Department of Natural Resources, Mines and Energy
Office of Groundwater Impact Assessment

Technical summary: terrestrial groundwater-dependent ecosystems in the Surat Cumulative Management Area

Literature review and desktop impact assessment method

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Queensland Government

This publication has been compiled by the Office of Groundwater Impact Assessment, Department of Natural Resources, Mines and Energy. The Queensland Herbarium developed the method in Appendix B.

Summary

Queensland has established a comprehensive regulatory framework to oversee the development of mining and coal seam gas (CSG) extraction projects. Proponents are required to obtain environmental authorities from the government department that regulates environmental management. Major projects can be required to complete environmental impact statement (EIS) processes under the *Environmental Protection Act 1994* (EP Act), preceding and in addition to the environmental authority stage.

For CSG project proponents in the Surat and southern Bowen basins, springs fed by Great Artesian Basin aquifers were initially a key consideration in preparing EISs. This reflects:

- the listing of 'The community of species dependent on discharge of groundwater from the Great Artesian Basin' as a Matter of National Environmental Significance (MNES) under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act)
- the requirement provided in Chapter 3 of the *Water Act 2000* (Water Act) for the Office of Groundwater Impact Assessment (OGIA) to include a Spring Impact Management Strategy (SIMS) in the Surat Underground Water Impact Report (UWIR), including all springs in the Surat Cumulative Management Area (CMA).

The EPBC Act was amended in June 2013 to provide that water resources are MNES, defined as groundwater and surface water, and including organisms and ecosystems that contribute to the physical state and environmental value of the water resource – all groundwater-dependent ecosystems (GDEs).

In December 2016, amendments were made to the Water Act and the *Mineral Resources Act 1989*, expanding the scope of OGIA's assessment beyond springs to include a description of the impacts on environmental values due to the exercise of underground water rights (s376). UWIRs must now describe the impacts of groundwater drawdown on terrestrial GDEs as well as impacts on other environmental values including springs.

In parallel with the developing legislative and policy framework, there has been an improved understanding of GDEs informed by the experience of proponents and regulators engaging in EIS processes, the availability of the national GDE Atlas and state GDE mapping, and increased acceptance of a systematic approach to GDE identification and management.

In many cases, CSG companies have initiated desktop and field investigations to identify vegetation that uses groundwater (terrestrial GDEs), but there is no standard guidance or method in this area.

This report –*Terrestrial groundwater-dependent ecosystems in the Surat CMA* – presents a method to identify groundwater impacts on terrestrial GDEs and outlines field investigations to confirm groundwater dependency and refine the subsequent condition-monitoring program, using the Surat CMA as a case study. A literature review (Appendix A) discusses the nature of groundwater use by terrestrial GDEs.

Results from continued monitoring at field sites will inform regular review and update of the conceptual models, hypotheses and techniques.

The method to assess the impacts of groundwater drawdown on terrestrial GDEs has two stages.

Stage 1 Desktop

- Select the study area and use the Queensland GDE mapping to identify terrestrial GDE polygons (and their component regional ecosystems) for which the source aquifers are potentially affected formations.
- Prioritise selected regional ecosystems for field investigation. Apply risk assessment integrating time to predicted impact, predicted rate of change in groundwater level (likelihood) and biodiversity status (consequence). Select locations for field sites based on confidence in the GDE mapping.
- Using an ecohydrological conceptual model for the site and technical information from the scientific literature and the Queensland Herbarium, hypothesise the potential impacts of groundwater drawdown on the high-risk regional ecosystems.

Stage 2 Field investigation and monitoring

- Design a field program to confirm groundwater dependency.
- Once confirmed, design a condition-monitoring program at selected impact sites and control sites for each regional ecosystem, including measures to test the hypotheses of groundwater use by the ecosystems. Use results to test and revise conceptual models and hypotheses.

The desktop component uses publicly available datasets and technical information. It assumes that the Queensland GDE mapping is the point of truth used to identify putative GDEs for assessment, so does not in the first instance seek to identify new areas of terrestrial GDEs.

However, application of the method will provide results that will contribute to testing, validation and updating of the mapping. The method is applicable to other areas of Queensland where equivalent input datasets (groundwater model outputs, GDE and regional ecosystem mapping and supporting technical information) are available. The desktop component is repeatable when updated versions of the GDE mapping become available.

The underpinning hypothesis is that groundwater drawdown leads to changes in three categories of ecological response in terrestrial GDEs: productivity, biodiversity and recruitment. In the short term (within three years), reduced productivity is expressed as reduced leaf biomass (measured by litterfall and percentage of crown cover) and in the medium term as an absence of saplings (measured by fewer occurrences of smaller size classes). In the longer term, biodiversity is lost and the community structure and composition alter. The hypothesised ecohydrological relationships and responses are illustrated by a conceptual model.

Indicators of condition for each category of response are provided for each priority regional ecosystem within the Surat CMA case study area. Finer-scale and ecosystem-scale attributes are included because of the role of groundwater in sustaining the whole ecosystem. The specific value for each indicator is based on BioCondition Benchmarks derived by the Queensland Herbarium and from the reference values for the specific field site.

In Stage 2, analysis of data from detailed field investigations in selected priority areas is used to test, validate and revise the proposed ecohydrological relationships, hypotheses and conceptual models. Where possible, the GDE mapping and expert advice from the Queensland Herbarium should inform the selection of control sites in each regional ecosystem where the stressors, antecedent rainfall and fire history are comparable to those of the impact sites, but where impacts from groundwater drawdown are not predicted.

Concurrent measurement of water sources accessed by the likely groundwater-using species is necessary to confirm the hypothesis that the vegetation community is using groundwater and to validate the ecohydrological relationships illustrated by the conceptual model. The expected outcome of the project is a robust iterative method to assess the impacts of groundwater drawdown on terrestrial GDEs. Analysis of results from medium-term and long-term monitoring efforts will contribute to the understanding of vegetation responses to groundwater drawdown and will inform mitigation, recovery and restoration programs.

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Abbreviations and glossary

AET....................... Actual evapotranspiration
ANPP.................... Above-ground net primary production
CMA...................... Cumulative Management Area
CSG...................... Coal seam gas
DBH...................... Diameter at breast height
DTW .... Depth-to-water
EIS........................ Environmental Impact Statement
EP Act................... *Environmental Protection Act 1994 (Qld)*
EPBC Act .... *Environment Protection and Biodiversity Conservation Act 1999 (Cwlth)*
GAB...................... Great Artesian Basin
GDE...................... Groundwater-dependent ecosystem
IAA........................ Immediately Affected Area – the area of an aquifer within which water levels are predicted to fall, due to water extraction by petroleum tenure holders, by more than the trigger threshold within three years
LAA....................... Long-term Affected Area – the area of an aquifer within which water levels are predicted to fall, due to water extraction by petroleum tenure holders, by more than the trigger threshold at any time in the future
LAI .... Leaf area index – the amount of leaf area (in square metres) directly above a square metre of ground
Land zone............. Categories that describe the major geologies and associated landforms and geomorphic processes in Queensland (Wilson & Taylor 2012).
MNES .... Matter of National Environmental Significance
NDVI..................... Normalised Difference Vegetation Index
NDWI.................... Normalised Difference Wetness Index
NWQMS .... National Water Quality Management Strategy
OGIA..................... Office of Groundwater Impact Assessment
Phreatophyte .... A plant growing with its roots in the water table or the capillary fringe above it at any time in its life cycle
RE......................... Regional ecosystem – in Queensland, vegetation communities in one of 13 bioregions that are consistently associated with a particular combination of geology, landform and soil
REDD .... Regional Ecosystem Description Database
UWIR.................... Underground Water Impact Report
WA........................ *Water Act 2000 (Qld)*

1 Introduction

Queensland has established a comprehensive regulatory framework to oversee the development of mining and coal seam gas (CSG) extraction projects. Proponents of such projects are required to obtain environmental authorities from the government department that regulates environmental management. Major projects can be required to complete environmental impact statement (EIS) processes under the *Environmental Protection Act 1994* (EP Act), preceding and in addition to the environmental authority stage.

