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

Consultation draft – not for official use

Consultation on Assessing Groundwater-Dependent Ecosystems: IESC Information Guidelines Explanatory Note.

The Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (IESC) is seeking comment on the draft Explanatory Note, 'Assessing Groundwater-Dependent Ecosystems: IESC Information Guidelines Explanatory Note.'

The IESC notes the draft nature of the Explanatory Note and welcomes feedback on the content, usability and applicability. In particular, views are sought on:

- **the technical content within the draft Explanatory Note. Are there any areas that are missing or not captured adequately?**
- **the relevance to your specific area of work and any views on its uptake and adoption.**
- **potential options to increase uptake and adoption.**

The IESC and the Information Guidelines

The IESC is a statutory body under the *Environment Protection and Biodiversity Conservation Act 1999* (Cth) (EPBC Act). 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 (CSG) and large coal mining development proposals that are likely to have a significant impact on water resources.

The Information Guidelines outline the information project proponents should provide to enable the IESC to provide robust scientific advice on potential water-related impacts of CSG and large coal mining development proposals. The Explanatory Note supports the Information Guidelines by providing further information and guidance on undertaking comprehensive assessment and management of impacts to groundwater dependent ecosystems (GDEs).

The Explanatory Note,* 'Assessing Groundwater-Dependent Ecosystems: IESC Information Guidelines Explanatory Note.*'

The EPBC Act lists "a water resource, in relation to coal seam gas development and large coal mining development" as a matter of national environmental significance. A water resource is defined under the *Water Act 2007* (Cth) and incorporates ecosystems that contribute to the physical state and environmental value of the water resource. As such, environmental assessments for proposed CSG and large coal mining developments are required to identify potential GDEs and assess and manage potential impacts to GDEs from a proposed development.

The draft Explanatory Note is intended to assist proponents in preparing environmental assessments for projects potentially impacting GDEs. The Explanatory Note compiles information, and provides guidance, on the use of a diverse range of tools and methodologies currently available for identifying potential GDEs and their condition, characterising groundwater reliance of GDEs, risk assessment and assessing potential impacts. The Explanatory Note also explores avoidance, mitigation, monitoring and management options, providing practical examples of their application in a range of environments.

Assessing Groundwater-Dependent Ecosystems: IESC Information Guidelines Explanatory Note

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Executive Summary

Groundwater-dependent ecosystems (GDEs) are ecosystems that rely upon groundwater for their continued existence. They may be 100% dependent on groundwater, such as aquifer GDEs, or may access groundwater intermittently to supplement their water requirements, such as riparian tree species in arid and semi-arid areas. These ecosystems are sensitive to changes in the groundwater regimes that support them, as an increase in depth to groundwater may draw water down beyond the reach of vegetation roots or remove water from caves, creating water stress for the GDEs.

GDEs are classed as:

- Aquifer and cave ecosystems (**Subterranean GDEs**)
  - caves or aquifers
- Ecosystems dependent on the surface expression of groundwater (**Aquatic GDEs**)
  - River-base flow systems – aquatic and riparian ecosystems that exist in or adjacent to streams (including the hyporheic zone) fed by groundwater
  - Wetlands – aquatic communities and fringing vegetation dependent on groundwater-fed lakes and wetlands. These include palustrine, lacustrine and riverine wetlands that receive groundwater discharge and can include some spring ecosystems
  - Ecosystems which rely on submarine discharge of groundwater for its nutrients and/or physico-chemical attributes
- Ecosystems dependent on the subsurface expression of groundwater (**Terrestrial GDEs**)

Coal seam gas (CSG) and large coal mining (LCM) developments are important to the economy and production of fuel in Australia yet pose potential risks to nearby GDEs. These risks include alterations of groundwater regimes and water quality that may impact on GDEs in the vicinity of proposed and operational CSG and LCM developments.

The purpose of this Explanatory Note is to describe the information required and tools available to assess the potential risks to GDEs from CSG and LCM development, and to help a proponent who is required to prepare an environmental impact assessment with a section specifically devoted to GDEs. A logical framework is provided to guide the proponent through the steps, which include:

- defining the project area (including the footprint of surface infrastructure and the potential extent of groundwater depressurisation) – **Chapter 5**
- undertaking a desktop study to identify potential GDEs in the project area – **Chapter 5**
- assessing the level of groundwater dependence for each GDE and pathways of cause and effect – **Chapter 5**
- identifying baseline ecological condition for each GDE – **Chapter 6**
- assessing the likelihood, frequency and magnitude of potential impacts to each GDE and determine the risks related to the CSG or LCM operation – **Chapter 7**
- prioritising options to avoid or mitigate impacts to GDEs and establish a monitoring plan to assess effectiveness of mitigation or identify unexpected impacts – **Chapter 8**

Case studies are included to provide examples and support suggested guidance. Recommendations are highlighted throughout and summarised in Chapter 9. The expected outcomes of key steps in the framework are given within each chapter and summarised below.

Identify GDEs in project impact area

- The proponent will have a list and map of potential GDEs that may include alluvial aquifers, wetlands, rivers, springs and vegetation communities, together with an indication of the likelihood of groundwater dependence for each potential GDE in the project impact area.

Characterising ecosystem reliance on groundwater

- 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 be updated with new information.

Determine baseline conditions

- The proponent will have assessed 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, determination of ecological value and condition, level of groundwater dependence, suitable data analysis and well-justified management options. The collected information will provide an understanding of the natural variability in each GDE and inform decisions to determine an 'acceptable level of change' with consideration of the ecological value of each GDE. Monitoring programs should state the goals of monitoring, what is to be measured, where and how often, how each variable relates to potential impacts and GDE responses, and how the data will be stored, analysed and presented.

Assess impacts and risk of CSG and LCM

- The proponent, after defining the baseline condition of each GDE within and outside the area of impact, will have identified how the GDEs and the services they provide are likely to respond to changes in groundwater regime and water quality, all processes 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/national levels.

Avoidance, mitigation and management plans

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

This Explanatory Note will help proponents provide the most comprehensive information possible within an environmental impact assessment, based on the available data, to avoid delays in decision-making and ensure that decisions are well informed.

1 Background

1.1 Purpose

To provide appropriate scientific advice to the Commonwealth Environment Minister and relevant state ministers, the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (the IESC) requires specific information to be included in coal seam gas (CSG) and large coal mining (LCM) development proposals. This ensures decisions are fully informed and reduces delays in decision-making.

Specific information requirements are presented in the IESC Information Guidelines (IESC). For some topics, Explanatory Notes have been written to supplement the IESC Information Guidelines, giving more detailed guidance on particular topics to help proponents and consultants prepare their Environmental Impact Assessments (EIAs).

The current Explanatory Note describes what is required to assess potential risks of CSG and LCM development on groundwater-dependent ecosystems (GDEs). It outlines a logical sequence of activities to identify and map GDEs, investigate their groundwater dependence, water requirements, baseline condition and value, identify potential threats and assess risks to GDEs from the proposed project. Relevant mitigation and management strategies are described, including monitoring protocols to survey GDEs, detect potential impacts and demonstrate the success of mitigation strategies. Tools and methods for GDE assessment are reviewed to help proponents choose the most effective approaches, highlighting that where risks are higher, more effort is required to prevent decline in GDE condition as a result of CSG or LCM development.

1.2 Legislative context

The management of GDEs is incorporated in the National Water Initiative (NWI, 2004), an intergovernmental agreement which highlights the importance of groundwater and a 'whole of water cycle' approach to protect water resources. The initiative acknowledges that a better understanding of the relationship between groundwater resources and GDEs is required to facilitate their protection.

Australian and state regulators who are signatories to the National Partnership Agreement seek the IESC's advice under the *EPBC Act 1999* 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.

A water resource is defined 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)' by the Commonwealth *Water Act 2007* (Water Act, 2007), which supports the National Water Initiative.

2 Groundwater-dependent ecosystems

2.1 GDE typology

GDEs are complex dynamic 'natural 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' (Richardson et al., 2011). The presence of diverse GDEs is driven by temporal and spatial groundwater flow variability dependent on geology, climate and land use.

Groundwater, for the purpose of this Explanatory Note, is defined as (i) water naturally occurring below ground level in a zone of saturation (e.g. aquifer) and its capillary fringe, or (ii) groundwater that has been pumped, diverted or released to that place for the purpose of being stored there (not including water held in underground tanks, pipes or other works; Water Act, 2007). The definition includes water in the soil capillary zone 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.

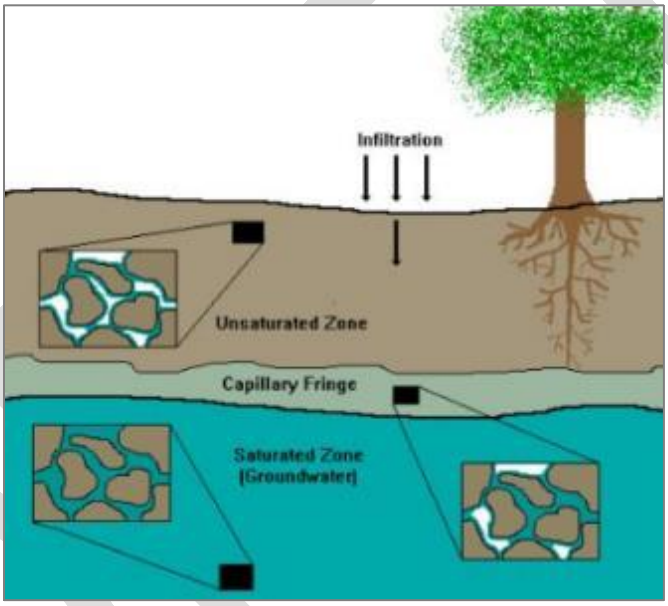


Figure 1. Conceptual model to define groundwater with respect to GDEs. SOURCE: Michigan State University (Image)

GDEs have groundwater-related ecological water requirements, both in quantity and quality (Boulton and Hancock, 2006; Eamus et al., 2006; Kath et al., 2014). Quantity refers to aspects of the groundwater regime, including the volumes, pressures, timing and variability of groundwater supply that govern the location, timing, frequency and duration of groundwater connection. Quality refers to physical and chemical characteristics such as temperature and water quality (especially salinity and nutrient concentrations). 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 GDE groundwater connection, and ecosystem composition (e.g. vegetation types, stygofauna species). This is particularly important when GDEs are relying on perched or highly localised groundwater systems that may not be adequately considered in regional groundwater models, and where existing data is limited.

Stygofauna include subterranean animals that live in groundwater systems and inhabit the interstitial spaces of sedimentary aquifers, the cavities of karstic aquifers, or the fissures of rock aquifers. The presence of stygofauna in an aquifer is often used as an indicator that the aquifer is an ecosystem. However, there are other organisms, such as bacteria or the roots of phreatophytic trees that use aquifers and thus define the aquifer as an ecosystem.

GDEs occur in coastal and inland regions (Figure 2). In this Note, GDEs are defined using a combination of typologies from Hatton and Evans (1998) and the GDE Toolbox (Richardson et al., 2011) and include:

- Aquifer and cave ecosystems (**Subterranean GDEs**)
    - caves or aquifers
- Ecosystems dependent on the surface expression of groundwater (**Aquatic GDEs**)
    - River-base flow systems – aquatic and riparian ecosystems that exist in or adjacent to streams (including the hyporheic zone) fed by groundwater
    - Wetlands – aquatic communities and fringing vegetation dependent on groundwater-fed lakes and wetlands. These include palustrine, lacustrine and riverine wetlands that receive groundwater discharge and can include some spring ecosystems
    - Ecosystems which rely on submarine discharge of groundwater for its nutrients and/or physico-chemical attributes
- Ecosystems dependent on the subsurface expression of groundwater (**Terrestrial GDEs**).

The terms 'Subterranean', 'Aquatic' and 'Terrestrial' GDEs are consistent with the classification system used in the Groundwater-Dependent Ecosystem Atlas (GDE Atlas), where these GDE types are discussed in greater detail (GDE Atlas).

For in-depth tutorials on GDEs and wetlands, refer to the Queensland Government education modules (WetlandInfo). These provide details on the different types of GDEs, their value, and how they function. GDE types and importance of GDEs are described in WetlandInfo. Refer to the GDE Toolbox Pt1 for detailed descriptions of GDE types and case studies to demonstrate groundwater dependence within each type.

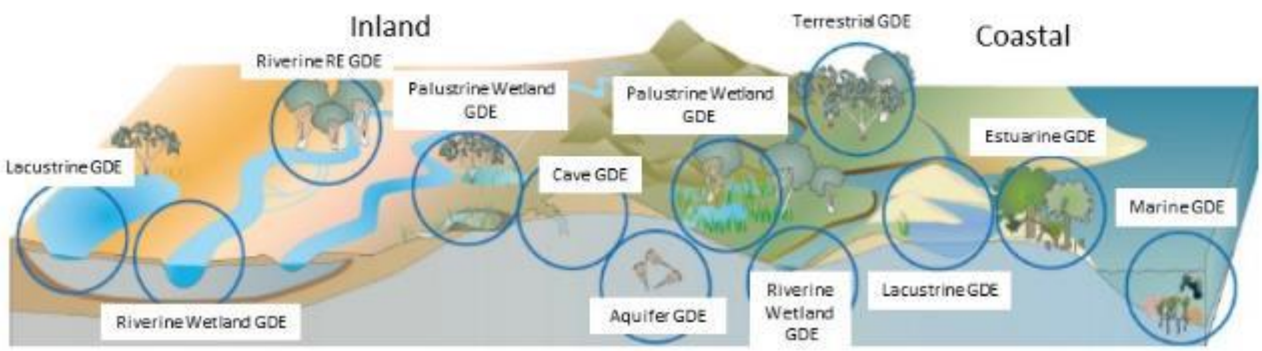


Figure 2. Illustration of GDE typology described above in section 2.1. SOURCE: Wetland Info (https://wetlandinfo.ehp.qld.gov.au)

RECOMMENDATION: A number of helpful publications are mentioned throughout this Explanatory Note to aid proponents. 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 as a low, one-off cost.

