geological structure (e.g. fractured rock aquifer); geophysics	Maps, reports, ground surveys, geophysical survey	Interactive maps —geophysics (GA undated c)
River flow data	River gauge data	Water data online (CoA undated a) Regional water information (CoA 2018e) Real-time data NSW (WaterNSW undated) Water monitoring and data QLD (Queensland Government 2017a) WaterConnect SA (Government of South Australia 2017) Water monitoring VIC (Victoria State Government undated a)
Consumption infrastructure (bores)		National groundwater information system (CoA 2018b)
Climate data		Bureau of Meteorology (CoA 2018f)
Soil mapping	Maps, ground surveys, geological survey, site assessment	Soil and landscape grid of Australia (CSIRO undated) Australian soil resource information system (CSIRO 2014)
Hydrogeology (water table salinity; aquifer boundaries; principal hydrogeology)	Maps, ground surveys, geological survey, site assessment	National groundwater information system (CoA 2018b)
Recharge/discharge areas	Remote sensing, geological mapping information	Recharge-discharge estimator suite (Crosbie et al. 2015)
Land use	Aerial imagery, remote sensing	ACLUMP (CoA 2018g)
National water balance		Australian landscape water balance (CoA 2018h)
<i>Ecosystem datasets</i>		
Vegetation (classification and composition) mapping	Maps, ground surveys, aerial photographs, satellite imagery	NVIS (CoA undated b)

Ancillary data	Data types	Dataset link and source
Known GDEs (especially subsurface), potential GDEs	Reports, ground surveys, satellite imagery	GDE Atlas (CoA 2018a)
IDE layer (data on IDE likelihood)	GDE Atlas	GDE Atlas (CoA 2018a)
Wetland classification mapping	National Wetland Inventory	Directory of important wetlands in Australia (DoE 2015)
EPBC Act listing (flora and fauna, Threatened Ecological Communities)		Databases and applications—EPBC Act (CoA undated c)
Leaf area index		MODIS (ORNL DAAC undated)
Vegetation condition	Reports, maps, site assessments, satellite imagery	Derive from Landsat mosaic; MODIS (ORNL DAAC undated)

Appendix D: Resources available for specifically identifying/assessing GDEs—state level

App Table 4. Summary of resources available to specifically identify/assess GDEs for each state and territory (includes GIS layers, reports and websites). This list should be used as a starting place because it is not an exhaustive list

State/territory	Data/reports available
Queensland	Queensland Spring Database (Queensland Government undated b) Queensland GDE dataset (QDSITIA 2013) Wetland Maps (Queensland Government 2018b) Biodiversity Status of Remnant Regional Ecosystems (Queensland Government 2017b) Matters of State Environmental Significance (Queensland Government 2017c) Water Monitoring Portal (Queensland Government undated c) EIS information guidelines (Queensland Government 2016) Guideline for the Environmental Assessment of Subterranean Aquatic Fauna: Sampling Methods and Survey Considerations (Queensland Government 2015) A method for catchment scale mapping of groundwater-dependent ecosystems to support natural resource management (Queensland, Australia) (Glanville et al. 2016a)
New South Wales and Australian Capital Territory	Risk assessment guidelines for groundwater dependent ecosystems Volume 1 —The conceptual framework (Serov et al. 2012) Volume 2 —Worked examples for seven pilot coastal aquifers in NSW (Williams et al. 2012) Volume 3 —Identification of high probability groundwater dependent ecosystems on the coastal plains of NSW and their ecological value (Kuginis et al. 2012a) Volume 4 —The ecological value of groundwater sources on the coastal plains of NSW and the risk from groundwater extraction (Kuginis et al. 2012b) GDE Dataset (NSW Office of Water 2013) Method for the identification of high probability groundwater dependent vegetation ecosystems (Kuginis et al. 2016) A review of groundwater dependent terrestrial vegetation and groundwater depth for the Namoi CMA, NSW (Stygoecologia 2013) Real-time data NSW (WaterNSW undated) SEED Environmental Data Portal (NSW Government undated)