The terms of reference for EISs require an assessment of the impacts of the proposed projects on biodiversity and environmental values, including those identified as a Matter of National Environmental Significance (MNES) listed under the Commonwealth *Environmental Protection and Biodiversity Conservation Act 1999* (EPBC Act).

For proponents of CSG extraction projects in the Surat and southern Bowen basins, springs fed by Great Artesian Basin (GAB) aquifers were initially a key consideration in EISs. This is because 'The community of species dependent on discharge of groundwater from the Great Artesian Basin' is an MNES, and Chapter 3 of the *Water Act 2000* (Water Act) requires the development of a spring impact management strategy (SIMS). The Office of Groundwater Impact Assessment (OGIA) includes a SIMS in its Underground Water Impact Report (UWIR) required under Chapter 3 of the Water Act.

The EPBC Act was amended in June 2013 to provide that a water resource is a MNES, in relation to coal seam gas and large coal mining development. A water resource is defined as groundwater and surface water, and includes organisms and ecosystems that contribute to the physical state and environmental value of the water resource. This definition captures all groundwater-dependent ecosystems.

Following amendments to the Water Act and the *Mineral Resources Act 1989* which came into effect in December 2016, the scope of a UWIR has also expanded to include a description of the impacts on environmental values due to the exercise of underground water rights (s376).

Section 9 of the EP Act defines an environmental value as 'a quality or physical characteristic of the environment that is conducive to ecological health or public amenity or safety'. The object of the EP Act is to protect Queensland's environment while allowing for ecologically sustainable development. The object is achieved through a management program, which includes defining environmental objectives and environmental values to be protected.

Schedule 5 of the Environment Protection Regulation 2008 sets out the environmental objective for groundwater: 'the activity will be operated in a way that protects the environmental values of groundwater and any associated surface ecological systems'. The performance outcome for this environmental objective sets out that 'the activity will be managed to prevent or minimise adverse effects on groundwater or any associated surface ecological systems'. The term 'environmental value' derives from the National Water Quality Management Strategy (NWQMS), which applies the term to particular values or uses of the environment. In Queensland, the principles of the NWQMS are embodied in the Environmental Protection (Water) Policy 2009, which protects the quality of natural waters, including groundwater. This legislative and policy framework allows for recognition of the health of a groundwater-dependent ecosystem (GDE) as an environmental value of the groundwater in a GDE's source aquifer. Development projects that result in groundwater drawdown must consider impacts on terrestrial GDEs as well as those on surface-expression GDEs, i.e. springs and watercourse springs (gaining streams).

It is understandable that discussion of GDEs in EISs for the initial CSG project proposals was restricted to GAB springs. Over time, parallel with the developing legislative and policy frameworks, there has been an improved understanding of GDEs informed by the experience of proponents and regulators engaging in EIS processes, the availability of the national GDE Atlas and state GDE mapping, and increased acceptance of a systematic approach to GDE identification and management. Recent EIS documentation reflects a trend towards a standard GDE definition and typology and demonstrates efforts to identify and assess GDEs; however, there is considerable variation in approaches to GDE conceptualisation, field investigation and data analysis, and little guidance on best-practice approaches.

There is a strong desire from industry for a consistent approach to identifying GDEs, assessing the nature of groundwater use, and monitoring their resilience and responses to groundwater drawdown, and for guidance on selection of candidate monitoring variables and methods for integrating modelling outputs and available GDE datasets. The method described in this report addresses this need. It is a scientifically robust method for the identification of groundwater impacts on terrestrial GDEs. It was used to inform the 2019 UWIR for the Surat Cumulative Management Area (CMA). More broadly, there is an increasing awareness of the need to consider impacts on GDEs in the environmental impact assessment of all development projects that involve groundwater extraction.

1.1 What are terrestrial groundwater-dependent ecosystems?

Terrestrial GDEs are vegetation communities that use groundwater. They comprise one of the three broad categories of GDEs recognised in Australia. ‘GDE’ is not an intrinsic ecosystem type but rather a sub-set of many ecosystem types, being specifically those 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. 2011a).

The three categories of GDE are: aquifer and cave systems; ecosystems dependent on the surface expression of groundwater (surface-expression GDEs); and ecosystems dependent on the subsurface presence of groundwater (terrestrial GDEs) (Eamus et al. 2006b). The last two categories may overlap in riparian zones where vegetation may access groundwater in the subsurface but also via its surface expression during overbank flooding of streamflow sourced from baseflow.

For vegetation to access groundwater in the subsurface, the roots must be able to reach the capillary zone above the water table at some time during the plant’s life cycle. A widely adopted rule of thumb is that vegetation use of groundwater is **likely** where depth-to-water (DTW) is 0–10 metres below ground level (mbgl), **possible** at depths of 10–20 mbgl, and **unlikely** at depths of >20 mbgl (Eamus et al. 2006b). However, vegetation use of groundwater from greater depths should not be ruled out. Vegetation communities that are solely reliant on shallow soil moisture are not terrestrial GDEs. Those that access perched groundwater are terrestrial GDEs, but may not be priority terrestrial GDEs for the purpose of this method if the perched groundwater is not connected to groundwater in the target formation(s).

Appendix A provides detail on terrestrial GDEs including a discussion of the terms ‘obligate’ and ‘facultative’ phreatophytes, background information on GDE mapping in Australia and information on methods to assess vegetation condition and groundwater use, and impacts of groundwater drawdown.

The literature review shows that it is not useful to categorise species as obligate or facultative groundwater users; groundwater use by a species varies with local environmental conditions, and even episodic use may be vital to the persistence of the population. Plants cannot necessarily switch to using other water sources if groundwater availability is reduced, nor can they always respond by rapid root growth to follow falling water levels. Loss of access to groundwater via deep roots reduces the resilience of vegetation. A body of literature demonstrates the importance of hydraulic redistribution to and from shallow and deeper roots in response to rainfall variability and changes in soil moisture, thus indicating the role of groundwater in sustaining ecosystems and confirming that an ecosystem-level focus – rather than a species-level focus – is appropriate for conceptualising, predicting and monitoring the impacts of groundwater drawdown.

1.2 Aim of Stage 1 of the method

Stage 1, the desktop component of the method, aims to identify:

- priority terrestrial GDEs that may be affected by groundwater drawdown in the target formation.
- hypothesised impacts of groundwater drawdown on terrestrial GDEs
- assessment and monitoring tools to inform field investigations in Stage 2 to test and refine the conceptualisations and hypotheses.

The method is suitable for use during an EIS to identify terrestrial GDEs using aquifers that may be affected by proposed resource development, and to inform the development of ecohydrological conceptual models, the prediction of likely impacts and the design of monitoring programs. It is compatible with *EIS information guideline – Groundwater dependent ecosystems* (Department of Environment and Heritage Protection, 2016) and is applicable in areas where Queensland GDE mapping is available.

1.3 Identifying risk and recognising uncertainty

The method described here seeks to identify priority terrestrial GDEs: those at highest risk of groundwater drawdown in the target formation(s). Risk is assessed as a function of the likelihood and consequences of groundwater drawdown in the target formation for a terrestrial GDE. Useful criteria for the assessment of likelihood of impact from groundwater drawdown are the timing and magnitude of drawdown in target formations, as predicted by the regional groundwater flow model.