2.2 GDE values and ecosystem services

With respect to GDEs, the term 'ecosystem value' has been used in the literature to mean two distinctly different things: i) *the natural ecological processes occurring within ecosystems and the biodiversity of these systems* (Richardson et al., 2011), 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 expresses the *value* of the biodiversity and ecological processes that underpin the provision of ecosystem services by an ecosystem. Ecosystem services are the benefits that people obtain from ecosystems, and GDEs provide many such services (Griebler and Avramov, 2015).

Ecosystem *value* differs from ecosystem *condition*. Ecosystem value is when 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, 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 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 NSW (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 must 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., 2011).

Ecosystem value based on expert knowledge requires an understanding of 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).

Another aspect of GDEs that should be considered when determining their value is the ecosystem services they provide to humans. The full range of their ecosystem services is unlikely to be fully realised yet, as this area of research is still developing. Ecosystem services provided by the different types of GDEs are shown below, noting that all GDE types have the potential to support endangered and threatened species, be biodiversity hotspots and provide water for human consumption (Griebler and Avramov, 2015):

- 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 zone and subsequent discharge to surface waters)
- mitigation of floods (aquifers receive and retard large volumes of surface water) and droughts (groundwater discharge sustains surface waters).

Ecosystems dependent on the surface expression of groundwater (Mitsch et al., 2015) may also provide the following services:

- habitat for animals (e.g. timing of water availability, temperature regulation)
- timber/peat harvesting
- improve water quality

- mitigate flood and storm damage (e.g. wetlands receive and retard large volumes of surface water)
- sustain human culture (e.g. tourism)
- soil development
- hydraulic redistribution of deep water to shallow soil
- pollinator habitat
- prevention of soil erosion.

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.

GDEs are vulnerable to CSG and LCM developments because of hydrological, hydrogeological and geological links between the development and adjacent GDEs. Aquifers are the connecting features, and impacts from developments can be transferred to GDEs through changes in either the rock or sedimentary structure of the aquifer 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 but may be relevant in the context of on-shore shale/tight gas operations.

Current environmental impact assessments of CSG and LCM are often limited to GDEs that rely on groundwater access on a permanent or near permanent basis (such as spring communities), overlooking more episodic and opportunistic groundwater users. Additionally, only protected or threatened ecological communities that are listed, tend to be considered. However, the legislative intent of the 'water trigger' (Section 1.2) is that potential impacts from CSG and LCM to **all** GDEs should be assessed. The next chapter discusses potential threats and impacts in more detail, along with their likely pathways of effect.

RECOMMENDATION: Proponents need to consider **all** GDEs, including those which are only partially dependent on groundwater and do not support any listed species. For this reason, an assessment of ecological condition, rather than ecological value is critical in establishing a baseline indication of ecological condition.

3 Potential impacts of CSG and LCM development on GDEs

Groundwater dependence in ecosystems is extremely variable through both space and time, and among organisms. Dependence by biota can be continuous (e.g. stygofauna living in aquifers), ephemeral (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, whilst in river baseflow systems groundwater contributions 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 requirement for other groundwater components potentially makes substitution by 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 life-of-mine. There are often long lag times between an impact occurring and symptoms appearing in an ecosystem. All of this variability, coupled with the varying temporal and spatial nature of groundwater dependence, make assessments of longer-term impacts difficult. Assessments must use the best available data and knowledge to forecast potential impacts into the future, focusing on both the period of CSG or LCM operations and beyond to at least 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 magnitude and type 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), and consists of four main conduits (Figure 3, defined in greater detail in Holland et al., 2016):

- subsurface depressurisation and dewatering (A; Figure 3)
- subsurface physical flowpaths (B; Figure 3)
- surface water drainage (C; Figure 3)
- operational water management (D; 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 by activities that:

- interrupt 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, or
- result from cumulative impacts from multiple CSG and LCM operations and other activities, including reduced groundwater recharge.

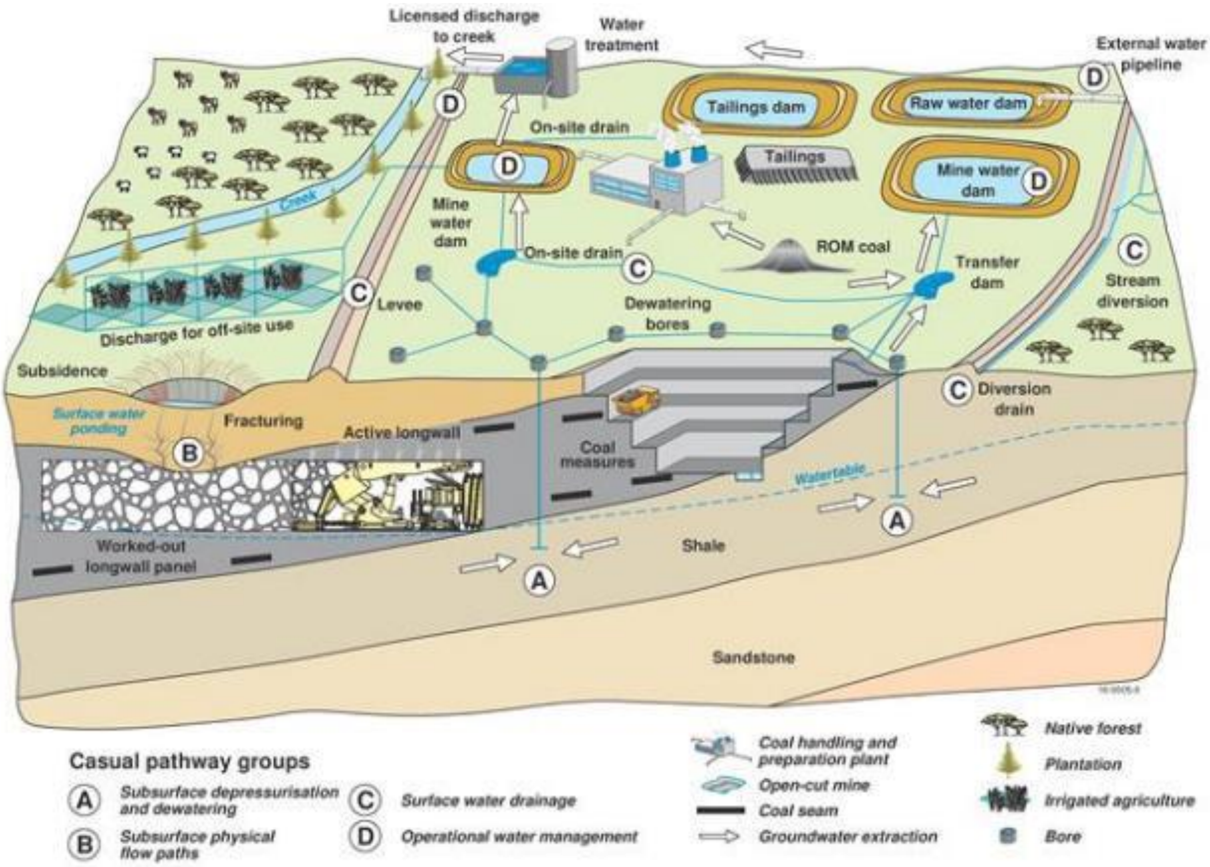


Figure 3. Causal pathways of CSG or LCM development. SOURCE: Bioregional Assessments

Groundwater dewatering has several potential impacts on GDEs (Figure 4). One impact is the lowering of the groundwater level around groundwater-dependent terrestrial vegetation which reduces the availability of water that can be accessed by an established vegetation root network, impairing the condition (or health) 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 Gnangara Mound, see CASE STUDY 6). Another impact is the lowering of 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, reducing spring flow and riparian 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 (baseflow) conditions, as well as more cease-to-flow events than under natural conditions. A permanently flowing river may become ephemeral, drastically changing its aquatic ecosystem characteristics. Lowering groundwater levels near rivers also reduces the availability of water to surrounding groundwater-dependent riparian vegetation and may put them under water stress, impairing riparian vegetation community condition (Doody et al., 2009). The direction of groundwater flow can be reversed by lowered groundwater levels near rivers such that surface water recharges the aquifer, changing the river from gaining to losing, further reducing surface water flow and changing water quality, so it may no longer be suitable habitat for native aquatic fauna but may favour exotic species.

The impacts of lowering groundwater levels near wetlands resemble those listed above for rivers. However, there are several additional processes that may be disrupted related to the reduced size and extent of wetlands, such as potential exposure of acid sulphate soils resulting in water acidification (e.g. Sommer and Horwitz, 2009) and reduced production of peat (e.g. Armandine Les Landes et al., 2014).

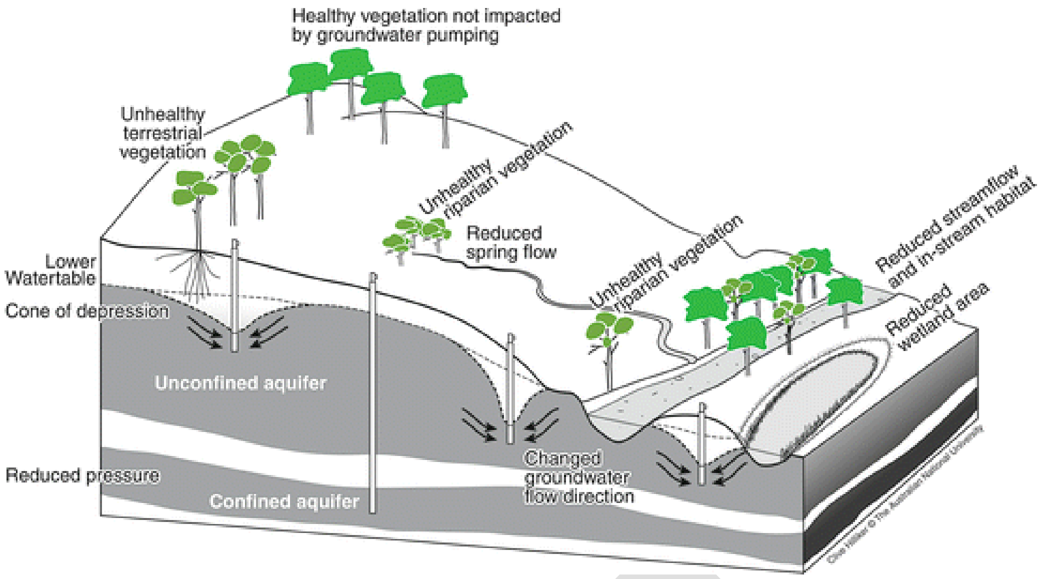


Figure 4. Diagram demonstrating some impacts from Causal Pathway A - subsurface dewatering or lowering groundwater levels, and how GDEs are potentially impacted (SOURCE: Eamus et al., 2016)

3.1.1 Interrupted connectivity

GDEs can decline in condition when the ecosystem becomes hydrologically isolated from the aquifer it is dependent on. Isolation 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*.

It is also important to consider interruptions in connectivity between aquifers and their recharge areas, as this can lead to a gradual decline in water level and altered groundwater physico-chemistry. 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. Many GDEs also depend on surface water for part of the time, so their biodiversity and ecological processes may be impacted if surface water flow and volume changes.

CSG and LCM activities that cause interrupted connectivity include:

- dewatering unconfined aquifers, which can lower the watertable 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 watertable below a threshold where surface-derived organic matter and oxygen become limiting.
- depressurisation of confined aquifers, thus removing water, gas or rock from confined aquifers that may lead to a loss in the hydraulic pressure pushing water 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 diverting runoff and river water, can impact aquifer ecosystems, reduce surface water levels and isolate surface-expressed GDEs.

- changes to subsurface flow paths by pumping water from mine pits and production bores, or the free draining of groundwater through the walls and floors of mine pits, can alter the direction and velocity of subsurface flow paths. This can result in water moving away from GDEs and towards the extraction point.
- fracturing of confining layers, which may occur when less-porous layers of rock that separate aquifers of differing water quality are penetrated during mining or drilling, or fractured following longwall subsidence. This could lead to the transfer of pressurised or gravity-mobilised water between aquifers.

CASE STUDY 1 – *Impacts of longwall mining on 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 plan layout.*
- *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 swamp 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 to interrupt 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^{-1}) 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 major potential threat to groundwater quality is the release or leakage of saline water from coal seams into aquifers linked to GDEs. This can occur if CSG or LCM activities cause a fracturing of less-permeable rock layers, either during mining or afterwards as subsidence that allows coal seam water to mix with alluvial water. Saline

water is often pumped from a coal seam to allow resource extraction, then stored in dams prior to 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 offsite, using trucks or rail. Prior to disposal, the risk of leaking or overflow from storage dams must be considered. Treated fresh water makes up the largest volume of the two products of reverse osmosis, and although 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 watertable and are left open after mining cessation can fill with groundwater. However, pit water chemistry can change through evapoconcentration and other hydrogeochemical processes, and the water can become toxic, with acidic pH and higher concentrations of dissolved metals, metalloids and sulphates (Bowell, 2002). Seepage of water from the pit and into an aquifer can 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 EPA 2017).