State/territory	Data/reports available
Victoria	Victorian Wetland Inventory (Victoria State Government 2018a) Ecological Vegetation Classes (Victoria State Government undated b) Mapping terrestrial groundwater dependent ecosystems (Dresel et al. 2010) Wimmera GDEs (Victoria State Government 2018b) Species Tolerance Grid—GDEs (Victoria State Government 2018c) Groundwater Data (Federation University Australia 2018) Groundwater Quality Data (Victoria State Government 2017)
South Australia	Delivering a strategic approach for identifying water-dependent ecosystems at risk (Harding and O'Connor 2012) South Australian Wetlands (South Australian Department for Water 2010)
Western Australia	WA Government data portal (Government of Western Australia 2018c) Managing groundwater on the Dampier Peninsula (Government of Western Australia 2017) Northern Perth Basin GDEs (Government of Western Australia 2009) Perth groundwater map (Government of Western Australia undated)
Northern Territory	A fight for flow—conservation, preservation and management of groundwater dependent ecosystems, Berry Springs, Northern Territory, Australia (Williams 2009) Inventory and risk assessment of water dependent ecosystems in the Daly basin, Northern Territory, Australia (Begg et al. 2001)
Tasmania	A desktop assessment of groundwater dependent ecosystems in Tasmania (Eberhart 2004) Integrated management of groundwater and surface water in Tasmania (Houshold 2011) Freshwater Ecosystems Values (CFEV) Program (Tasmanian Government 2015)

Appendix E: Rules to guide GDE identification

App Table 5. Rules to guide the identification of GDEs using remotely sensed or existing data, as used to develop the GDE Atlas (Doody et al. 2017, SKM and CSIRO 2012), supplemented for aquifer ecosystems for this Explanatory Note and cross-referenced with questions posed by Eamus et al. (2006) shown in Table 1. These rules may not be relevant at all scales but show types of criteria that help to identify GDEs; almost all rules assume that water quality is not a limiting factor (e.g. not saline or contaminated) for GDE potential

Rules of GDE potential	Datasets required	Cross-reference with Table 1
SUBSURFACE GDEs		
Vegetation in landscapes with shallow water table (<5 m or 10 m) will use groundwater when required	Water table depth; vegetation type; vegetation map	
Specific vegetation types have been shown to use groundwater and can be used to indicate where groundwater use may be occurring	Vegetation type; vegetation known to access groundwater; vegetation map	
Vegetation that is using groundwater can be identified by water use and growth patterns during summer months and has a higher annual evapotranspiration (ET) than rainfall	Leaf area index; sapflow; MODIS evapotranspiration; vegetation map	7, 8
Vegetation communities that exist adjacent to persistent water bodies are likely to be accessing groundwater	Wetland/river map; vegetation type; water persistence map; vegetation map	6
Native vegetation surrounding a known spring location or a known GDE is more likely to be a GDE	Spring/wetland map; vegetation map	5, 6, 9
Vegetation growing in soil that has a low water storage capacity and soil depth is more likely to be accessing groundwater	Vegetation map; vegetation type; soil type map; soil water-holding capacity; depth to groundwater	
Vegetation growing in areas where cracking soil plains exist is more likely to rely on trapped surface water or water stored in the unsaturated zone than groundwater	Soil mapping; vegetation type; vegetation map	

Rules of GDE potential	Datasets required	Cross-reference with Table 1
Vegetation surrounding GDEs identified in previous studies is likely to be using groundwater except where the water feature is located on coastal floodplains where Holocene marine muds are present, or on cracking clay soil plains	Known GDE location/map (GDE Atlas); soil type map; floodplain/inundation map	4, 5, 6, 9
Certain types of landscapes or topography are more indicative of shallow groundwater and are therefore more likely to support GDEs (only applied when an existing depth to water table mapping is not available)	DEM; landscape type mapping; vegetation map; vegetation type	
Constant vegetation activity throughout the year indicates use of a water source other than rainfall (possibly groundwater)	Remote sensing greenness/wetness; PAR	8
Groundwater discharge related to the presence of faults	Geologic mapping; groundwater depth	
High-probability IDEs (8–10) are potential GDEs; IDEs ≤ 5 are not GDEs; IDEs ≥ 5 around wetlands are potential GDEs	IDE map (GDE Atlas); vegetation type; vegetation map	
Vegetation occurring in estuaries and in coastal floodplains at less than 5 m elevation, or on cracking clay soils, is unlikely to be a GDE	DEM; vegetation type; vegetation map; floodplain/inundation map	
Alluvial aquifers that are connected to rivers > Strahler Order 4 are likely to have stygofauna	Strahler Stream Order layer; geological mapping	
Karstic or limestone aquifers are likely to have stygofauna, as are alluvial aquifers downstream	Geological mapping; hydrogeology data	
Alluvial aquifers are likely to have high stygofauna diversity close to recharge areas, where water table is <10 m, and beneath phreatophytic vegetation	Vegetation mapping; groundwater level data	
If stygofauna are known to occur in part of an aquifer, it can be assumed that other parts of the aquifer are also suitable	Geological mapping; existing stygofauna survey data	
Aquifers that have no direct hydrological connection to the land surface, or that are not immediately connected to an alluvial, limestone, or calcrete aquifer, are unlikely to be aquifer ecosystems	Geological mapping; hydrogeological data	