Evaluating the consequences of the predicted drawdown on terrestrial GDEs is more complex. Consideration of a regional ecosystem's (RE) biodiversity status is the first step in inferring the significance of a predicted impact on that RE. The biodiversity status reflects the condition of an RE and the extent remaining compared with its pre-clearing extent. For more detailed evaluation of consequences, specific information is needed about the ecological response of the RE to varying degrees of groundwater drawdown.

There are multiple uncertainties associated with detection of ecological responses, and particularly so with studies of impacts on GDEs. The sensitivity of terrestrial GDEs to changes in groundwater regime is determined by the nature of the ecohydrological relationship between groundwater and vegetation. Large error terms are associated with the quantification of this relationship (Eamus et al. 2006a). These include uncertainties regarding the identification of source aquifers for GDEs and uncertainties resulting from the scale and the level of confidence of GDE mapping. Results from monitoring of the identified priority REs will inform development of criteria for evaluation of the consequences of groundwater drawdown, for inclusion in future iterations of the method.

The method described here draws available data, scientific literature and expert advice into a framework for identifying terrestrial GDEs at highest risk and conceptualising and hypothesising their responses to groundwater drawdown. Field investigations (Stage 2) are necessary to test the hypotheses, address uncertainties regarding source aquifers and the nature of groundwater use, and revise the conceptualised ecological responses. The final output will be a two-part method (desktop and field work) to assess the impacts of groundwater drawdown on terrestrial GDEs.

2 Existing assessments and investigations of terrestrial GDEs

This section provides a high level summary of the assessments and investigations of terrestrial GDEs in the Surat CMA carried out by CSG companies as part of environmental approval processes.

The conditions of EPBC Act approval of Santos's GLNG Gas Field Development Project require the development of a groundwater-monitoring network for the early detection of impacts on non-spring based GDEs. To meet this requirement, Santos is implementing the water monitoring strategy specified in the UWIR. To address the requirement that monitoring should enable early detection of impacts to non-spring based GDEs, Santos assessed potential likelihood of impact to terrestrial GDEs through analysis of predicted depressurisation, application of GDE mapping and a literature review of rooting depths. On the basis that the potential likelihood of impact was low, no further site-specific monitoring was considered necessary. It was noted that re-assessment would be required with a new UWIR.

The conditions of EPBC Act approval of Arrow's Surat Gas Project require an assessment of potential impacts on non-spring based GDEs and the development of early warning indicators and trigger thresholds, including for Lake Broadwater and Long Swamp and other GDEs that may be potentially impacted. Arrow's approach has been to: conceptualise potential impacts on terrestrial GDEs using modelled drawdown in potential source aquifers; select field sites through analysis of remote sensing data; and carry out field verification of vegetation and soil types, groundwater levels and landscape setting. Areas of potential risk will be the subject of more detailed field investigation and monitoring. At Lake Broadwater and Long Swamp, Arrow has conducted coring to identify rooting depths, installed nested groundwater monitoring bores, and carried out stable isotope and leaf water potential analyses to verify groundwater use.

The conditions of EPBC Act approval of QGC's Surat North Project require an assessment of potential impacts on non-spring based GDEs, including in areas adjacent to the Dawson River. QGC's program of work includes: construction of shallow instrumented groundwater-monitoring bores adjacent to the Dawson River; instrumentation of existing bores; soil sampling and vegetation surveys.

The conditions of EPBC Act approval of the APLNG/Origin Project do not refer to terrestrial GDEs. Desktop analysis concluded that groundwater dependency of ecosystems is likely to be low and species associated with drainage lines are considered to be at very low risk of impacts.

Senex has carried out baseline studies and site surveys to identify the environmental values of the proposed project area for its Western Surat and Atlas Gas projects. GDEs were identified using the Queensland GDE mapping and verified through hydrogeological field survey. Impacts were assessed using the modelled drawdown for the underlying formation and consideration of vegetation rooting depths. Low potential impacts on terrestrial GDEs were predicted based on assumed rooting depths.

3 Data sources and method

3.1 Data sources

As a case study, the method was implemented with the datasets available in the Surat CMA, integrating outputs from OGIA's 2016 regional groundwater flow model for the Surat CMA, the Queensland GDE mapping and other available datasets, scientific literature and expert opinion. The method aimed to identify terrestrial GDEs potentially impacted by the predicted drawdown, describe ecohydrological relationships between groundwater and terrestrial GDEs, and the likely ecological responses to drawdown.

The GDE mapping data are sourced from the Queensland Spatial Catalogue (QSpatial, http://qldspatial.information.qld.gov.au/catalogue/), an online portal that provides public access to spatial data including GDE mapping, Queensland wetland mapping and regional ecosystem mapping. The Queensland GDE mapping indicates the likely locations of GDEs at a catchment scale. In Queensland, regional ecosystems (REs) are vegetation communities in 13 bioregions that are consistently associated with a particular combination of geology, landform and soil. Detailed descriptions of REs are available in the Regional Ecosystem Description Database (REDD).

3.2 Workflow (Stages 1 and 2)

1. Using the Queensland GDE mapping products and outputs from a groundwater model for the area of interest, apply the method detailed in Appendix B to obtain a shapefile of terrestrial GDE REs that are potentially sourced from target formations in the area of interest (Sections 4.1 and 4.2). If required, interrogate this dataset to identify priority REs based on time to impact and biodiversity status. (Section 4.3).

2. Locate three pairs (control and impact) of potential monitoring sites for the priority REs using the RE mapping. Proposed sites should be selected from homogeneous-RE polygons of the priority REs where available or from heterogeneous-RE polygons in which the priority RE occupies at least 80% of the polygon. (Section 4.3).

3. If groundwater level data are available, characterise the groundwater regime of the potential monitoring sites. Obtain hydrogeological advice on the likelihood that groundwater from target formations is available to vegetation at the potential monitoring sites, either directly or via overlying formations. If unlikely, then select new sites or revise the priority RE list if no new sites are available.

4. Informed by the technical descriptions for relevant REs (e.g. in Pollock et al. (2015)), conduct site inspections at the potential monitoring sites to ground-truth the RE mapping, record the landform and soil type, and confirm that the vegetation at the sites is correctly mapped.

5. On the basis of groundwater regime and botanical characteristics, articulate assumptions and specific hypotheses describing ecohydrological relationships between groundwater and vegetation at each site. Develop conceptual models to illustrate these relationships and the three categories of hypothesised response to predicted groundwater drawdown at each site.

6. Select the appropriate response variables for monitoring for the three categories of hypothesised response for each pair of control and impact sites for each RE. Record the baseline values and compare with the BioCondition Benchmark where available. Ground-truthing the baseline values of the response variables is necessary to account for site-specific

variations resulting from antecedent conditions, the age and condition of the trees at the particular site and the influence of stressors such as grazing.

7. Repeat site measurements to identify any structural, functional and compositional changes. Monitoring should be at least twice per year (e.g. wet season and dry season) and should occur in the same months each year for at least three years
8. Concurrent with condition monitoring, confirm use of groundwater by the vegetation in control and impact sites using multiple lines of evidence. For details, see the references in Section A.6 of this document.
9. Analyse the data annually, corroborating results from multiple lines of evidence.
10. Review hypotheses and ecohydrological conceptual models and report three-yearly. Revise monitoring design on the basis of review.

4 Case study: Surat CMA

This chapter describes the application in the Surat CMA of the method for steps A to D in Section 4.7. Step E consists of field testing of the method. The complete method will comprise steps A to F.

4.1 Select study area

Using the 2016 OGIA regional groundwater flow model outputs for the Surat CMA, areas of interest were identified in outcrop areas of water-bearing formations of the Great Artesian Basin (GAB). These 'target formations' included the Clematis Sandstone, Precipice Sandstone, Boxvale Sandstone of the Evergreen Formation, Hutton Sandstone, Walloon Coal Measures, Springbok Sandstone and the Gubberamunda Sandstone.