3.1.3 Direct disturbance

Risk assessments must consider activities that are not linked to groundwater, but which can also potentially impact GDEs. These include vegetation clearing, river realignment, aquifer excavation and wetland draining. Often, the impacts from these will be considered in other EIA sections and not considered in the context of GDEs. This leads to oversights in the mitigation or management of risks. For example, if groundwater-dependent vegetation is cleared and offset against a similar vegetation type that is not groundwater-dependent, then offsetting does not protect the GDE nor does it protect the crucial role that 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 neglects the consequences of lost aquifer connectivity.

3.1.4 Cumulative impacts

Cumulative impacts to GDEs need to be considered if there is a possible compounding effect from the proposed CSG or LCM activity with an adjacent one or other activities unrelated to CSG and LCM operations. Examples occur when a cone of depression from one mine intersects the cone of depression from one or more nearby mines and amplifies drawdown near a GDE. Plans for mine 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).

More than two mines might occur across a localised region (e.g. Hunter Valley). Consideration should be given to coordination between proponents of adjoining developments to assess the cumulative impacts operating together and to share monitoring data and plans to effectively mitigate cumulative impacts.

Agriculture, urban water supply, power generation and other developments can also impair groundwater quality and interrupt connectivity. Where these occur near a mine, their cumulative impacts must be considered and compared to conditions at reference sites (representative monitoring sites outside the project impact area, see section 6).

As consequences of CSG or LCM activities potentially occur over decades or centuries, it is important that project area 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 CSIRO (Climate), and impacts to GDEs from CSG or LCM activities should be considered under these or newer forecasts as they are developed. Nugent et al. (2013) provide a risk framework to manage GDEs under a changing climate.

4 Framework for assessing GDEs in an environmental impact statement

GDEs can be assessed using a logical framework (Figure 5) to (i) define the project area (which includes the footprint of surface infrastructure and the extent of groundwater depressurisation), (ii) undertake a desktop study to identify potential GDEs in the project area, (iii) assess the level of groundwater dependence for each GDE and the potential pathways of cause and effect of CSG or LCM activities, (iv) identify baseline ecological condition and value for each GDE, (v) assess the likelihood, frequency and magnitude of potential impacts to GDEs and determine the risks related to the CSG or LCM activities, and (vi) prioritise options to avoid or mitigate impacts to GDEs and establish a monitoring plan to test effectiveness of mitigation strategies and identify unexpected impacts.

In 2011, the Australian groundwater-dependent ecosystems toolbox (GDE Toolbox; Richardson et al., 2011) was published to aid 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). Many of these methods are updated in the current Explanatory Note, and form a 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 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.

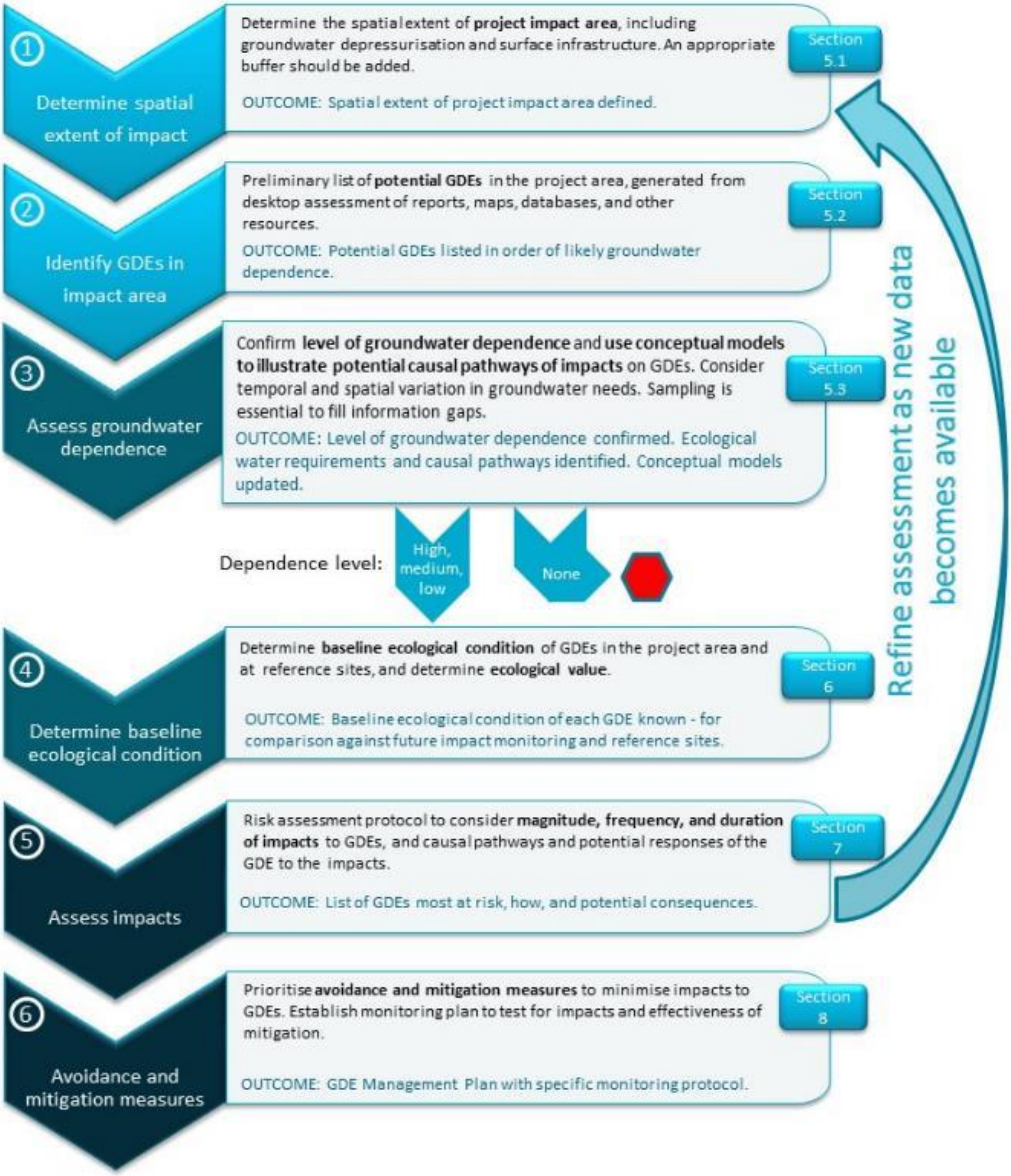


Figure 5. A logical framework of steps to aid a proponent's understanding of the process undertaken to inform an Environmental Impact Assessment for assessing and describing potential impacts, risks and mitigation options of CSG and LCM activities on GDEs.

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 will likely 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 or not. As it is not feasible to wait until groundwater impact assessments provide a final boundary of groundwater impact, proponents are likely to have only a rudimentary understanding of how far impacts are likely to spread. Therefore, impact boundaries should be drawn up by proponents based on the best available information in the initial phases of an EIA, and then an appropriate buffer should be added. The 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 generate a 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 what GDEs exist in the project area and are therefore potentially at risk.

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). Direct indicators are obtained from field studies such as those that measure plant water use.

Where available, site-specific information should be used to develop a conceptual understanding of the interactions between GDEs and groundwater (see section 5.3.1), along with potential causal pathways (section 3.1). However, in the absence of sufficient local information, there are regional and national databases available to undertake an initial assessment (App Table 3 and App Table 4). A logical starting point for GDE assessments is the GDE Atlas (GDE Atlas).

The Australian National Aquatic Ecosystem (ANAE) classification scheme aids with classifying aquatic GDEs (ANAE) 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).

5.2.1 Key indicators of groundwater dependence

Landscape indicators representing GDE presence can be hydrologic, geologic, 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 (App Table 5 and App Table 6). Eamus et al. (2006) pose a series of questions to aid in the identification of GDEs reliant on the surface expression of groundwater (Table 1). A suggested set of ancillary data for this purpose is presented in App Table 3.

Table 1. Questions to guide the assessment of groundwater use in ecosystems (Eamus et al., 2006). Questions are cross-referenced to GDE rule sets shown in App Table 7

Cross reference to App Table 6	Positive answers to the following questions suggest an ecosystem may use groundwater:
1	Does a stream/river continue to flow all year, despite prolonged periods of 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?
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 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 does not receive either sub-surface or surface run-on?
8	Are plant water relations (especially pre-dawn and mid-day water potentials and transpiration rates) indicative of less water stress (potentials closer to zero; transpiration rate larger) than vegetation located nearby but not accessing the groundwater discharged at the surface? The best time to measure this is during rain-less 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) are likely to be GDEs as they can often quite easily reach and extract groundwater (Canadell et al., 1996). App Table 7 provides a list of guiding rules used in the GDE Atlas.

5.2.2 **Ancillary data sets and expert knowledge**

In a 'first pass' assessment of potential GDEs in the impact area, data sets and information can be collated to help represent some of the variables of the indicators above. Mapping the likely presence of GDEs at this stage is 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. In the GDE Toolbox, this step is referred to as Tool 1 – Landscape mapping (App Table 2). A non-exhaustive list of example spatial data layers is given in App Table 3, with links to national and state data sets (in App Table 4). Online resources, such as the GDE Atlas 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 (<90 - 250 m^2). Examples of databases to complement searches of the GDE Atlas include Geomorphic Wetland Mapping in Western Australia, and the Queensland Groundwater Database.

For example, GDE mapping for the Comet, Dawson and Mackenzie River sub-basins in Queensland was completed using the Queensland GDE Mapping and Classification Method (DSITI, 2016). Digital maps were generated by integrating spatial data with expert local knowledge collected over three workshops. This collation of knowledge overcame one of the shortcomings of previous broad-scale mapping projects in not accounting for site- or region-specific information in mapping rule sets.

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 literature review including journal papers, reports and other EIAs.

5.2.3 Remotely sensed data

Increasingly, remotely sensed imagery is becoming easily accessible and free. MODIS imagery, for example, can be extracted via NASA (MODIS data) and includes many variations of analysis-ready products that suit identification of GDEs such as vegetation indices at 250 – 500-m pixel resolution every 8 days. Landsat, which has coarser temporal resolution (16-day return) but finer spatial resolution (30-m pixels), is also free from USGS (Landsat data) but requires additional corrections before it is fit-for-purpose. The Australian Government is overcoming this constraint with the Data Cube, which is pursuing a user-friendly interface to download Landsat products that are user-ready, similar to that of MODIS.

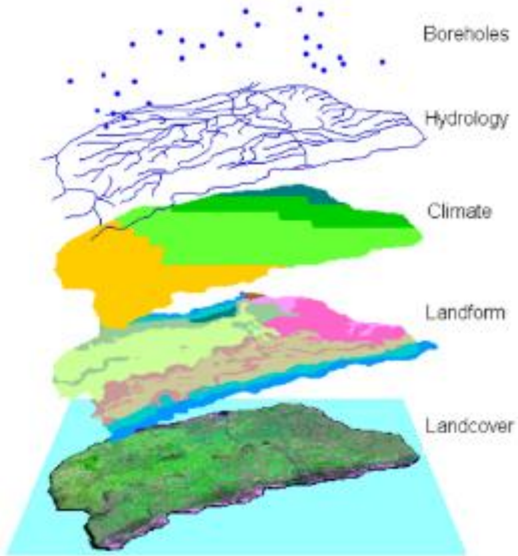
Using remotely sensed data provides a way to assess the landscape across broad to fine scales, and is encouraged as a method to identify potential GDEs and their groundwater dependence before and after CSG and LCM operations. Landsat, for example, has a long archive of imagery which is important to understand conditions prior to development. As remote scientific analysis methods progress, remote sensing will become an economic and valuable tool to provide an indication of level of groundwater dependence (section 5.3) in conjunction with other methods in a multiple lines-of-evidence approach (Doody et al., 2017). Suitable skills will be required to undertake and interpret analysis.

CASE STUDY 2: *Integrated mapping of GDEs across Victoria*

In order to identify threatened terrestrial GDEs across Victoria, a landscape mapping approach was undertaken to identify potential GDEs (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; remote sensing Landsat greenness; MODIS photosynthetic activity; land use; groundwater depth; groundwater salinity; and surface geology.

Data overlaid in a GIS provided an approach to identify potential GDEs. For example, vegetation where the ecosystem maintained a constant greenness over a dry period and was associated with a wetland ecosystem implies a high probability of GDE presence.



RECOMMENDATION: Use the GDE Atlas, national-, state- and local-scale spatial data, remote sensing, expert knowledge and scientific studies to create and update conceptual models in an integrated desktop study guided by GDE rules of likely groundwater dependence. This will indicate potential GDE presence in and around the project impact area and capture the relationships between potential GDEs and groundwater.

OUTCOME: The proponent will have a list and map of potential GDEs that may include alluvial aquifers, wetlands, rivers, springs and vegetation communities, together with an indication of the likelihood of groundwater dependence for each potential GDE in the project impact area.

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 area (see arrow 3 in Figure 5). Conceptual models (see section 5.3.1) will 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 they are aspects of groundwater regime or water quality that are likely to affect the GDE if changed (e.g. amount, location, timing, frequency, episodicity of groundwater use).

5.2.4 **Conceptualisation**

Conceptual models, often presented as stylised diagrams, help illustrate the relationships and interactions of GDEs and groundwater, and are an important step in identifying GDEs and understanding their groundwater dependence. It is critical that these models show how CSG or LCM activity is linked to GDEs via the aquifer that connects them. Conceptual models provide a way to visualise complex processes simply, and are useful in elucidating and illustrating likely impacts and their causal pathways (section 3.1). 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).