Rules of GDE potential	Datasets required	Cross-reference with Table 1
SURFACE GDEs		
Wetlands inundated for prolonged periods, especially through prolonged dry periods, are likely to be connected to groundwater	Wetland/spring map; groundwater regime; temporal inundation map	4
Specific wetland types are indicative of groundwater discharge (i.e. deep marsh) (Dahlhaus et al. 2010)	Wetland classification	
In Victoria, the dominant source of water of wetlands has previously been established	Victorian wetland source map	
During dry periods, active vegetation within and surrounding wetlands indicates shallow groundwater levels. Groundwater is likely to be connected to the wetland, but may not discharge enough to cause inundation	Rainfall data; remote sensing greenness/wetness, PAR; wetland map; groundwater depth	
Areas with persistent surface water are likely to receive inputs from groundwater with the exception of water bodies in parts of the Lake Eyre Basin	Permanent water map (remote sensing); wetland/river map	1, 4
Vegetation identified as ‘GDEs that rely on the surface presence of groundwater’ indicate the presence of shallow water tables and potential diffuse groundwater discharge into adjacent wetlands	GDE Atlas; vegetation map	6
Waterbodies that occur in the same geomorphic setting as losing rivers are less likely to be connected to groundwater	Geologic mapping; wetland/river map; river classification map; aquifer map; depth the water table	
Wetlands that contain peaty soils are likely to have been formed through groundwater discharge	Soil type map; wetland map	
Underlying aquifer indicates groundwater discharge to surface	Aquifer map; wetland/river map	
Underlying geology indicates potential for groundwater discharge to surface—baseflow contribution from fractured rock aquifer, limestone and alluvium	Geologic mapping; aquifer map; wetland/river map	
Rivers and streams in regions of shallow water tables are more likely to be connected than in regions of deeper water tables	Wetland/river map; depth to groundwater	

Rules of GDE potential	Datasets required	Cross-reference with Table 1
Where groundwater levels are the same or higher elevation than the base of a water body, groundwater discharge occurs to that water body	DEM; depth to groundwater; wetland/river map	
Where major rivers have been mapped as losing (Parsons et al. 2008), other rivers within the same landscape unit are also likely to be losing and not support GDEs	Wetland/river map; river classification	
Where cracking clay soils or Holocene muds exist, water bodies are less likely to be groundwater fed	Soil map; wetland/river map	
Waterbodies intersecting a known spring location are more likely to be GDEs	Wetland/river map; known spring locations	
Rivers flowing through fractured rock aquifers in the Adelaide Geosyncline and through the Great Artesian Basin aquifers are likely to receive groundwater inputs	Aquifer type; wetland/river map	
Certain swamp vegetation communities indicate likely groundwater inflows or known GDE vegetation	Wetland/river map; vegetation map; depth to groundwater	6
Permanent water regime indicates groundwater discharge which maintains flow/water during the dry season, except when Holocene muds and cracking clays are present	Surface water regime; rainfall/ climate; soil type map	1, 4
Certain geological formations are more likely to contribute baseflow to rivers (fractured rock in the Adelaide Geosynclines, and outcropping Great Artesian Basin aquifers)	Geologic map; aquifer map	
Non-permanent water bodies may receive groundwater contributions if they are in certain lithological and geomorphological units	Geologic map; wetland/river map; lithological information	
Large fluctuations in water table can result in groundwater discharge to non-permanent water bodies late in the wet season. Large fluctuations in water table are expected to occur where rainfall is high (>1000 mm/yr) and intense (>60% of annual rainfall occurs in a 3-month period and there are at least 10 days of >25 mm rainfall)	Groundwater regime; rainfall	
Low-lying and break-of-slope (<5°) landscapes are likely to have shallow water tables	Aspect map; DEM; depth to groundwater	