Areas of interest were delimited by the predicted 0.2-m drawdown contour for each of the four target formations in which drawdown is predicted by the 2016 OGIA regional groundwater flow model (Walloon Coal Measures, Springbok Sandstone, Hutton Sandstone and Gubberamunda Sandstone) and a line 1500 m outside the surface contact of the target formation outcrop with the outcrop of the adjacent formation (Figure 1).

The 0.2-m drawdown contour was selected because it is the current threshold applied to identify potentially affected springs, which triggers research investigations as part of the UWIR Spring Impact Management Strategy. For this study, this area represents the area of interest to inform further investigations. This area does not necessarily represent affected terrestrial GDEs, but provides an area to inform subsequent risk assessment and to focus further investigations.

The 1500-m buffer reflects the 1500 × 1500 m cells of the 2016 Surat regional groundwater flow model. As a general principle, the buffer reflects the coarsest resolution of cell size of groundwater flow modelling used to produce the 0.2 drawdown contour in the target formations. The areas of interest for each target formation were then joined to identify the study areas (Figure 2). Areas of interest in which a drawdown of 0.2 m or greater is predicted within three years define the Immediately Affected Area (IAA) for the purpose of this method. The remainder of the areas of interest is the Long-term Affected Area (LAA) for the purpose of this method (Figure 3).

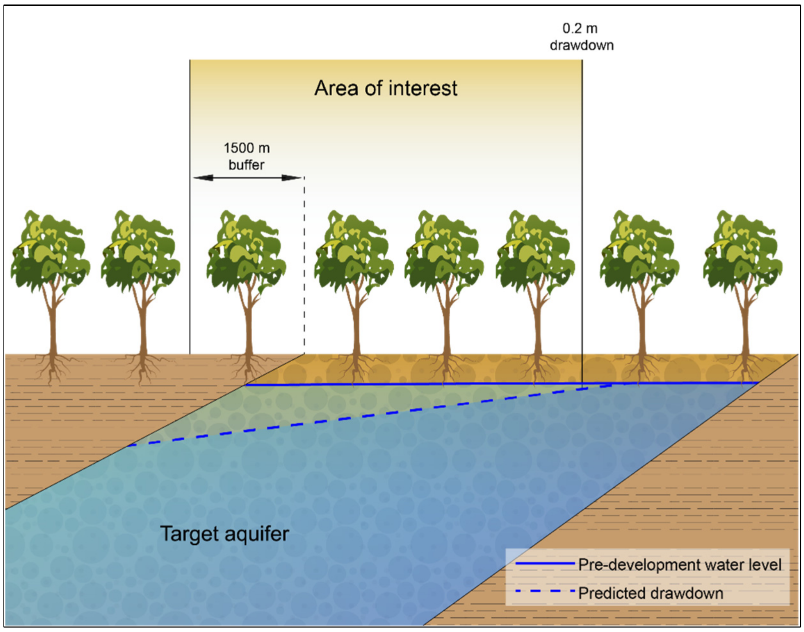

Figure 1 Schematic of the definition of areas of interest

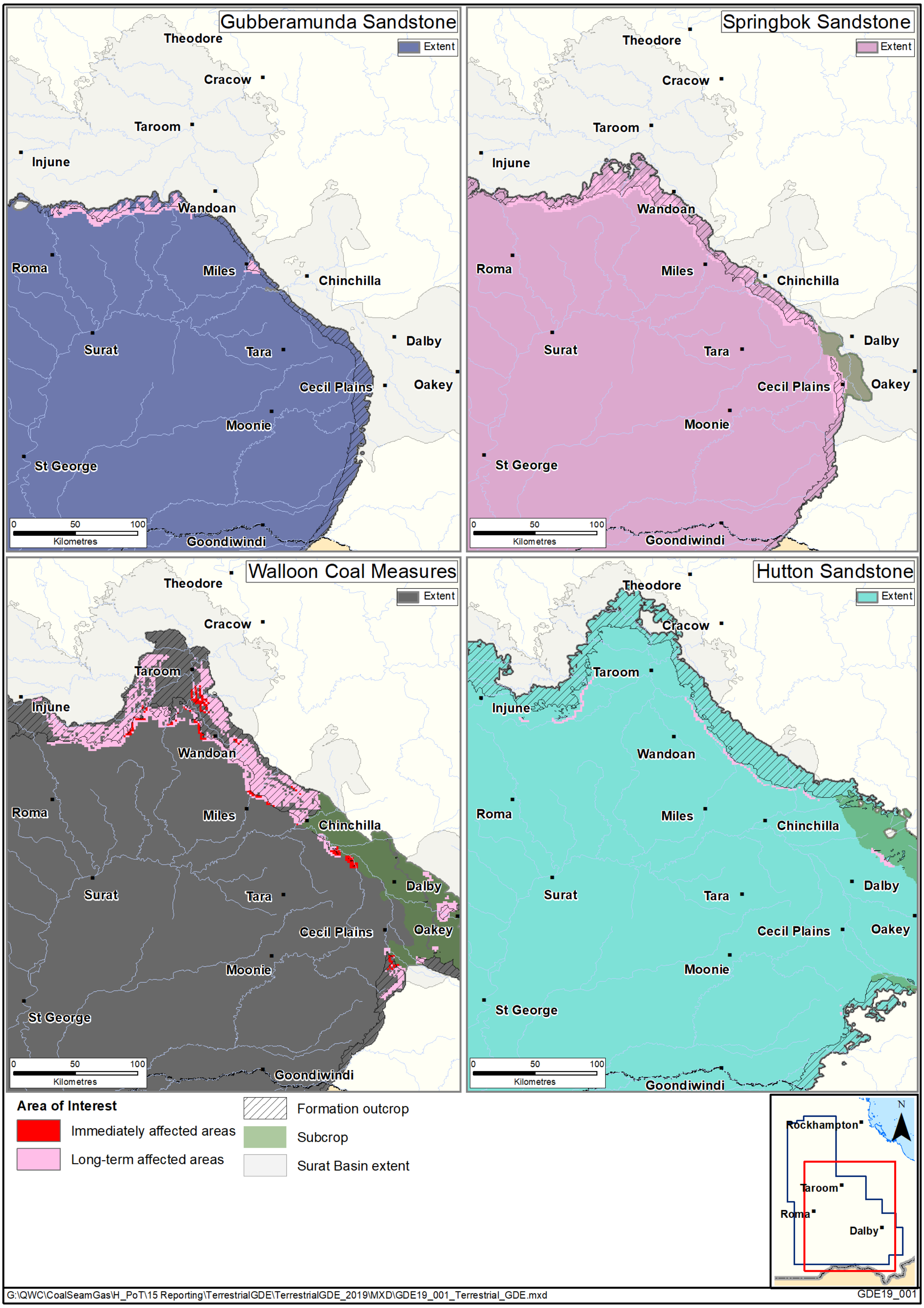

Figure 2 Location of study areas

4.2 Identify terrestrial GDEs potentially using groundwater from the target formations

The Queensland GDE mapping was used to identify terrestrial GDE polygons, and their component REs, in the study area that potentially use groundwater sourced from the water-bearing GAB formations, either directly or via overlying formations. Appendix B provides details of a generic method to analyse the Queensland GDE mapping data to identify REs that potentially use groundwater sourced from formations of interest.

There are 22 REs in the area of interest identified in the GDE mapping as terrestrial GDEs potentially using groundwater sourced from GAB aquifers either directly or through overlying alluvial aquifers (Table 1 and Table 2). The 22 identified REs occur in three land zones (Wilson & Taylor 2012): land zone 3, recent Quaternary alluvial systems; land zone 9, fine-grained sedimentary rocks; and land zone 10, coarse-grained sedimentary rocks. Land zone 3 is included due to possible hydraulic connection between a GAB aquifer and overlying alluvium. Land zones 9 and 10 are logical candidates because outcropping areas of water-bearing formations of the GAB are classified to either of these land zones.