Conceptual models are a suggested tool in the GDE Toolbox (T2 – conceptual modelling; App Table 2), and Queensland's Wetland Info site provides a step by step approach to their development (WetlandInfo). Serov et al. (2012) present conceptual models to clarify groundwater and its relationship to GDE type.

5.2.5 **Ecological water requirements of GDEs**

Ecological water requirements of GDEs are those aspects of the natural groundwater regime that support the persistence of critical ecosystem characteristics (biodiversity, ecological structure) and processes (ecosystem function; Richardson et al., 2011). This section is specifically focused on the features of groundwater (flow, depth to watertable, 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.

A number of methods exist for establishing the ecological water requirements and groundwater dependence of GDEs and are detailed in App Table 2 and summarised in Table 2. Tools T3 - T6 aim to identify the sources of water used by vegetation, and tools T7 - T8 and NT5 (see CASE STUDY 3) aim to identify whether vegetation uses more water than is likely to be available without access to groundwater. A multiple-lines-of-evidence approach is required to determine level of groundwater dependence (high, medium, low, nil). Dependence level is related to 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 employed when insufficient data exists to determine dependence.

Table 2. Summary of tools for assessing GDEs which incorporate field data (see App Table 2 for full details). T=Tool shown in the GDE Toolbox; NT=New Tool

Code	Tool
T3	Pre-dawn water potential
T4	Plant water stable isotopes
T5	Plant water use modelling
T6	Plant rooting depth and morphology
T7	Plant groundwater use field methods
T8	Vegetation water balance
T9	Stygofauna sampling
T10	Evaluation of surface water – groundwater interactions
T11	Environmental tracers
T12	Introduced tracers
T13	Long-term observation of ecosystem response to change
T14	Numerical groundwater modelling
NT4	Genetic/DNA analysis

Shallow alluvial aquifers inherently have a high likelihood of being GDEs, and require sampling for stygofauna to confirm this (T9). 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 will likely become more readily available as a tool for consultants in the next five years (see CASE STUDY 4). Tools T10 - T12 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 will occur over a continuum that varies proportionally 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 is an indication that the ecosystem does use groundwater and its likely level of dependence, and that 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 change. This can be achieved through targeted monitoring programs designed along causal pathways (section 3.1), which test specific hypotheses of how ecosystems are affected by changes to the aquifer (e.g. T13 and T14, Table 2; App Table 2). CASE STUDY 5 presents an example of long-term monitoring of ecosystem response to change in groundwater conditions (T13).

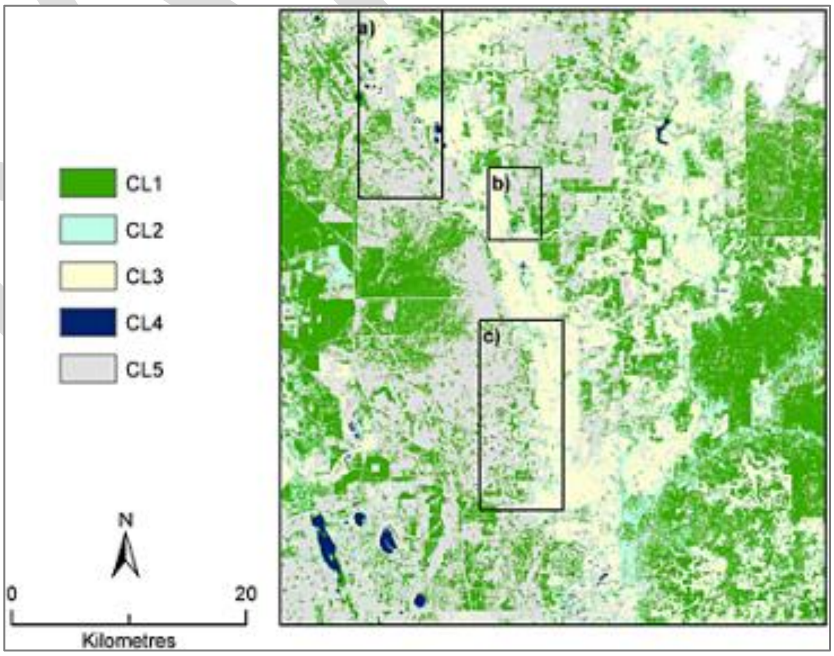
It is important to return to section 3.1 at this stage to ensure all causal pathways likely to impact on the GDEs are identified and documented. Conceptual models should also be updated.

RECOMMENDATION: Assess ecological water requirements of GDEs and use these to confirm causal pathways (section 3.1) that may create a change in GDE status through altered groundwater regimes. Use multiple lines of evidence to determine groundwater dependence where possible.

CASE STUDY 3: <u>*Landsat remote sensing delineation of GDEs*</u>

Remote sensing provides a broad-scale, fine-resolution and temporal ability to map GDEs. Landsat imagery is especially suitable with a long, freely accessible global archive and 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 GDEs by defining vegetation status over prolonged dry periods. It is expected that vegetation dependent on groundwater (phreatophytes) will 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.

A study undertaken in the south-west of Western Australia identified GDEs using NDVI and NDWI (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 localised groundwater, diffuse discharge zones and riparian vegetation. The study was founded on the theory that due to 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 were likely to have access to groundwater. The research identified two land cover classes (CL) of GDEs, two classes of non-GDEs and a class which identified open water bodies. All classes are shown in the associated map, where CL1 contains GDEs with permanent access to water (high greenness and wetness); GDEs in CL2 have reduced access to groundwater but remain green over a long dry period (slow-drying GDEs); CL3 ecosystems have no groundwater connection and hence are not GDEs in a fast-drying landscape; CL4 highlights 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 demonstrated good agreement 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.



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 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 groundwater ecosystems has typically been based on assessment of the presence of obligate groundwater invertebrates (stygofauna). However, these represent a very small portion of the ecosystem diversity, and the microbial component of the aquifer ecosystem is responsible for the key ecosystem functions relating to water quality. Using eDNA provides an opportunity to rapidly identify a more representative suite of microorganisms that exist within an aquifer.

Advances in eDNA processing will continue to improve the capacity to identify the presence of a range of microorganisms within an aquifer, and to map and monitor the distribution of endangered, rare (e.g. Gorički et al., 2017) and invasive species. In standing waters, such as lakes and ponds, eDNA has been used to estimate population abundance of target species. However, the spatial and temporal distribution of eDNA in flowing waters is a more complicated process and requires more research (e.g. Shogren et al., 2017).

5.2.6 **Confirming the likelihood of groundwater dependence**

A measure of GDE likelihood identifies regions of the project impact area that require further assessment to characterise levels of groundwater connectivity and thresholds beyond which condition of the GDEs will decline if groundwater alteration occurs. Likelihood of accessing groundwater may be used as a proxy for groundwater dependence in the early stages of impact assessment. Without detailed field surveys, it is difficult to quantify the likelihood, so it can be reported qualitatively as high, medium, low and nil. For groundwater-dependent vegetation communities, the likelihood of dependence can be determined initially by the species of tree (for species that have a known dependence on groundwater, see App Table 5) or groundwater depth as reported by local or regional monitoring data. For example, a stand of Red Gum on a floodplain where the watertable is 5 m deep will have a high likelihood of accessing groundwater, based on published records (App Table 5 and App Table 6).

Rivers are assigned a high likelihood of groundwater dependence if groundwater levels near the river channel are shallow and the watertable intersects or runs just below the lowest point in the river cross-section. All subterranean waters in alluvial aquifers are likely GDEs and are assigned a high likelihood of groundwater dependence. 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.

To determine likelihood requires a further targeted desktop study once potential GDEs have been identified. The guiding questions provided in Eamus et al. (2006; Table 1) aid assessment of likelihood, whereby a positive answer to any one question infers likelihood of being a GDE. To answer these questions, additional data and analysis such as stream flow or groundwater regime are required. Vegetation dependence on groundwater can be determined from literature reviews and species information given in App Table 5 and App Table 6. Additional remote sensing analysis at this stage can generate datasets or highlight relationships to groundwater which help to reveal likely groundwater dependence (Eamus et al., 2015a).

Various approaches using desktop analysis to identify likelihood of GDEs include vegetation analysis, groundwater-surface interaction studies, remote sensing and geologic mapping (Dresel et al., 2010). Integrative methods using geological, hydrogeological and ecological data sets with the inclusion of expert opinion (and location of known GDEs) are now commonly used to provide reliable estimates of likelihood, employing a multiple-lines-of-evidence approach. The method undertaken to create the GDE Atlas provides a relevant example of data integration (Doody et al., 2017) as does CASE STUDY 2.

Using desktop analysis and integration of three indirect data sources (vegetation community mapping, groundwater level data and remote sensing greenness), DPI (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 a classification of 1, 2, 3 and 4 responds to high, medium, low and no potential (or likelihood) to extract groundwater, respectively (Table 3).

Table 3. Groundwater depth (m) and number of times in a 10-year period that greenness remained above a determined threshold to indicate groundwater use for woody vegetation. 1=high, 2=medium, 3=low, 4= no potential. See DPI (2016) for full methods.

	1-4 times	5-8 times	9-10 times
0-8 m	3	2	1
8-12 m	3	2	2
12-16 m	3	3	2
16-20 m	4	3	3
>20 m	4	4	3

OUTCOME: 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 be updated with new information.

6 Baseline ecological condition assessment and field survey requirements

The baseline ecological condition of a GDE is the state of the ecosystem prior to the start of CSG and LCM activities. Where the GDE occurs in an agricultural or other modified landscape, there may already be some pre-existing influences on the ecosystem that have moved it from a pristine condition and this should be considered. In an EIA, the main purpose of determining baseline ecological value is to understand the 'starting point' of the ecosystem prior to development. This becomes a benchmark that future monitoring can be compared against. If a GDE is in a poor state prior to CSG or LCM development, there should be an aim to improve its condition during and beyond operations.

6.1 Baseline conditions

To define the baseline condition of GDEs prior to CSG and LCM activities (see arrow 4 in Figure 5), the spatial extent and magnitude of groundwater drawdown or depressurisation needs to be determined, as do any changes expected to water quality. The vulnerability of each GDE to predicted changes in water chemistry, volume and/or pressure can then be assessed using data collated for each GDE in the project impact area. Monitoring programs and conceptual modelling of causal pathways (section 3.1) are critical for defining how GDEs are likely to respond to groundwater system threats.

Prior to commencement of activities that may affect groundwater regime and water quality, it is critical to establish the baseline ecological and hydrological conditions within and outside the project impact area to ensure that changes due to CSG or LCM activities can be distinguished from those due to natural variability and climate change. This can be achieved using a combination of published and unpublished reports, databases, remote sensing and field assessment (see section 5). Detailed guidelines for determining baseline condition exist for aquifer communities in Western Australia and Queensland (WA EPA, 2016; DSITI, 2014). These guidelines use the stygofauna community as the main biological indicator to assess ecological condition of aquifers.

6.2 Requirements for GDE field surveys

Field surveys of GDEs are required for two key purposes: i) to confirm the presence of all potential GDEs in the project area (ground truthing), select reference sites outside the project impact area, and assess the baseline condition of GDEs; and ii) to identify a representative subset of GDEs to use for detecting impacts and monitoring the effectiveness of mitigation strategies.

When establishing a field survey protocol in the impact assessment phase of a CSG or LCM project, it is important the proponent considers how the sites, protocols and sampling regimes will be used throughout the project, including beyond completion of CSG and LCM activities. This saves time, and will likely improve impact assessment efficiency. Ideally, GDE data collection sites and protocols can be consistently used to (i) establish if the ecosystem is groundwater-dependent; (ii) determine baseline condition and ecological value; (iii) monitor for impacts during CSG or LCM activities; and (iv) where applicable, assess GDE recovery after operations cease. This Note is concerned mostly with (i) and (ii) although proponents should also consider uses (iii) and (iv) when establishing their survey routines.

6.3 Field surveys and monitoring

As mentioned in section 5.3 field surveys for GDE assessment are important to confirm each potential GDE identified in the desktop study is groundwater-dependent, and 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 either to confirm that there is a connection between the ecosystem and an aquifer (in the case of GDE vegetation communities, wetland GDEs and river baseflows) or that stygofauna are present (for aquifer ecosystems). 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 ecological value of the ecosystem once it has been confirmed as a GDE. 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 as 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).

Sufficient understanding of baseline conditions is essential so that 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 an aquifer) and data should be collected more than once, with one survey occurring at or near the time of optimal groundwater dependence.

Proponents must also establish reference sites outside the expected impact area. Doing so indicates whether changes observed across GDEs in the impact area exceed changes in the broader region which may be explained by climate variability or other sources of variability.

A key consideration for sampling in the 'impact assessment' phase of a project is how it will be used to inform monitoring during the operational and post-operational phases. The type of data and how, when, and where it is collected during the initial stages of a monitoring program will need to be compatible with future surveys designed to detect changes from impacts. Preference should be given in the 'impact assessment' phase to choosing sites that can be included in subsequent monitoring programs throughout the life of a project. During the early stages of field surveying, the proponent can sample intensively to identify redundancies in sites and variables, and then refine these to a representative subset of sites and variables for efficient long-term monitoring.

6.4 Site selection

To assess the condition and value of GDEs in the early phase of an EIA, sites need to be selected that are representative of the GDE types that exist within 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 to each aquifer type (CASE STUDY 5; App Table 8).