Rules of GDE potential	Datasets required	Cross-reference with Table 1
Slope on specific geology types is an indication of shallow water tables	Aspect map; geology map; depth to groundwater	
Vegetation is an indicator of groundwater discharge (known GDE)	Known vegetation GDEs; depth to groundwater	6
Geology is an indicator of groundwater connection to wetland groundwater discharge (only applies to Bruny Island)	Geologic map; wetland/river map	
Elevation is an indicator of groundwater connection to wetlands (only applies to Bruny Island, Napier region, Struan region)	DEM; wetland/river map	

Appendix F: Assessing aquifer ecosystems

Almost all shallow aquifers contain life in the form of microbes, and can be reasonably presented as ecosystems. Although microbes play key roles in many of the ecosystem services provided by aquifer ecosystems, it is not yet practical to take a census of aquifer microbial communities for impact assessment. Currently, a more pragmatic approach in assessing the biological community is to determine whether the aquifer supports a stygofauna community, using this as the main indicator that an aquifer ecosystem is present. Both Western Australia and Queensland have guidelines for sampling stygofauna during assessments of aquifer ecosystems (Queensland Government 2018a: 139–147, Government of Western Australia 2016, Queensland Government 2015).

‘Stygofauna’ is a collective term that incorporates a broad suite of animal species, all adapted to living in groundwater. It includes species of crustaceans, beetles, snails, mites, worms and other groups known only from aquifers. They often share physical characteristics such as blindness, elongation and lack of body pigmentation (Hose et al. 2015).

For impact assessments, the objective of stygofauna sampling should be to determine which species are living in the aquifers that will be affected by CSG or LCM activities (Queensland Government 2015). Once stygofauna are found, an equally important objective is to confirm whether the same species live outside the area of impact, so that there is some assurance that species will not be placed at risk of extinction.

Selecting the appropriate sampling points

Once suitable aquifers have been determined, the next step is to choose suitable sampling locations in those aquifers (App Table 6). Most stygofauna samples will be collected from piezometers, bores or wells (collectively referred to here as bores). Bores are rarely constructed specifically for stygofauna sampling. Instead, samples must be collected from an already existing network of bores whose original purpose includes groundwater quality monitoring, irrigation, abstraction and/or geological exploration. The type of bore sampled and its construction details and history can influence its effectiveness as an access point to collect stygofauna. Bores need to be located in a suitable area, be of large enough diameter to allow sampling nets or pump intakes, and be screened at the section of aquifer where stygofauna occur. Optimal bore characteristics for stygofauna sampling are summarised in App Table 6.

App Table 6. Characteristics of bores most likely to yield stygofauna, provided they are present in the aquifer

Bore parameter	Preferred option	Other suitable options
Diameter	At least 50 mm	Any suitable groundwater access point greater than 50 mm
Orientation	Vertical	Only vertical bores can be sampled with nets. Bores that are angled slightly away from vertical can be sampled with some pump types if cased
Casing type	PVC casing	Steel, concrete or uncased—provided internal surface is smooth
Slot location	Spanning the interface between vadose zone and water table, or within 10 m of water table	Casing is open at bottom of bore
Slot width	Bore slots should be at least 1 mm wide to allow entry of large taxa such as amphipods	Narrow slots will allow entry of small taxa, but may prevent larger taxa. Wider slots can be made in casings at regular intervals with a hand saw prior to installation.
Purpose of bore	Groundwater monitoring	Any other vertical bore accessing the desired aquifer
Other requirements	Contains no pumps, vibrating wires, loggers, or other permanent infrastructure	
	Bore has not been purged in the three months before sampling	Bore has not been purged for at least one month before sampling

Stygofauna tolerances

As a collective group, stygofauna are tolerant of a broad range of physico-chemical conditions, and occur in a variety of aquifer types. However, as with all fauna, they require favourable conditions to survive and not all aquifers are suitable. To increase the likelihood of collecting stygofauna from an aquifer, sampling effort should be greatest in areas where conditions are most favourable. These can be selected from available hydrogeological and water chemistry data, and are listed in App Table 7.