Table 1 Terrestrial GDEs potentially using groundwater from the GAB in the Immediately Affected Areas (IAA)

RE	Description[1]	BD Status[2]	Homogenous RE		Heterogenous RE	
			Area (ha)	Confidence[3]	Area (ha)	Confidence[3]
11.3.14	*Eucalyptus spp., Angophora spp., Callitris spp. woodland on alluvial plains*	NC	81	L	24	L
11.3.18	*Eucalyptus populnea, Callitris glaucophylla, Allocasuarina luehmannii shrubby woodland on alluvium*	NC	-	-	96	L , M
11.3.19	*Callitris glaucophylla, Corymbia spp. and/or Eucalyptus melanophloia open forest to woodland on Cainozoic alluvial plains*	NC	-	-	404	L , M
11.3.2	*Eucalyptus populnea woodland on alluvial plains*	OC	200	M , L	1,034	L , M , H
11.3.25	*Eucalyptus tereticornis or E. camaldulensis woodland fringing drainage lines*	OC	1,019	M , L	1,094	L , M , H
11.3.26	*Eucalyptus moluccana or E. microcarpa woodland to open forest on margins of alluvial plains*	NC	-	-	18	L
11.3.3	*Eucalyptus coolabah woodland on alluvial plains*	OC	-	-	97	M , H
11.3.4	*Eucalyptus tereticornis and/or Eucalyptus spp. woodland on alluvial plains*	OC	78	H	180	M , H
11.9.10	*Eucalyptus populnea open forest with a secondary tree layer of Acacia harpophylla and sometimes Casuarina cristata on fine-grained sedimentary rocks*	E	-	-	26	L
11.9.5	*Acacia harpophylla and/or Casuarina cristata open forest on fine-grained sedimentary rocks*	E	12	L	26	L
11.9.7	*Eucalyptus populnea, Eremophila mitchellii shrubby woodland on fine-grained sedimentary rocks*	OC	-	-	6	L
11.10.9	*Callitris glaucophylla woodland on coarse-grained sedimentary rocks*	NC	0	L	-	-

Notes:

1. Biodiversity Status (BD Status) = Endangered (E), Of concern (OC) or No concern at present (NC).
2. Confidence = Low (L), Moderate (M), High (H) in the GDE status of the polygon in the Qld GDE mapping.

Table 2 Terrestrial GDEs potentially using groundwater from the GAB in the long term affected areas (LAA)

RE	Description	BD Status[1]	Homogenous RE		Heterogenous RE	
			Area (ha)	Confidence[2]	Area (ha)	Confidence[3]
11.3.1	*Acacia harpophylla and/or Casuarina cristata open forest on alluvial plains*	E	-	-	83	L , H
11.3.14	*Eucalyptus spp., Angophora spp., Callitris spp. woodland on alluvial plains*	NC	687	L	2,790	L , H
11.3.17	*Eucalyptus populnea woodland with Acacia harpophylla and/or Casuarina cristata on alluvial plains*	E	139	H , M , L	9	L
11.3.18	*Eucalyptus populnea, Callitris glaucophylla, Allocasuarina luehmannii shrubby woodland on alluvium*	NC	7	L	840	L , M , H
11.3.19	*Callitris glaucophylla, Corymbia spp. and/or Eucalyptus melanophloia open forest to woodland on Cainozoic alluvial plains*	NC	-	-	302	L , M
11.3.2	*Eucalyptus populnea woodland on alluvial plains*	OC	665	M , L	4,572	L , M , H
11.3.25	*Eucalyptus tereticornis or E. camaldulensis woodland fringing drainage lines*	OC	4,357	H , M , L	7,563	L , M , H
11.3.26	*Eucalyptus moluccana or E. microcarpa woodland to open forest on margins of alluvial plains*	NC	-	-	612	L
11.3.27a	*Vegetation ranges from open water +/- aquatics and emergents …. A narrow fringing woodland commonly dominated by E. camaldulensis or E. coolabah but also a range of other tree species may be present*	OC		H, M	-	-
11.3.27b	*Vegetation ranges from open water +/- aquatics and emergents ... Often with fringing woodland, commonly Eucalyptus camaldulensis or E. coolabah but also a wide range of other species including Eucalyptus platyphylla, E. tereticornis, Melaleuca spp., Acacia holosericea or other Acacia spp. Occurs on billabongs. Lacustrine wetland (e.g. lake)*	OC	156 -	-	285	H

RE	Description	BD Status[1]	Homogenous RE		Heterogenous RE	
			Area (ha)	Confidence[2]	Area (ha)	Confidence[3]
11.3.27d	*Eucalyptus camaldulensis and/or E. tereticornis woodland. Occurs fringing large lakes. Palustrine wetland*	OC		H	-	-
11.3.3	*Eucalyptus coolabah woodland on alluvial plains*	OC		L		M , H
11.3.39	*Eucalyptus melanophloia +/- E. chloroclada open woodland on undulating plains and valleys with sandy soils*	NC	112 -	L	1,292	L
11.3.4	*Eucalyptus tereticornis and/or Eucalyptus spp. woodland on alluvial plains*	OC		H	1,403	M , H
11.9.10	*Eucalyptus populnea open forest with a secondary tree layer of Acacia harpophylla and sometimes Casuarina cristata on fine-grained sedimentary rocks*	E	1 21	L	3,181	L
11.9.5	*Acacia harpophylla and/or Casuarina cristata open forest on fine-grained sedimentary rocks*	E		L		L
11.9.5a	*Acacia harpophylla predominates and forms a fairly continuous canopy (10-18 m high). Other tree species such as Eucalyptus populnea, Casuarina cristata, Cadellia pentastylis and Brachychiton spp. may also be present in some areas and form part of the canopy or emerge above it. Scattered Eucalyptus orgadophila may occur, especially on upper slopes and crests.*	E	65 8	M , L	75 63	L
11.9.7	*Eucalyptus populnea, Eremophila mitchellii shrubby woodland on fine-grained sedimentary rocks*	OC	0 -	-	2	L
11.10.1	*Corymbia citriodora woodland on coarse-grained sedimentary rocks*	NC	-	-	2	L , M
11.10.11	*Eucalyptus populnea, E. melanophloia +/- Callitris glaucophylla woodland on coarse-grained sedimentary rocks*	NC	167	M , L	11 1,426	L , M
11.10.7a	*Eucalyptus crebra +/- Callitris glaucophylla +/- Angophora leiocarpa +/- Eucalyptus spp. woodland*	NC	-	-	8	M

RE	Description	BD Status[1]	Homogenous RE		Heterogenous RE	
			Area (ha)	Confidence[2]	Area (ha)	Confidence[3]
11.10.9	*Callitris glaucophylla woodland on coarse-grained sedimentary rocks*	NC	129	M , L	0	L

Notes:

1. Biodiversity Status (BD Status) = Endangered (E), Of concern (OC) or No concern at present (NC).
2. Confidence = Low (L), Moderate (M), High (H) in the GDE status of the polygon in the Qld GDE mapping.

11.3.27a and 11.3.27d are wetland polygons. The terrestrial GDE component of these polygons is a narrow fringing woodland, which comprises a small area of the polygon.

4.3 Prioritisation of GDEs (regional ecosystems)

A risk assessment is applied to evaluate impacts on terrestrial GDEs and the associated REs.