Preferably, GDE survey sites should be located close to existing groundwater monitoring bores as groundwater data is critical to understanding the specific nature of the groundwater and GDE 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 future potential impact, such as watertable 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 is usually collected limits assessment of GDE temporal variability. This data is seldom sufficient for use in establishing baseline conditions against which future monitoring will be compared. To overcome this problem, reference sites need to be established. These should be located in areas where impacts from CSG or LCM activities (which includes the project under assessment as well as existing and likely future operations) are negligible, but where the ecosystems are still subject to changes consistent with pressures 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 also experience similar pressures so that impacts due to CSG or LCM activities can be successfully distinguished.

Each high- and medium-value 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. Depending on the location of GDEs with respect to watertable drawdown, it may be necessary to stratify sampling to account for the impacts of different levels of drawdown. For example, a groundwater-dependent patch of vegetation 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 or 3 m (assuming there is not a threshold depth to watertable shallower than 2 m where major impacts abruptly occur).

CASE STUDY 5: *Carmichael Coal Mine and Rail Project Stygofauna Survey (GHD 2012)*

The Environmental Impact Statement Terms of Reference for the Carmichael Coal Mine, in Queensland's Galilee Basin, required the 'description to Order or Family taxonomic rank of the presence and nature of stygofauna', and specified that the sampling and survey methods should follow WA EPA (2003, 2007) guidelines for sampling. At the time, these guidelines were considered best practice for Australia.

The guidelines specify that sampling should occur over at least two seasons and collect samples from at least 40 bores (WA EPA 2003). These bores should access all aquifers present in the project impact area, but a higher emphasis should be placed on aquifers likely to have stygofauna (such as alluvial aquifers).

In reality, stygofauna sampling is restricted by bore availability. Bores are not always in the optimal location due to installation for purposes other than the collection of stygofauna samples. For the Carmichael Coal Mine, where the project tenement covers approximately 25,740 ha, 19 bores were sampled on each occasion, with only two of these in alluvial aquifers. This is because there were very few suitable bores present in the alluvium (GHD, 2013). Although two stygofauna taxa were collected from a clay aquifer and one of the coal seams, no bores were sampled from the alluvial aquifers of the two largest systems in the study area, the Carmichael and Belyando Rivers.

To better understand the stygofaunal diversity of the impact area, bores need to be installed in the alluvial aquifers, and more data collected. With only two bores sampled from alluvium, it is likely that stygofauna diversity in the Carmichael Mine was under-estimated.

With more specific and detailed sampling guidelines now in place in Queensland (DSITI 2014) and a better understanding of stygofauna ecology and distribution, subsequent stygofauna sampling regimes will be developed to target the appropriate aquifers and undertake sampling in sufficient spatial detail. For this to be achieved, it may be necessary to install monitoring bores that are not just located for the purpose of water quality sampling, but can also be used for stygofauna sampling.

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. Locate sites near groundwater monitoring bores.

6.5 Assessing ecosystem value

The purpose of assigning an ecosystem or ecological value to a GDE in impact assessment is to assess what might be lost as a result of development and to make informed decisions. It also provides a method to prioritise avoidance and mitigation strategies, and guide monitoring programs.

When assessing the ecological 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. They need to consider the ecological condition of the GDE under current and historical land management, how this differs from its likely condition prior to any impact from CSG or LCM activities, and the potential for the ecosystem 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 its regional significance. Usually, field surveys will be 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 8 and App Table 9.

In an EIA, it is critical to understand ecosystem value with respect to how GDEs interact with the surrounding environment and the myriad of ecosystem services that they may provide. 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 are outside the scope of this document.

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

- the sensitivity of GDE communities to changes in groundwater (e.g. *high value* - GDEs for which only slight changes in groundwater level can result in loss of biota or services; *moderate value* - GDEs that require a moderate change in groundwater to cause change in their distribution, composition or condition)
- location of GDEs (e.g. *high value* - within State Reserves)
- condition (e.g. *high value* - GDE is relatively unaltered with good condition; *low value* - highly modified from natural state and declining in ecosystem condition)
- uniqueness (e.g. *high value* - GDE contains endemic, relictual, rare or endangered species; *moderate value* - GDEs contain vulnerable or threatened biota)
- services (e.g. *high value* - GDEs that provide multiple ecosystem services to society)

6.6 Data requirements

The GDE Toolbox contains a list of different sampling methods available for GDEs (App Table 2). Pragmatically, the sampling regime must fit within the time constraints allowed for preparing the EIA, which means long-term data sets will not be available for most types of data.

Each GDE in a project impact area should be surveyed prior to commencing operations, and the levels of detail and sampling intensity are guided by GDE ecological value and condition (section 2.2), level of groundwater dependence and vulnerability (see section 7.2). A higher level of survey effort should be allocated to GDEs that have a high ecological value and/or are potentially at higher risk.

Remotely sensed data offers an opportunity to cover broad areas quickly and economically (see Section 5.2.3), and can be used to demonstrate changes through time in terrestrially expressed GDEs such as river baseflows, springs and vegetation communities. However, for many GDEs, field surveys are required to determine baseline condition. Prior to conducting field surveys, proponents need to consider the type of data required. Data needs to sufficiently fill any gaps identified in the desktop phase of the assessment (section 5), be useful for indicating ecological 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 groundwater connection).

Critically, ecological data needs to be paired with groundwater data so the link between GDE condition and groundwater level and quality can be determined and monitored. However, consideration should be given to lag effects (e.g. 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. health of a GDE might have declined and be on a declining trajectory before operations). The interaction between a patch of vegetation and groundwater that it depends on can be better understood (and later, better managed) if groundwater data comes from as near the source as possible. Once a GDE has been identified, one or more bores should be installed nearby to monitor local groundwater 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, and is often constrained by funds available to undertake sampling. 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., 2009; 2015). Sampling at least quarterly is advised to assess the seasonal trends related to vegetation dynamics. This can be supplemented with remote sensing of greenness to establish a long-term baseline of seasonal canopy response trends. GDEs that potentially serve as early warning indicators of groundwater change should be sampled with higher frequency (e.g. stygofauna).

All non-spatial data (e.g. water quality, ecological condition, groundwater level) should be linked to a known point on the landscape, such as a GPS point, for inclusion in spatial databases. Maps are often the main visual 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 example in Figure 6).

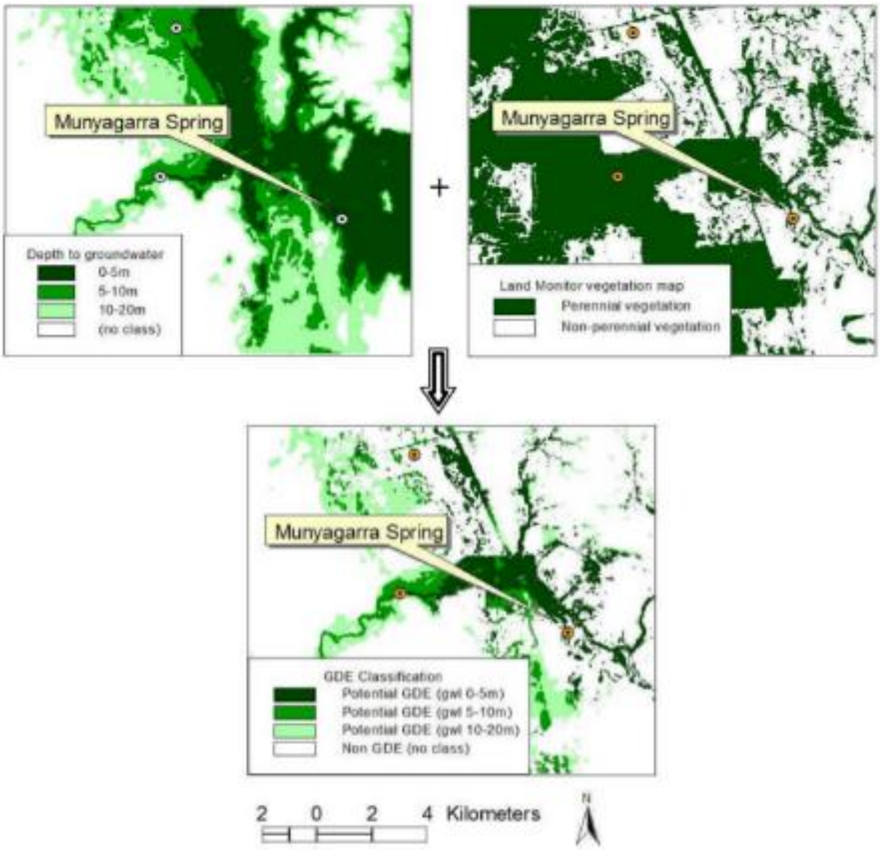


Figure 6. Mapping example demonstrating the combination of overlaying maps of depth to groundwater (top left) and vegetation (top right) to reveal potential GDEs from the intersection between the two (bottom), in three classes where groundwater is 0-5 m, 5-10 m and 10-20 m near Hill River in the Northern Perth Basin, Western Australia. Vegetation is not considered a GDE when groundwater depth is greater than 20 m in this example. SOURCE: 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), and this can be used to indicate value (e.g. biodiversity, presence of threatened species or communities) of communities that are also groundwater-dependent.

6.7 Survey level of detail

Generally, GDEs should be sampled at a level of detail sufficient to indicate the degree of groundwater dependence and their ecological condition and value. For this, the survey must include enough replication of each GDE to enable an understanding of their ecological condition over space and time. Greater detail will be needed if threatened species exist 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 groundwater-dependent trees, the population of orchids occurring in the patch of vegetation should be mapped so changes through time are evident.

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 ecological condition can be paired with groundwater data (e.g. water level and water quality)
- the number of surveys needed at each site to understand temporal patterns (e.g. seasonal or occasional water use) in each GDE
- variables required, and level of detail needed to adequately assess GDE value (e.g. for stygofauna, should identification be taken to species level?)

- 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 why particular variables (and their sampling regime) were chosen to detect and monitor impacts to GDEs

RECOMMENDATION: Proponents should 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) needs to reflect ecological value and condition, level of groundwater dependence and level of risk to the GDE, and must be justified in the EIA.

6.8 Data analysis and management

Spatial and non-spatial analyses are required to determine the extent and condition of GDEs.

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), and this can be determined using past data. For most GDE types, data on ecological condition will be sparse or non-existent prior to the initiation of EIA studies, so an understanding of natural variability will be limited. Management plans developed during the EIA phase need to acknowledge this and set realistic monitoring goals that are adaptable to new data. Impacts to 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, and 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 of similar projects.

Ideally, all data collected during GDE assessments for EIA projects should be stored in a central repository, such as the GDE Atlas, so it is available for use by other proponents or researchers wishing to increase our understanding of the interactions between GDEs and aquifers. There are several state-based databases where GDE datasets are stored (e.g. Wetland Info and the Subterranean Aquatic Fauna Database in Queensland).

Proponents must take responsibility for managing and storing the data collected. Throughout the life of a project, the consultant collecting data for the EIA may differ from the consultant conducting the monitoring during the operational phase. Therefore, data management and storage should sit with the project proponents. Unless the proponent requests raw data from the consultant and stores it appropriately, data will 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 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, determination of ecological value and condition, level of groundwater dependence, suitable data analysis and well-justified management options. The collected information will provide an understanding of the natural variability in each GDE and inform decisions to determine an 'acceptable level of change' with consideration of the ecological value of each GDE. Monitoring programs should state the goals of monitoring, what is to be measured, where and how often, how each variable relates to potential impacts and GDE responses, and how the data will be stored, analysed and presented.

7 Assessing risks of project-specific impacts to GDEs

Once baseline assessment has been undertaken for each GDE and its ecological value has been established, there must be an assessment of potential project impacts to develop a risk assessment protocol which 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 to GDEs exist in New South Wales (Serov et al., 2012) and Queensland (Department of Environment and Heritage Protection 2016). Both of these 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 an impact area have been identified and their ecological significance and condition are determined) are:

- determine the impact of the activity on all GDEs, including the aquifer community
- determine magnitude of risk to all GDEs
- apply a GDE Risk Matrix (App Table 10, Serov et al., 2012)
- develop a management plan consistent with the outcomes of the risk category determined in the Risk Matrix

The GDE Risk Matrix (App Table 10) outlines appropriate management responses for an environmental value under a particular activity. The matrix consists of a vertical axis that represents ecological value and a horizontal axis that represents the level of risk of an activity. The ranking of both ecological values and risk is assigned as being High, Moderate or Low (App Table 10).

The Risk Matrix management action table (App Table 11) identifies both the level of management action required and a time frame relevant to each GDE in which this action needs to be implemented (Action Priority). 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 timing of management actions varies in response to the risk level.

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

7.1.1 **Ecological response to change in groundwater condition**

Defining how GDEs might respond to changes in groundwater condition (e.g. change in regime such as magnitude of fluctuation, discussed in Richardson et al. (2011)) 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 justify predicted responses. Understanding GDE responses to changes in groundwater condition can then be supported by data and demonstrated relationships if they are available, once a conceptual understanding is developed.

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 6 to understand the interaction between the GDE and groundwater connection.

In general, changes in groundwater availability have been found to impact growth, reproduction, recruitment and mortality of groundwater-dependent biota and to alter the structure and function of GDEs (Eamus et al., 2006; Kath et al., 2014). 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 Red Gum 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 Red Gum will have significant impacts during times of extended drought when rainfall is below average and surface water flows are substantially reduced.