App Table 7. Water chemistry and aquifer conditions favourable to stygofauna

Parameter	Preferred type or range	Notes	References
Aquifer type	Most common in karstic and alluvial aquifers. Also known from fractured rock (sandstone, coal, basalt)	Fractured rock aquifers are often secondary habitat and will have stygofauna when there is sufficient hydrological connection to either limestone or alluvial aquifers	Hancock et al. 2005, Humphreys 2008, Glanville et al. 2016b, Hyde et al. 2018
Water table depth	Greater diversity and higher abundances likely when water table shallower than 20–30 m. Stygofauna also more likely in aquifer recharge areas	Areas with shallow water tables (<20 m or <30 m) generally have higher concentrations of organic matter and dissolved oxygen, making them more likely to have stygofauna	Hancock and Boulton 2008, Datry et al. 2005, Hyde et al. 2018
Hydraulic conductivity / aquifer porosity	Aquifers with high porosity and hydraulic conductivity greater than 10^{-4} cm/s	Pores, spaces and fractures must be large enough to allow stygofauna to move through them, and connected well enough to allow water to deliver dissolved oxygen and nutrients	Strayer 1994, Hahn and Fuchs 2009, Hose et al. 2015
Food availability	Higher stygofauna diversity likely beneath phreatophytic trees and in aquifer recharge areas	Phreatophytic trees provide a reliable source of organic matter for stygofauna, as does water moving into the aquifer	Jasinska et al. 1996, Datry et al. 2005, Hyde et al. 2018
Salinity	Stygofauna most likely in water with electrical conductivity (EC) less than 5000 mS/cm	Specimens have been collected from waters with EC up to 56 000 mS/cm, but diversity and abundance is higher at low EC	Hancock and Boulton 2008, Watts and Humphreys 2009, Schulz et al. 2013, Glanville et al. 2016b

Appendix G: Risk assessment

App Table 8. GDE Risk Matrix (Serov et al. 2012)

	Category 1: Low Risk	Category 2: Moderate Risk	Category 3: High Risk
Category 1: High Ecological Value (HEV), Sensitive Environmental Area (SEA)	A	B	C
Category 2: Moderate Ecological Value (MEV), Sensitive Environmental Area (SEA)	D	E	F
Category 3: Low Ecological Value (LEV)	G	H	I

App Table 9. GDE Risk Matrix management actions (Serov et al. 2012) for each risk matrix box A to I are derived from the GDE Risk Matrix in App Table 8

Risk matrix box	Descriptor	Management action		
		Short term	Mid term	Long term
A	High value / Low Risk	Protection measures for aquifers and GDEs	Continue protection measures for aquifers and GDEs	Adaptive management; continue monitoring
		Baseline risk monitoring	Periodic monitoring and assessment	
B	High Value / Moderate Risk	Protection measures for aquifers and GDEs	Protection measures for aquifers and GDEs	Adaptive management; continue monitoring
		Baseline risk monitoring; mitigation action	Monitoring and periodic assessment of mitigation	
C	High Value / High Risk	Protection measures for aquifers and GDEs	Protection measures for aquifers and GDEs	Adaptive management; continue monitoring
		Baseline risk monitoring; mitigation action	Monitoring and annual assessment of mitigation	
D	Moderate Value / Low Risk	Protection of hotspots	Protection of hotspots	Adaptive management; continue monitoring
		Baseline risk monitoring	Baseline risk monitoring	

Risk matrix box	Descriptor	Management action		
		Short term	Mid term	Long term
E	Moderate Value / Moderate Risk	Protection of hotspots	Protection of hotspots	Adaptive management; continue monitoring
		Baseline risk monitoring; mitigation action	Monitoring and periodic assessment of mitigation	
F	Moderate Value / High Risk	Protection of hotspots	Protection of hotspots	Adaptive management; continue monitoring
		Baseline risk monitoring; mitigation action	Monitoring and annual assessment of mitigation	
G	Low Value / Low Risk	Protection of hotspots (if any)	Protection of hotspots (if any)	Adaptive management; continue monitoring
		Baseline risk monitoring	Baseline risk monitoring	
H	Low Value / Moderate Risk	Protection of hotspots (if any)	Protection of hotspots (if any)	Adaptive management; continue monitoring
		Baseline risk monitoring; mitigation action	Monitoring and periodic assessment of mitigation	
I	Low Value / High Risk	Protection of hotspots (if any)	Protection of hotspots (if any)	Adaptive management; continue monitoring
		Baseline risk monitoring; mitigation action	Monitoring and annual assessment of mitigation	



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