The risk assessment includes both likelihood and consequence criteria. The likelihood of impact on a terrestrial GDE's source aquifer is assessed using the outputs from OGIA's regional model. Outputs that may be useful include magnitude of impact, timing of impact and rate of change. The consequences of impact may be assessed using the biodiversity status of the associated RE.

Biodiversity status reflects the condition of the RE and the extent remaining compared with its pre-clearing extent. Higher priority could be assigned to REs with 'Endangered' and 'Of concern' biodiversity status (Figure **3**). In future, improved understanding of the ecological responses of monitored GDEs will inform the development of consequence criteria for use in risk assessment.

Factors such as depth-to-water, landscape position, water-holding capacity of the soil, and aridity index may influence the likelihood of groundwater use by a vegetation community and could be considered in the prioritisation of REs. However, these factors are taken into account during the GDE mapping technical workshops and contribute to the GDE confidence rating, and so are already reflected in the Queensland GDE mapping.

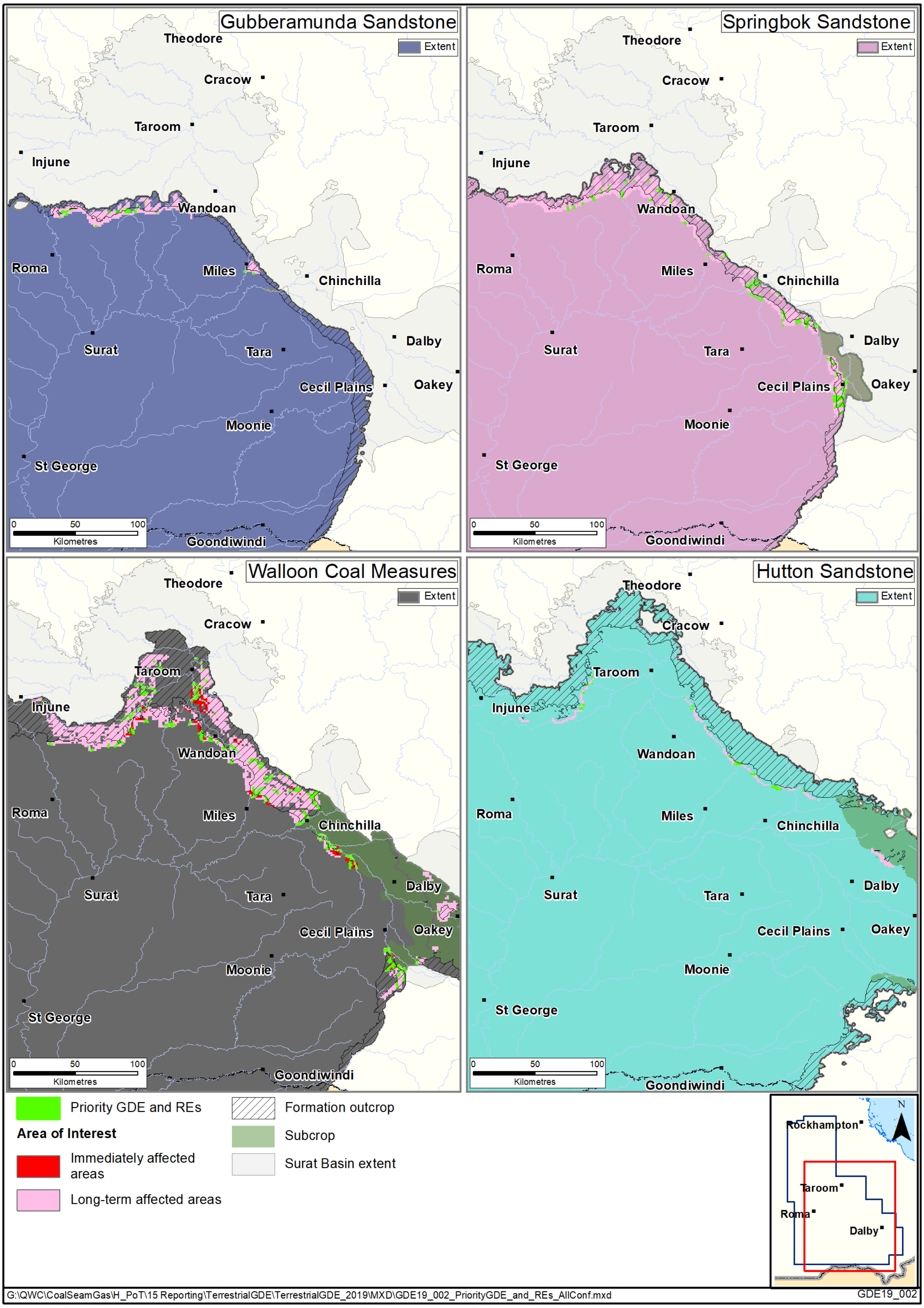

Figure 3 Priority GDEs and regional ecosystems

4.4 Guiding principles for site selection

Locations for field investigation for each priority RE should be selected through consideration of available polygons for the RE in the Queensland GDE mapping. The Queensland GDE mapping includes a field 'GDE_CONF' which indicates the confidence in the groundwater dependence of the ecosystem, with values including 'Known GDE' based on field data, three levels (H, M and L) of confidence (High, Medium and Low) for 'Derived GDEs' based on expert opinion, and 'Unknown'. Polygons attributed as 'known GDEs' and high confidence 'Derived GDEs' are preferred to those with a moderate or and low confidence. Table 1 and Table 2 show that most of the GDE mapping in the study area is based on expert opinion and is of moderate or low confidence. Where more than one level of confidence is shown for an RE, this indicates that more than one mapping rule was applied to identify the RE as a GDE. Different mapping rules may carry different levels of confidence. The GDE mapping data should be consulted to obtain the relevant level of confidence for a particular polygon.

Many polygons in the RE mapping are heterogeneous, i.e. comprise more than one RE. Because the precise location of each RE in heterogeneous polygons is not known, and the confidence in the GDE status of each RE varies with the GDE mapping rule that was applied, the Queensland Herbarium advises that it is preferable as a first step to locate field investigations within homogeneous polygons of the priority REs. Although the location of REs within heterogeneous polygons cannot be determined from the GDE mapping, the field 'PERCENT' can be used to derive an area for each RE in a heterogeneous polygon. Polygons with a large percentage (≥80%) of a priority RE may be suitable for field sites.

Consideration of heterogeneous polygons within the IAA (as defined by the method) which contain ≥80% of the priority REs increases the number of polygons available for selection for some REs, notably 11.3.4 (Table 1), and also 11.3.25 and 11.3.2 which already have large numbers of homogeneous polygons. For most REs, consideration of heterogeneous polygons does not improve the options for field site location because most of the REs occur as relatively small areas and many do not form the largest percentage of heterogeneous polygons.

Most of the identified REs occur as relatively small areas or few polygons. REs 11.3.25, 11.3.2, 11.3.14 and 11.3.4 have the greatest extent. Seven of the identified REs are not mapped as homogeneous polygons within the IAA.. These are likely to have adequate numbers of polygons of moderate confidence to allow selection of three monitoring sites for each RE. As all are land zone 3 REs, field confirmation of their GDE statuses at selected monitoring sites is necessary, as well as confirmation of a GAB source if their GDE statuses are confirmed.

Site selection should also take account of polygon size. To reduce the effects of fragmentation, field sites should be located in RE polygons of >5 ha to reduce the effects of fragmentation, following Fritz (2012). Field sites should be located at least 50 m from the edge of a polygon, to avoid edge effects.

It should be recognised that compromise is inherent in selection of sites for any field program, and final choice of sites will be constrained by feasibility.