Assessing GDE response to change in groundwater condition 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 GDEs persist
- the hydrological thresholds that represent the limits of ecosystem persistence and resilience or vulnerability

As uncertainty in determining thresholds between hydrologic regime and ecological response can be high, particularly during the early years of CSG and LCM development, NSW and Queensland integrated risk assessments into their protocols for determining threats to GDEs (section 7.2). This aims to minimise the 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 response to changes in groundwater regime (T13 - long term observation of ecosystem response to change, Table 2 and App Table 2) and modelling ecosystem response to potential threats to groundwater (T14 - numerical groundwater modelling, Table 2 and App Table 2).

CASE STUDY 6: _Long-term monitoring of ecosystem response to changes in groundwater condition: Gnangara Mound, Western Australia_

Gnangara Mound is a shallow unconfined aquifer that is used to supply groundwater to the Perth metropolitan area. Surface water, groundwater and vegetation have been monitored around Gnangara 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 commenced, groundwater levels declined by an additional 2.2 m during summer. The decline in watertable coupled with lower-than-average annual rainfall and a period of high summer temperatures resulted in extensive dieback of Banksia species (a loss of between 20 and 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). Many subsequent studies, summarised in Eamus et al. (2015b), examined the vulnerability of Banksia species to changes in the depth to the watertable by using a number of techniques for understanding 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 a declining watertable and dieback as groundwater levels rose, Canham et al., 2012).*
- *groundwater level declines of 50 cm year^{-1} resulted in mass dieback of both mesic and xeric species whereas at the reference site, groundwater level declines of 9 cm year^{-1} reduced the abundance of both mesic and xeric species but did not cause the replacement of mesic with xeric species (Froend and Sommer 2010).*
- *reduced groundwater levels have caused incidents of reduced groundwater quality, with salt water intrusion occurring in some coastal and estuarine parts of Gnangara Mound.*
- *lowered groundwater levels have contributed to acidification of some wetlands due to the exposure of acid sulphate 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 valuation, via a threat analysis, of how the current GDEs might change if groundwater conditions change (Richardson et al., 2011). 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 ecosystem, 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:

1. identifies GDE types and their inferred degree of dependence on groundwater
2. determines ecological value of the aquifer and its associated GDEs
3. determines likely impact of an activity on the aquifer and/or identified GDEs
4. determines the level of potential risk from an activity
5. develops management strategies through a risk matrix approach (App Table 10).

Where there are multiple threats, Richardson et al. (2011) suggest a risk analysis using a Bayesian Belief Network (BBN; e.g. Hart and Pollino, 2009).

By understanding the ecological value and vulnerability of GDEs to activities affecting groundwater, GDEs with high ecological value and/or subject to high risk can be identified so that management actions can be prioritised to minimise risk while monitoring programs seek to reduce uncertainty (Rohde et al., 2017; App Table 11). Monitoring programs may take years to produce sufficient data to reduce uncertainty about how dependent GDEs are on groundwater or to quantify what the relevant thresholds of change in groundwater condition are that will affect GDEs. Incorporating a 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 will still be required to better understand the relationships between ecosystem condition and groundwater availability using more advanced methods (e.g. Table 2 and App Table 2, Rohde et al., 2017).

RECOMMENDATION: Risk assessment must be undertaken in all EIAs to identify GDEs with high or medium ecological value and/or at high or medium risk from impacts of CSG and LCM activities so that management actions can be prioritised to reduce risks. **All** GDEs must be protected, however.

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, which in turn potentially results in underestimating impacts of CSG and LCM activities on GDEs in the project impact area. Examples of these gaps include:

- use of online databases only rather than incorporating field survey 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 tool or model for a task
- assessments that focus on only the area proposed for expansion, rather than the cumulative impact of the whole operation and adjacent activities
- gaps in legislated requirements (see CASE STUDY 7)
- uncertainty by 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 and models.

7.3.1 Information sharing between consultants during the EIA process

For CSG and LSM projects, GDE impact assessments are often completed in conjunction with other impact assessments of vegetation and aquatic ecology. During this EIA process, a vast amount of information is gathered about a region, and information not collected specifically for GDEs can be valuable in GDE assessments.

It is important that this relevant information be shared freely between consulting groups where possible, either through direct communication, via a facilitating party, or through the company undertaking the CSG or LCM activities. This will prevent the needless repetition of work, and allows 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.

CASE STUDY 7: <u>*Narrowing the gaps in impact assessment for aquifer ecosystems*</u>

In Queensland, up until 2014 there was a requirement only to identify stygofauna specimens to Family level and then assess their status as endemic. As there are few taxa that are endemic at the Family level, most assessments concluded that impacts to aquifer ecosystems would be negligible.

Only Family level identification was required because stygofauna taxonomy and understanding of stygofauna ecology and distribution was rudimentary. Many regions had not been sampled for stygofauna, so the species present were unknown, as was their ecology and any understanding of the species' ranges.

In Western Australia, stygofauna impact assessment guidelines required specimens to be identified to Species level using morphological features or DNA analysis (WA EPA 2003, 2007). This resulted in a vast increase in knowledge about stygofauna distribution, and led to a rapid increase in the number of known stygofauna species. It also meant that impact assessments were more robust, and proponents better able to assess the level of stygofaunal endemism in their impact area. In 2014, the Queensland Government released Guidelines for the Environmental Assessment of Subterranean Aquatic Fauna (DSITI 2014) which specified that most crustaceans were to be identified to Genus while other groups could be identified to Order or Family. Genus-level taxonomy is possible for most crustacean groups, and these groups are the ones most likely to be stygofauna. Where taxonomic expertise is limited, genetic analysis should be used following morphological assessment.

For assessments of potential impacts to aquifer ecosystems, there is a need for stygofauna collected for CSG and LCM projects to be identified to Genus or Species level. This will allow proponents to more reliably assess endemism in the collected stygofaunal taxa and will increase knowledge in stygofauna biodiversity and distribution in eastern Australia. Concurrent collection of environmental data (electrical conductivity, dissolved oxygen concentration, temperature, pH, depth of watertable below ground, depth of bore screen) will increase understanding of stygofauna tolerances to water quality and changes in groundwater level.

All data should be stored in a central state-based repository that is moderated and publically available, such as the 'Queensland subterranean aquatic fauna database'. A stygofauna database could be linked to the national GDE Atlas to enable searches by geographical region and taxonomic group.

OUTCOME: The proponent, after defining the baseline condition of each GDE within and outside the area of impact, will have identified how the GDEs and the services they provide are likely to respond to changes in groundwater regime and water quality, all processes 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/national levels.

8 Avoidance, mitigation and management options

Once the location and condition of GDEs in the project impact area are known, the key management aim is to protect them from impacts of CSG and LCM activities that will reduce their ecological value, whether the impacts occur in the pre-construction, construction, operational or post-operational phase (including rehabilitation). This requires strategic planning to prevent adverse impacts of CSG and LCM activities on GDEs, and development of management plans to mitigate the impacts on GDEs when impacts are unavoidable or unforeseen (see arrow 6 in Figure 5). This is best achieved with a GDE management plan that details the ecological components and water requirements of each GDE, their ecological condition and value, and the legislative status under which they might be protected. Research and monitoring must underpin any management plan to inform adaptive management which will reduce environmental impacts and contribute to an increased understanding and therefore protection of ecological values in the project impact area.

8.1 Management Plans

A management 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 conditions 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.

Research and monitoring are fundamental to inform the management plan and develop sampling regimes to assess GDEs against baseline conditions and reference sites (Section 6). All phases of operation should detail management control measures for each GDE against issues that might change as a result of CSG or LCM activities, such as groundwater drawdown, pest invasion and fire. 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).

If some change to condition occurs or is predicted, mitigation measures must be detailed for each GDE which outline what a trigger for corrective action might be (e.g. drawdown in the vicinity of a spring complex exceeding a threshold level that is determined through research and monitoring). The corrective action should also be described in full, and often involves some form of adaptive management. For example, monitoring could be repeated immediately and if non-compliant results recur, an incident report and investigation could commence that leads to implementation of suitable corrective action identified as part of the mitigation strategy.

The management plan should consider any opportunities to improve condition of GDEs even if they have become degraded through historical land use, both inside and around the project impact area. This will enhance the overall biodiversity values and ecological condition of the area.

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 development-specific. Example indicators given in GHD (2013) include:

- impacts on GDEs do not cause unacceptable or unapproved loss of biodiversity values
- downstream flow changes remain within natural fluctuations

- environmental values relating to aquatic ecosystems, stock and domestic use, and cultural values are maintained.

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 which will avoid impacts to 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.

RECOMMENDATION: Avoidance of impacts to 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 8 for an example). While avoidance is the preferred management option, usually CSG and LCM activities will have some impacts on GDEs which will need to 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 enhance the ecological values that characterise the project impact area and surrounding landscape before and during operations to reduce the overall impact on biodiversity values.

Mitigation actions include supplementing reduced hydrological connectivity to riparian 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 where the strategy has been successful
- a justification of why and how the proposed mitigation measures will be successful, 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 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.

RECOMMENDATION: Mitigation strategies to prevent impacts to GDEs are critical when avoidance is not possible. These strategies are required early in an EIA to protect areas potentially at risk. Targeted monitoring is needed to confirm the effectiveness of these mitigation strategies.

CASE STUDY 8: Mitigation strategy for reduced spring flow: Weeli Wolli Creek

Weeli Wolli Creek system, located 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 five active mines in 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 maintained perennial creek flow for approximately 2 km, becoming ephemeral further downstream. Permanent pools were also present on the creek bed near the spring. The perennial spring discharge was 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 are 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 2015). A number of creek line and hyporheic species of conservation and/or scientific value have been identified (WRM, 2015):

- *Hyporheic species: Vestenula n. sp. (Ostracod - new species), Chydaekata sp., Paramelitidae sp., Maarrka weeliwolli (Stygal paramelitid amphipods - short range endemic) and Pygolabis weeliwolli (stygal 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 - reducing spring flow and causing groundwater levels to drop out of reach of phreatophytic vegetation. To counteract this, surplus mine water is discharged at several locations in the creek line to maintain basal flow 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, however the overall ecosystem of the spring and creek appear to be functioning supported by artificial spring discharge (EPA, 2018). However, the impact of groundwater dewatering and artificial watering at Weeli Wolli Spring on stygofauna, hyporheic and macroinvertebrate species is not apparent in currently available literature.

Concern remains that discharge of surplus water into the creekline, 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) or measures to compensate for the residual adverse impacts (unavoidable impacts) of an action on the environment. Offsets counterbalance the impacts that remain after avoidance and mitigation measures. They are required if residual impacts are significant. Where GDEs have endemic species or a spring complex has a rare combination of species, offsetting is unlikely to be a viable option if residual impacts are significant. Therefore, other options require investigation.

Offsets do not reduce the likely impacts of a proposed action but compensate for any residual significant impact. 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, although a proposal is made in the GDE Management Plan for Carmichael Coal Mine to offset 4 ha of groundwater-dependent waxy cabbage palm (GHD 2014). There are 2744 ha of suitable waxy cabbage palm habitat available outside the impact area, so direct offsetting may be possible 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 threatening processes to waxy cabbage palms
- conservation activities in waxy cabbage palm habitat outside of the project impact area.

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 NSW Aquifer Interference Policy 2012, proponents are required to provide a security deposit to be held by the NSW Government to 'cover the costs of remediation works for unforeseen impacts or ongoing post-closure activities'. The amount deposited is to reflect the level of risk to the aquifer or its dependent ecosystems, and is determined separately for each case.

8.1.5 **Monitoring**

Monitoring is essential to measure the effectiveness of the 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. changes in pre-dawn leaf water use). In establishing a monitoring program to assess 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 rapidly to allow adaptive management actions and the mitigation of unforeseen impacts

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

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

RECOMMENDATION: Identify hydrological and/or ecological variables that serve as early indicators of groundwater change to draw attention to imminent impacts to GDEs.

It can be relatively easy to use historical data to establish thresholds beyond which GDEs are impacted by changes in groundwater regime and/or water quality, but harder to establish valid biological benchmarks by which to formulate thresholds for monitoring ecosystem condition. For example, surveys during impact assessment can be used to confirm that stygofauna are present, but datasets are usually small because stygofauna are often sparsely distributed (WA EPA 2007). This leads to problems in setting baseline conditions to which future monitoring data should be compared.

In the Carmichael Mine example in CASE STUDY 5, only two stygofauna taxa were collected during the impact assessment. One was represented by two specimens, and the second by one specimen. With such limited baseline data, it is difficult to state whether or not future mining is having an impact on the stygofauna if variables of only stygofauna diversity and abundance are used.

Nevertheless, although there are currently difficulties in setting benchmarks for impact to stygofauna communities, an initial indication of aquifer biodiversity is a critical part of an EIA. As techniques in analysing environmental DNA (eDNA) become more refined (see CASE STUDY 4), it may be easier to detect if a species has become absent from an aquifer. Currently, eDNA is useful in detecting distribution of indicator and rare species of macroinvertebrates (Machler et al., 2014) and fish species richness (Olds et al., 2016). Modelling techniques are being developed that should soon allow estimates of fish densities (Chambert et al., 2017). Samples of eDNA have also been used to map the distribution of cryptic subterranean salamanders (Gorički et al., 2017), so is likely to be a useful tool in future assessments of aquifer ecosystems and ecological processes (Korbel et al., 2017).

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

9 Concluding statements and recommendations

New CSG and LCM projects in Australia and expansions to existing developments need to consider impacts to GDEs because of legislative requirements. 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 becomes available has resulted in some inconsistencies in how impacts to GDEs are considered. This Explanatory Note provides an assessment framework that is consistent with requirements in both 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 GDEs use groundwater, and how they are then affected when the groundwater is removed or contaminated. 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 adapt to new knowledge that becomes available.

Online spatial and non-spatial databases are critical components to 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 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.

Many of the options for mitigating impacts to 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 success of the proposed mitigation strategies. Options should also be given in the event of failure.

9.1 Summary of recommendations

All recommendations apply to both CSG and LCM developments, and expansion of existing projects.

- A number of helpful publications are mentioned throughout this Explanatory Note to aid proponents. 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 as a low, one-off cost.
- Proponents need to consider **all** GDEs, including those which are only partially dependent on groundwater and do not support any listed species. For this reason, an assessment of ecological condition, rather than ecological value is critical in establishing a baseline indication of the ecological condition
- Use the GDE Atlas, national-, state- and local-scale spatial data, remote sensing, expert knowledge and scientific studies to create and update conceptual models in an integrated desktop study guided by GDE rules of likely groundwater dependence. This will indicate potential GDE presence in and around the project impact area and capture the relationships between potential GDEs and groundwater.
- Assess ecological water requirements of GDEs and use these to confirm causal pathways (section 3.1) that may create a change in GDE status through altered groundwater regimes. Use multiple lines of evidence to determine groundwater dependence where possible.

- Proponents should 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) needs to reflect ecological value and condition, level of groundwater dependence and level of risk to the GDE, and must be justified in the EIA.
- Risk assessment must be undertaken in all EIAs to identify GDEs with high or medium ecological value and/or at high or medium risk from impacts of CSG and LCM activities so that management actions can be prioritised to reduce risks. **All** GDEs must be protected, however.
- GDE impact assessments must not rely solely on online data bases but should be followed up with desktop and field surveys by qualified specialists who use appropriate methods and models.
- Project consultants should share information during all stages of EIA development to provide a full assessment of potential impacts on GDEs.
- Avoidance of impacts to GDEs is the preferred option for preventing significant impacts from CSG and LCM activities.
- Mitigation strategies to prevent impacts to GDEs are critical when avoidance is not possible. These strategies are required early in an EIA to protect areas potentially at risk. Targeted monitoring is needed to confirm the effectiveness of these mitigation strategies.
- Identify hydrological and/or ecological variables that serve as early indicators of groundwater change to draw attention to imminent impacts to GDEs.

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11 Abbreviations and acronyms

ACLUMP	Australian Collaborative Land Use and Management Program
BBN	Bayesian Belief Network
BOM	Bureau of Meteorology
CSG	Coal seam gas
CSIRO	Commonwealth Scientific Industrial Research Organisation
DEM	Digital Elevation Model
DPI	Department of Primary Industries
DSITI	Department of Science, Information Technology and Innovation
EIA	Environmental Impact Assessment
EIS	Environmental Impact Statement
EPA	Environment Protection Agency
EPBC	Environment Protection and Biodiversity Conservation
ET	Evapotranspiration
GA	Geosciences Australia
GDE	Groundwater-Dependent Ecosystem
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
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NDVI	Normalised Difference Vegetation Index
NDWI	Normalised Difference Wetness Index
NVIS	Native Vegetation Information System
NWI	National Water Initiative
Project area	Likely area of impact from CSG or LCM activity, plus a buffer zone
TEC	Threatened Ecological Community

12 Glossary

Bioregional assessment is 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 is defined under the EPBC Act 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), either in its own right or when considered with other developments, whether past, present or reasonably foreseeable.

Conceptual model is 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 is defined as the total impact of a CSG and/or large coal mining 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 are part of the components that contribute to the physical state and environmental value of a water resource and can include processes such as nutrient cycling, eutrophication and carbon metabolism.

Facultative GDE are deep-rooted plant species that tap into groundwater, via the capillary fringe, to satisfy at least some portion of their environmental water requirement, but will also inhabit areas where their water requirements can be met by soil moisture reserves alone. That is, the species will be groundwater-dependent in some environments, but not in others.

Groundwater-dependent ecosystems (GDEs) are ecosystems that require access to groundwater on a permanent or intermittent 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 is the prevailing pattern of groundwater movement through 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. Input to the aquifer, changes to aquifer hydraulic conductivity, and water lost from the aquifer also need to be included.

Hyporheic zone is the region beneath and alongside a stream/river/wetland bed, where there is mixing of shallow groundwater and surface water.

Inflow-Dependent Ecosystem is 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 which use sources of water other than rainfall (e.g. surface water, water stored in the unsaturated zone, irrigation).

Known GDEs are those GDEs which have previously been identified using field studies or desktop studies. They can be sought from reports and scientific publications.

Large coal mining development is defined under the EPBC Act 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), either in its own right or when considered with other developments, whether past, present or reasonably foreseeable.

Numerical models divide space and/or time into discrete pieces. Features of the governing equations and boundary conditions (for example, aquifer geometry, hydrogeological properties, pumping rates or sources of solute) can be specified as varying over space and time. This enables more complex, and potentially more realistic, representation of a groundwater system than could be achieved with an analytical model.

Obligate GDE are organisms that only inhabit areas where they can access groundwater, via the capillary fringe, to satisfy at least some proportion of their environmental water requirement.

Piezometer is a specially designed bore with a short intake screen to monitor groundwater levels at a specific point in an aquifer.

Phreatophytes are deep-rooted plants that obtain a significant portion of their required water from the phreatic zone (zone of saturation) or the capillary fringe above the phreatic zone. Phreatophytes are plants that are supplied with surface water and often have their roots constantly in touch with moisture.

Riparian vegetation is vegetation that is adjacent or situated on the banks of a river or wetland.

Significant impact is defined by the Significant Impact Guidelines (DoE 2013) as an impact which 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 is 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. Activities in CSG and LCM development that potentially impact on GDEs. These activities present risks to GDEs that include altering the number of native species and species composition within GDE communities; disrupting ecological processes that deliver ecosystem services; damage 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	Watertable lowering; change timing and magnitude of groundwater level fluctuations	All	Aquifer connection to surface GDE; aquifer likely to have stygofauna (alluvial, karstic, calcrete) with dewatering at a magnitude and duration outside natural variability	Magnitude, duration, frequency, and timing of dewatering; how these compare to pre-impact conditions
				Initial watertable depth; water level fluctuation range over annual and supra-annual timescales, amplitude and rate of change
				Watertable lowering – will it convert gaining stream/wetlands to losing ones?
Aquifer depressurisation	Loss of artesian pressure	Springs	Depressurisation 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
Excavation of overburden	Removal of upper aquifer	All GDE types	When overburden is an aquifer that supports GDEs	Watertable depth in overburden; aquifer porosity
				Alteration of subsurface flow paths with excavation
Surface topography changes	Alter groundwater recharge patterns	Vegetation; wetlands; river baseflow; aquifer GDEs	Major landscape changes such as excavation of mine pit; subsidence of longwall panels	Alteration to channelling of water to or from aquifer recharge zones; availability of groundwater modelling
				Potential flow changes considered in groundwater modelling
				If GDEs have some level of reliance on surface water
River diversion	Disconnect river and aquifer	River baseflow; aquifer GDEs	If connection exists between channel and aquifer	If the diverted reach is dependent on groundwater, either locally or upstream

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
Leaking of saline water from surface storage or through fractures between aquifers	Increase in aquifer salinity; decline in water quality	All GDEs	Pressurised, lower aquifer of poor water quality occurring beneath an aquifer with better quality water that supports GDEs	If dilution of saline water will occur
			Overflow or leakage from storage dams and water infiltrates aquifers	Rate of saline water dispersal
			When hydraulic fracturing is planned and there is potential for a confining layer to be ruptured.	Chemistry of saline water compared to receiving aquifer
Construction and operation of surface infrastructure (buildings, roads, rail, pipelines, stockpile areas)	Permeable surface compaction; pollution from effluents, petrochemicals, explosives, other on-site chemicals	All GDEs	Location of infrastructure on upslope of aquifer recharge areas (including coal and rock stockpiling areas)	Footprint of disturbance area
Leachates from coal or rock stockpiles	Potential groundwater pollution from saline or acid drainage	Aquifer GDEs	Potentially toxic stockpile leachate	Geochemical characteristics of the stockpiled rock; process of stockpile draining
Vegetation clearing	Direct impact to groundwater-dependent vegetation; removal of organic matter source for aquifer communities	Vegetation; aquifer GDEs	Removal of large vegetation areas considered	Frequency of vegetation groundwater extraction
Open pit lake	Aquifer impact through poor water quality	Aquifers; river baseflow; wetlands	When potential for pit lake to leak into aquifer supporting GDEs	Potential to release water into the surrounding aquifer through seepage
				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 (Evans et al., 2013). Tools T1-T14 are shown in the Toolbox. New tools (NT1-NT5) have been included as tools not documented in the Toolbox, but relevant to identification of GDEs

Code	Tool	Brief description	Further information
T1	Landscape mapping	Locating and identifying ecosystems that are potentially groundwater-dependent based on a number of biophysical parameters such as depth to watertable, 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
T2	Conceptual modelling	Documentation of a conceptual understanding of the location of GDEs and interactions between ecosystems and groundwater	GDE Toolbox
NT1	GDE Atlas	A web-based national dataset of Australian GDEs. The Atlas includes a national inflow-dependent landscapes layer which is derived from remotely sensed data. It indicates the likelihood that a landscape is utilising water in addition to rainfall GDE Atlas	Bureau of Meteorology
NT2	ANAE classification	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	Department of the Environment and Energy
NT3	GDE typology	1. Aquifer and cave ecosystems 2. Ecosystems dependent on the surface expression of groundwater 3. Ecosystems dependent on the subsurface expression of groundwater	GDE Toolbox
T3	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
T4	Plant water stable isotopes	Use of naturally occurring stable isotopes of water to identify sources of water used for plant transpiration	GDE Toolbox
T5	Plant water use modelling	Identification of sources and volumes of water used for plant transpiration, by using mathematical simulations of plant function	GDE Toolbox
T6	Plant rooting depth and morphology	Comparison of the depth and morphology of plant root systems with measured or estimated depth to the watertable, in order to assess the potential for groundwater uptake	GDE Toolbox

Code	Tool	Brief description	Further information
T7	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
T8	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
T9	Stygofauna sampling	Techniques available to collect groundwater fauna	GDE Toolbox
T10	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
T11	Environmental tracers	Environmental tracers are a naturally occurring physical or chemical property of water, or any substance dissolved in water, that can be used to trace its flowpath. Analysis and interpretation of these properties of surface water and groundwater can be used to identify groundwater contribution to dependent ecosystems	GDE Toolbox
T12	Introduced tracers	Analysis of deliberately introduced hydrochemical tracers to identify water sources and surface water – groundwater mixing relationships	GDE Toolbox
NT4	Genetic/DNA analysis	Analysis of environmental DNA, or DNA collected from captured stygofauna, to identify species present in an aquifer	
NT5	Literature	Review existing journal articles and reports. Look up conservation status and endemism of ecosystems	
T13	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
T14	Numerical groundwater modelling	Construction of mathematical models to simulate groundwater flow systems	GDE Toolbox
NT5	Remote sensing	Use of vegetation greenness, wetness, land surface temperature to discriminate GDEs. Use of wetness index to delineate water bodies.	

Appendix C Resources required for identifying GDEs, including national data availability

App Table 3. Landscape and ecosystem data sets that are useful to help identify GDEs. National-scale dataset sources are shown

Ancillary data	Likely source	National dataset/Source
Landscape datasets		
DEM/surface elevation	Aerial photograph, satellite imagery	9-second DEM (GA)
Groundwater depth	Maps, reports, observation bore records	National groundwater information system (BOM) Groundwater Insight; BOM Groundwater Explorer
Groundwater flow systems and elevations; hydrogeology	Maps, reports, observation bore records, DEM	Groundwater flow systems
Surface water level	Maps, reports, observation bore records, river gauge data	Surface water level (BOM)
Surface water (rivers, wetlands, springs) mapping	Aerial photographs, satellite imagery, Google Earth	Geofabric (BOM); Flow direction grid (GA); Water Observations from Space (GA); Surface water (GA) Geofabric Water Observations from Space Surface Hydrology
Groundwater quality (including temperature and salt)		
River connectivity/classification map GW-SW connectivity	Geological and geomorphological mapping	River classification report
Underlying geology and geological structure (e.g. fractured rock aquifer); geophysics	Maps, reports, ground survey, geophysical survey	Geophysics (GA)
River flow data	River gauge data	Water storages (BOM) State sources of data
River regime	River gauge data	State sources of data
Consumption infrastructure (bores)		Bore locations (BOM)
Climate data		Bureau of Meteorology BOM
Soil mapping	Maps, ground surveys, geological survey, site assessment	National soil database
Hydrogeology (watertable salinity; aquifer boundaries; principal hydrogeology)	Maps, ground surveys, geological survey, site assessment	National groundwater information system (BOM) Hydrogeology
Recharge/discharge areas	Remote sensing, geological mapping information	CSIRO Recharge Tool Tool to calculate recharge/discharge
Landuse	Aerial imagery, remote sensing	ACLUMP
Ecosystem datasets		

Ancillary data	Likely source	National dataset/Source
Vegetation (classification and composition) mapping	Maps, ground surveys, aerial photographs, satellite imagery	NVIS
Known GDEs (subsurface especially), potential GDEs	Reports, ground surveys, satellite imagery	GDE Atlas
IDE layer (data on IDE likelihood)	GDE Atlas	GDE Atlas
Wetland classification mapping	National Wetland Inventory	NWI
EPBC listing (flora and fauna, Threatened Ecological Communities)	Department of Environment and Energy	EPBC
State protected/vulnerable flora and fauna	Department of Environment and Energy	Threatened Ecological Community TEC
Leaf Area Index	MODIS - NASA	MODIS
Root depth	Reports, site assessments	
Vegetation condition	Reports, maps, site assessments, satellite imagery	Derive from Landsat mosaic; MODIS

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/territory (includes GIS layers, reports and websites).