4.5 Conceptualisation and hypotheses of impacts

4.5.1 Conceptual models

After site selection, the first step is to develop a conceptual model for each selected site, illustrating the specific ecological, topographic and hydrogeological setting at the site. This conceptual model depicts the current understanding of the ecohydrological relationships at the site including the composition of the vegetation community and any available information on the water sources accessed by the vegetation, the stratigraphy at the site, depth-to-water and water quality data.

4.5.2 Hypotheses of impacts

To predict the impacts of groundwater drawdown on terrestrial GDEs, a specific ecohydrological relationship between groundwater and attributes of the vegetation community must be hypothesised (Eamus et al. 2015). However, it may be simplistic to expect that a demonstrable direct relationship exists between an aspect of groundwater regime and an ecological trait (Boulton 2009). Identification of direct quantitative relationships between a hydrological change (such as groundwater drawdown) and an ecological response (a change in the health, vigour or composition of a terrestrial vegetation community) is challenging due to the natural variability in biophysical characteristics and the effects of other stressors such as grazing, weed infestation and population fragmentation. For example, severe impacts may result if heavy grazing (by cattle or feral animals) and water stress coincide so that plants are unable to respond to grazing pressure by increased leaf growth (Naumburg et al. 2005). Water stress coincident with high temperatures may result in increased mortality in deep-rooted tree and understorey species (Groom, Froend & Mattiske 2000). In both these examples, the impacts cannot be attributed solely to water stress. Impacts can only be attributed to water stress if the stress is primarily caused by groundwater drawdown. For these reasons, clear conceptualisation of the ecohydrological relationships and recognition stressors is critical.

The impacts of groundwater drawdown on the prioritised REs are hypothesised as three categories of response: productivity and growth; biodiversity; and reproduction and recruitment (Figure 4). In the short term (within three years), decreased availability of groundwater is more likely to be evident in changes in the productivity of vegetation. The hypothesis is that groundwater drawdown is associated in the short term with reduced leaf production (measured by litterfall, leaf area index (LAI) and/or percentage of crown cover) and slower rates of growth, and in the longer term with an absence of saplings (measured by fewer occurrences of smaller values of diameter at breast height), loss of biodiversity and changes in community structure and composition. These three categories of hypothesised response are applicable to all REs.

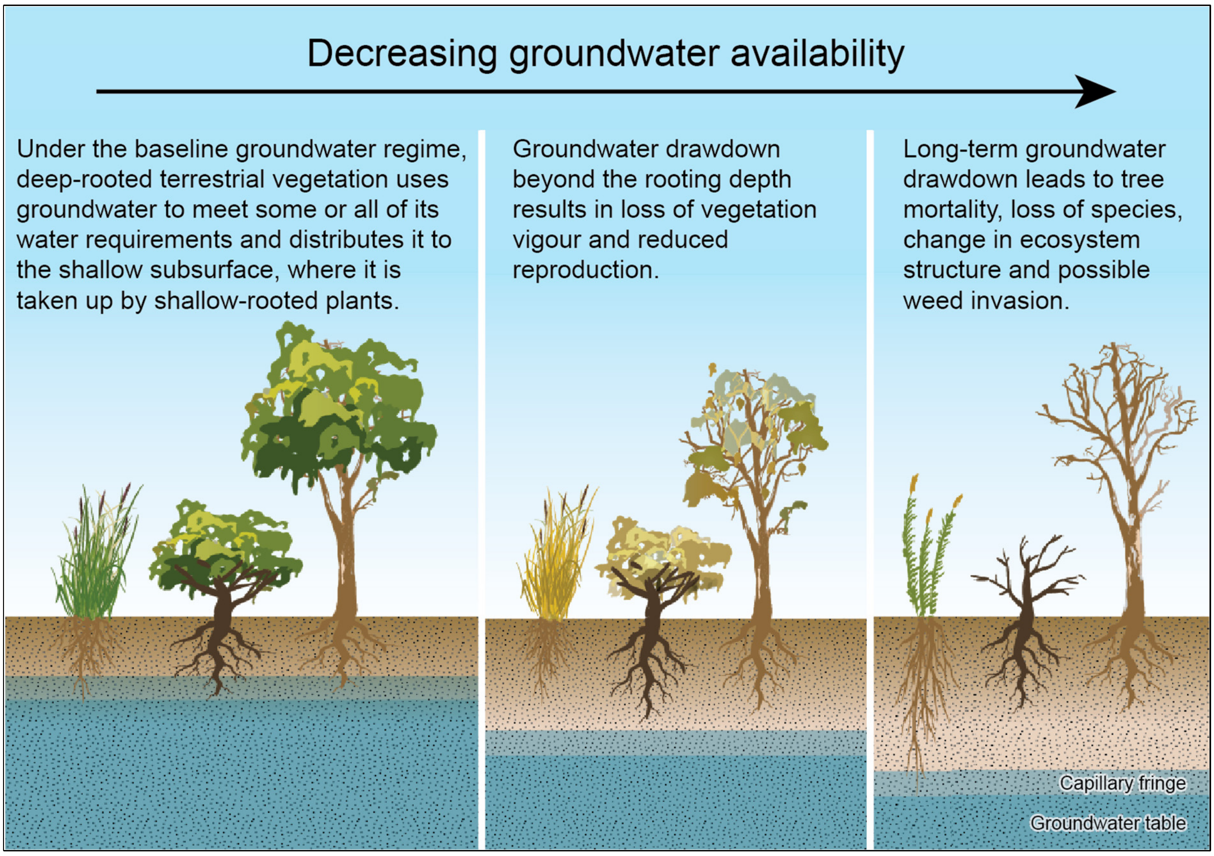

Figure 4 Hypothesised responses of terrestrial vegetation to groundwater drawdown, modified from Rohde et al. (2017) and Eamus et al. (2006)

4.6 Monitoring design

Good monitoring design includes a clear stipulation of the purpose of the monitoring and where, when and how many observations or sampling units are taken to provide the data from which inferences will be made against specified objectives (Downes et al. 2002). Adequate investment of time and effort in scoping and designing the field program will improve the inferential strength of the analysis.

In the case study in the Surat CMA, the purpose of the field program is to test the hypothesised ecohydrological relationships between groundwater drawdown and ecological response in terrestrial GDEs, and to confirm groundwater use by the putative terrestrial GDEs. Groundwater use can be indicated by:

- measuring predawn leaf water potential (it is hypothesised that predawn water potential remains elevated where trees are accessing groundwater) and sap flow (it is hypothesised that greater sapflow indicates use of groundwater)
- conducting stable isotope analysis if monitoring bores are available (groundwater is expected to have higher concentrations of stable heavy isotopes than recent precipitation)
- corroborating these findings with trace data from dendrometers and remote sensing analyses of NDVI.

If feasible, site-specific weather station infrastructure can provide valuable information on local conditions. A GAB source can be confirmed through modified application of the methods described in Madden et al. (2011).

In any monitoring program, comparative data are required from control sites as well as impact sites. The method described here employs paired control and impact sites. Control sites should be as similar as possible to the impact sites (Downes et al. 2002), for example with similar stressors, antecedent rainfall and fire history, but without the additional stressor of groundwater drawdown. Collection of comparative data from paired control and impact sites will aid discrimination of the confounding influence of stressors others than groundwater drawdown. If a similar response is observed in both the control and impact sites, then the response cannot be ascribed to groundwater drawdown. Any assumptions about the effects of other stressors, for example that the effects of these stressors are constant for control and impact scenarios, should be made explicit.