Scale	Data Available
Queensland	Queensland Spring Database Queensland GDE dataset Wetland Maps Biodiversity Status of Remnant Regional Ecosystems Matters of State Environmental Significance Water Monitoring Portal
New South Wales and Australian Capital Territory	GDE Risk Assessment Guidelines GDE Dataset GDE Policy GDE Method Namoi GDE Review Groundwater Data
Victoria	Victoria Wetland Inventory Ecological Vegetation Classes GDE Mapping Method Wimmera GDEs Species Tolerance Grid - GDEs Bore data Groundwater Data Groundwater Quality Data
South Australia	Water Connect South Australian Wetlands Artesian Springs
Western Australia	Geomorphic wetland mapping Dampier GDEs Northern Perth Basin GDEs Groundwater Data
Northern Territory	Berry Springs GDEs Daly Basin GDEs
Tasmania	Tasmania GDEs Karst GDEs Groundwater-Surface Water connectivity Freshwater Ecosystems Values Framework

Appendix E Vegetation species that are likely to be GDEs

App Table 5. Vegetation species that in Australia have been shown to access groundwater. The depth to watertable (WT) range has been summarised across studies and locations. Information sourced from A – Orellana et al., 2011; B – Sommer and Froend, 2010; C- DPI (2006); D- Wetland Info (WetlandInfo); E – Froend and Drake (2006)

Species	WT Depth (m)	Source	Species	WT Depth (m)	Source
Acacia harophylla	-	D	*Eucalyptus largiflorens*	2-5	A
Acacia stenophylla	3-4	A	*Eucalyptus longirostrata*	-	D
Angophora bakeri	-	A	*Eucalyptus marginata*	6->30	A
Angophora floribunda	-	D	*Eucalyptus melanophloia*	-	D
Angophora leiocarpa	-	D	*Eucalyptus microtheca*	-	D
Astartea fascicularis	<6.43	A	*Eucalyptus parramattensis*	-	A
Banksia aemula	-	D	*Eucalyptus platyphylla*	10	A
Banksia attenuata	2.5-30	A	*Eucalyptus robusta*	-	C
Banksia ericifolia	-	D			
Banksia ilicifolia	2.5-30	A	*Eucalyptus rudis*	<11.7	B
Banksia littoralis	<6.27	B	*Eucalyptus saligna*	-	D
Banksia menziesii		E	*Eucalyptus tereticornis*	-	D
Banksia oblongifolia	-	D	*Eucalyptus victrix*	-	C
Banksia prionotes	-	C	*Hibbertia hypericoides*	2.5-30	A
Barringtonia acutangulata	-	C	*Juncus kraussii*	-	D
Baumea articulata	<1.64	B	*Leptospermum juniperinum*	-	D
Baumea juncea	-	C	*Leptospermum liversidgei*	-	D
Callistemon viminalis	-	D	*Lepyrodia interrupta*	-	D
Callitris glaucophylla	-	D	*Livistonia lanuginosa*	-	D
Casuarina cunninghamiana	-	D	*Lophostemon suaveolens*	10	A
Casuarina glauca	1.6-3.0	A	*Leptocarpus tenax*	-	D
Castanospora alphandii	-	C	*Melaleuca argentea*	-	C
Corymbia clarksoniana	10	A	*Melaleuca glomerata*	-	C
Corymbia opaca	-	C	*Melaleuca halmaturorum*	0.3-1.2	A
Corymbia tessellaris	-	D	*Melaleuca preissiana*	<13.9	B
Doryphora aromatica	-	C	*Melaleuca quinquenervia*	-	C
Eucalyptus camaldulensis	1.3-6	A	*Melaleuca rhapiophylla*	<9.27	B
Eucalyptus coolabah	2.7-5.7	A	*Melaleuca tamariscina*	-	D
Eucalyptus globulus	-	C	*Melaleuca viridiflora*	10	A
Eucalyptus grandis	4-6	A	*Restio pallens*	-	D
Eucalyptus kochii	8.5-14	A	*Schoenus brevifolius*	-	D
Eucalyptus kochii subsp. *borealis*	4.5	A	*Sprengelia sprengelioides*	-	D
Eucalyptus intertexta	-	D	*Syncarpia glomulifera*	-	D
Eucalyptus laevopinea	-	D	*Typha orientalis*	<2.4	B

App Table 6. Maximum root depth of Australian vegetation species. SOURCE: Canadell et al., 1996

Species	Max root depth (m)	Species	Max root depth (m)
Banksia marginata	2.4	*Jacksonia furcellata*	2
Banksia ornata	2.4	*Laudonia behrii*	2
Calytrix flavescens	2	*Leptospermum myrsinoides*	2.3
Casuarina muelleriana	2	*Melaleuca scabra*	2
Casuarina pusilla	2.4	*Melaleuca seriata*	2.1
Daviesia brevifolia	2	*Petrophile linearis*	2
Eremaea beaufortioides	6	*Phyllota pleurandroides*	2.3
Eremaea pauciflora	2.4	*Phyllota remota*	2.4
*Eucalyptus grandis**	15.8	*Pinus pinaster*	7
Eucalyptus marginata	40	*Pinus radiata*	10-15
Eucalyptus regnans	2.7	*Scholtzia involucrata*	1.9
Eucalyptus signata	3	*Spyridium subochreatum*	1.9
Hibbertia hypericoides	2.1	*Stirlingia latifolia*	2.6
Jacksonia floribunda	3.1	*Xanthorrhoea australis*	2.4

* Christina et al., 2011

Appendix F Rules to guide GDE identification

App Table 7. Rules to guide the identification of GDEs using remotely sensed or existing data, developed from known studies. These rules were used to develop the GDE Atlas (SKM, 2012; Doody et al., 2017) and supplemented for aquifer ecosystems for this Explanatory Note. Rules are cross-referenced with questions posed by Eamus et al. (2006) in Table 1

Cross reference with Table 1.	Rules of GDE potential	Potential datasets required
	SUBSURFACE GDEs	
	Vegetation in landscapes with shallow watertable (<5 m or 10 m) will use groundwater when required	Watertable 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
7, 8	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
6	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
5, 6, 9	Native vegetation surrounding a known spring location or a known GDE is more likely to be a GDE	Spring/wetland map; vegetation map
	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
4, 5, 6, 9	Vegetation surrounding GDEs identified in previous studies are 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
	Certain landscapes or topography are more indicative of shallow groundwater, and are therefore more likely to support GDEs (only applied when an existing depth to watertable mapping is not available)	DEM; landscape type mapping; vegetation map; vegetation type
8	Constant vegetation activity throughout the year indicates utilisation of a water source other than rainfall (possibly groundwater)	Remote sensing greenness/wetness, PAR
	Groundwater discharge related to the presence of faults	Geologic mapping; groundwater depth
	High probability IDEs (8-10) are potential GDEs; IDE ≤ 5 not GDEs; ≥ 5 around wetland are potential GDEs	IDE map (GDE Atlas); vegetation type; vegetation map
	Vegetation occurring in estuaries and in coastal floodplains at less than 5m 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 if water quality is good	Strahler Stream Order layer; geological mapping
	Karstic or limestone aquifers are likely to have stygofauna if water quality is sufficient, as are alluvial aquifers downstream	Geological mapping, hydrogeology data
	Alluvial aquifers are likely to have high stygofauna diversity close to recharge areas, if water quality is good, where watertable is < 10 m, and beneath phreatophytic vegetation	Vegetation mapping, groundwater level data,

Cross reference with Table 1.	Rules of GDE potential	Potential datasets required
	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 with 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
	SURFACE GDEs	
4	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
	Specific wetland types are indicative of groundwater discharge (i.e. deep marsh) (Dahlhaus, 2010)	Wetland classification
	In Victoria, the dominant source of water of wetlands has previously been established	Victoria 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, Photosynthetically Active Radiation; wetland map; groundwater depth
1, 4	Areas with persistent surface water are likely to receive inputs from groundwater with the exception of waterbodies in parts of the Lake Eyre Basin	Permanent water map (remote sensing); wetland/river map
6	Vegetation identified as 'GDEs that rely on the surface presence of groundwater' indicate the presence of shallow watertables and potential diffuse groundwater discharge into adjacent wetlands	GDE Atlas; vegetation map
	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 watertable
	Wetlands that contain peaty soils are likely to have been formed through groundwater discharge	Soil type map; wetland map
	Underlying aquifer indicating 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	Geology mapping; aquifer map; wetland/river map
	Rivers and streams within regions of shallow watertables are more likely to be connected than in regions of deeper watertables	Wetland/river map; depth to groundwater
	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 exist or Holocene muds, waterbodies 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 GAB aquifers are likely to receive groundwater inputs	Aquifer type; wetland/river map
6	Certain swamp vegetation communities indicate likely groundwater inflows or known GDE vegetation	Wetland/river map; vegetation map; depth to groundwater
1, 4	Permanent water regime is indicative of groundwater discharge which maintains flow/water	Surface water regime; rainfall/climate; soil type map

Cross reference with Table 1.	Rules of GDE potential	Potential datasets required
	during the dry season, except when Holocene muds and cracking clays are present	
	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 waterbodies may receive groundwater contributions if they are in certain lithological and geomorphological units	Geologic map; wetland/river map; lithological information
	Large fluctuations in watertable can result in groundwater discharge to non-permanent water bodies late in the wet season. Large fluctuations in watertable 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 where >25 mm rainfall)	Groundwater regime; rainfall
	Low lying and break of slope (less than 5°) landscapes are likely to have shallow watertables	Aspect map; DEM; depth to groundwater
	Slope on specific geology types is an indication of shallow watertables	Aspect map; geology map; depth to groundwater
6	Vegetation is indicator of groundwater discharge (known GDE)	Known vegetation GDEs; depth to groundwater
	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 and Napier region, Struan region)	DEM; wetland/river map
1, 3, 4	Streams an indicator of groundwater discharge	Wetland/river map
	Geological contacts within steeply incised basalt valleys within the Northwest incised basalt plateau regions are an indicator of spring occurrences	Soil map; geologic map; wetland/river map

Appendix G Assessing Aquifer Ecosystems

Almost all shallow aquifers contain life in the form of microbes, and can be reasonably presented as ecosystems. While microbes are a key component in many of the ecosystems services provided by aquifer ecosystems, it is not yet practical to take a census of aquifer microbial community for the purpose of impact assessment. Currently, a more pragmatic approach in assessing the biological community is to determine whether the aquifer supports a stygofauna community, with this as the key indicator that an 'aquifer ecosystem' is present. 'Stygofauna' is a collective term that incorporates a broad suite of animal species, all adapted to living in groundwater, and includes crustaceans, beetles, snails, mites, worms, as well as 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 (DSITI, 2014). Once stygofauna are found, an equally important objective is to confirm the same species live outside the area of impact, so that there is 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 8). 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 pumps, and be screened at the section of aquifer where stygofauna occur. Optimal bore characteristics are summarised in App Table 9.

App Table 8. 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 watertable, or within 10 m of watertable.	Casing is open at bottom of bore.
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 prior to sampling	Bore has not been purged for at least one month prior to 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 enhance 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 8.

App Table 9. 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., 2016, Hyde et al., 2018
Watertable depth	Greater diversity and higher abundances are likely when watertable is shallower than 20-30 m. Stygofauna are also more likely in aquifer recharge areas	Areas with shallow watertables (<20 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., 2004, 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., 2004, Hyde et al., 2018.
Salinity	Stygofauna are most likely in water with electrical conductivity (EC) less than 5000 µS/cm.	Specimens have been collected from waters with EC up to 56 000 µS/cm, but diversity and abundance is higher at low EC.	Hancock and Boulton, 2008, Watts and Humphreys, 2009, Schultz et al., 2013, Glanville et al., 2016

Appendix H Risk Assessment

App Table 10. GDE Risk Matrix (Serov et al., 2012)

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**
	Category 1: Low Risk	**Category 2:** Moderate Risk	**Category 3:** High Risk

App Table 11. Risk Matrix management actions (Serov et al., 2012)

Risk Matrix Box	Descriptor	Management action		
		Short term	Mid-term	Long term
A	High value/Low risk	Protection measures for aquifer 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 aquifer and GDEs	Protection measures for aquifer 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 aquifer and GDEs	Protection measures for aquifer and GDEs	Adaptive management. Continue monitoring.
		Baseline risk monitoring; Mitigation	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	
E	Moderate Value/Moderate Risk	Protection of hotspots	Protection of hotspots	Adaptive management. Continue monitoring.
		Baseline risk monitoring		

Risk Matrix Box	Descriptor	Management action		
		Short term	Mid-term	Long term
			Monitoring and periodic assessment of mitigation	
		Mitigation action		
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	Protect hotspots (if any)	Protect hotspots (if any)	Adaptive management; Continue monitoring
		Baseline risk monitoring	Baseline risk monitoring	
H	Low Value/Moderate Risk	Protect hotspots (if any)	Protect hotspots (if any)	Adaptive management; Continue monitoring
		Baseline risk monitoring; Mitigation action	Monitoring and periodic assessment of mitigation	
I	Low Value/High Risk	Protect hotspots (if any)	Protect hotspots (if any)	Adaptive management; Continue monitoring
		Baseline risk monitoring; Mitigation action.	Monitoring and annual assessment of mitigation	