Comparison of data from control and impact sites also aids analysis of the change in the value of a variable; for example, the seasonal change in LAI may be more useful than its absolute value (Cooper et al. 2006). Plant size should be similar in control and impact sites, to avoid the confounding effect of plant size on response variables such as LAI which relate to productivity. Monitoring should be carried out in paired control and impact sites for each RE. Monitoring could be extended along a gradient of predicted drawdown for each priority RE. Data collection for the various response variables should be carried out at least twice per year and at the same time for control and impact sites. Table 3 shows candidate short-term (within three years) and longer-term response variables for the three categories of ecological response to groundwater drawdown. Growth rates may be slow in established trees – for example, overall mean growth of *E. camaldulensis* in two NSW catchments was 2 cm over five years (Ellis, Taylor & Rayner 2017) – and so the response variable of DBH is most useful in the longer term. Reproduction and recruitment are similarly more appropriate for the longer term. Nevertheless, values for all response variables should be recorded from the start of monitoring in order to establish a baseline for future comparison and analysis.

Monitoring of variables applicable to the plant community reflects the role of groundwater in supporting environmental values of the whole community. The response variables include structural (e.g. LAI), functional (above ground net primary production) and compositional indicators (species richness), and are drawn from the literature (see Appendix A) and a common suite of BioCondition attributes.

Table 4 shows relevant BioCondition attributes and Benchmark values for each RE in the study area. Not all BioCondition attributes are relevant for all REs; for example, emergent tree canopy cover is not applicable for RE 11.9.7, *E. populnea, Eremophila mitchellii* shrubby woodland on fine-grained sedimentary rocks. In this case, this attribute would not be monitored for this RE. Where the BioCondition attributes are applicable, specific BioCondition Benchmarks, which are quantitative values for each attribute, have been developed for some REs and are shown in the table. For definitions and values for BioCondition attributes and Benchmarks, see Queensland Herbarium (2016a). Whether or not BioCondition Benchmarks are available, starting values for the response variables should be recorded as a reference in both control and impact sites. An online glossary provides definitions for terms used in BioCondition Benchmarks.

Depending on the specific ecohydrological relationship and the time scale of interest, indicators from more than one of these categories of response are likely to be needed to describe the impact of groundwater drawdown on a vegetation community. A combination of fine- and larger-spatial-scale indicators provide multiple lines of evidence and cross-validation.

4.7 Summary of method

The method may be summarised as follows:

A. Select the area of the target aquifer that is predicted to be affected by drawdown (Section 4.1).

B. Identify terrestrial GDEs (and their component REs) for which the source aquifer is a target formation (Section 4.2).

C. Prioritise selected REs for field investigation based on time to impact, rate of change in the groundwater regime, biodiversity status, and confidence in the GDE mapping (Section 4.3)

D. Select locations within the priority RE polygons for field investigations (Section 4.4).

E. Using an ecohydrological conceptual model for the site and technical information from the scientific literature and the Queensland Herbarium, hypothesise the potential impacts of groundwater drawdown on the prioritised REs (Section 4.5).

F. Design a condition-monitoring program at selected field sites and control sites for each RE, including measures to test the hypothesis of groundwater use by the ecosystem (Section 4.6).

G. Analyse and report the results. Incorporate the results from the monitoring program into the GDE mapping and the method document.

4.8 Stage 2 – Field investigations

The purpose of Stage 2 is to apply the method developed in Stage 1 and establish pilot field sites to:

- test, validate and refine the conceptual models and hypotheses developed in Stage 1
- clarify the groundwater dependency of the mapped GDE REs
- test the feasibility and utility of the candidate response variables (e.g. LAI) and suitable measures (e.g. visual assessment) of the response variables as indicators of short-term (three years) and longer-term impacts of groundwater drawdown
- identify additional or alternative response variables and measures, supported by a rationale linked to the hypotheses and conceptual models
- test the feasibility and utility of measures to confirm groundwater use by the putative GDE REs
- trial the field program design including selection of impact and control sites, source aquifer investigations, monitoring design, variable selection and timing of field work

A report on the Stage 2 field investigations should:

- describe the field investigations, including site selection, conceptualisations, and the field techniques that were applied
- provide analysis and interpretation of the results of the field investigations consistent with the reporting recommendations of the Department of Environment and Science's Guideline for underground water impact reports and final reports
- recommend analytic approaches for future users of the method
- discuss obstacles encountered and any solutions

- identify any knowledge gaps and uncertainties
- recommend methods and tools for upscaling results from the field to the landscape scale
- recommend field protocols and procedures for data quality assurance/quality control, storage and transfer to nominated databases including the GDE mapping and RE mapping
- confirm, or propose refinements to, the workflow (section 3.2).

Table 3 Candidate response variables for monitoring the impact of groundwater drawdown on terrestrial GDEs

	Time scale of response – three years		Time scale of response – greater than three years	
Response category	**Response variable**	**Method**	**Response variable**	**Method**
Productivity and growth	Litterfall (P)	Zolfaghar et al. (2014)	DBH of large eucalypt trees from BioCondition benchmark for the specific REs (E)	Queensland Herbarium (2016a); Eyre et al. (2015)
	Huber value (P)	Eamus et al. (2006a)	DBH of large non-eucalypt trees from BioCondition benchmark for the specific REs (E)	
	Above ground net primary production (ANPP) (E)	Zolfaghar et al. (2014)	Number of large eucalypt trees per hectare (E)	
	Leaf area index/ projective foliage cover/NDVI (E)	Gleason et al. (2018)	Number of large non-eucalypt trees per hectare (E)	
	Tree emergent canopy cover (E)		Canopy median height (E)	
	Tree canopy cover (E)			
	Shoot extension rate (P)			
Biodiversity	Native plant species richness (E)	Queensland Herbarium (2016a); Eyre et al. (2015)	Native plant species richness (E)	Queensland Herbarium (2016a); Eyre et al. (2015)
Reproduction and recruitment	Nectar production Fruit production		Recruitment of dominant canopy species (100%)	Queensland Herbarium (2016a); Eyre et al. (2015)

Notes:
For BioCondition Benchmark values for specific REs, see Table 4.
P = applicable to populations of the same species; E = applicable to plant community.

Table 4 Response variables and BioCondition Benchmark values, where available, for REs in the study area (Queensland Herbarium 2016a)

RE	Productivity and growth										Biodiversity	Recruitment
	Litterfall (kg ha^{-1})	Huber value (m^2 m^{-2})	ANPP (Mg C ha^{-1} $year^{-1}$)	LAI (m^2 m^{-2})	Tree emergent canopy cover (%)	Tree canopy cover (%)	Native shrub cover (%)	Large tree DBH (eucalypt)	Large tree DBH (non-eucalypt)	Density of large Euc/ha	Spp richness	Canopy recruitment
11.3.1					29	9	8	na	28	na	20	100
11.3.2					na	40	2	40	na	22	30	100
11.3.3					na	28	4	45	na	10	35	100
11.3.4					na	17	1	48	24	26	23	100
11.3.14												100
11.3.17					na	29	8	38	30	6	41	100
11.3.18												100
11.3.19												100
11.3.25					na	22	1	49	29	14	26	100
11.3.25d												100
11.3.27a												100
11.3.27b												100
11.3.27d												100
11.3.36					na	39	1	38	22	14	40	100
11.3.39												
11.9.4a					na	54	41	na	17	na	40	100
11.9.5					na	59 (e), 32 (w)	11(e), 19(w)	na	30 (e), 26 (w)	na	25 (e), 24(w)	100
11.9.5a												100

RE	Productivity and growth										Biodiversity	Recruitment
	Litterfall (kg ha^{-1})	Huber value (m^2 m^{-2})	ANPP (Mg C ha^{-1} year^{-1})	LAI (m^2 m^{-2})	Tree emergent canopy cover (%)	Tree canopy cover (%)	Native shrub cover (%)	Large tree DBH (eucalypt)	Large tree DBH (non-eucalypt)	Density of large Euc/ha	Spp richness	Canopy recruitment
11.9.6					na	84	14	na	17	na	25	100
11.9.7					na	27	1	40	22	14	47	100
11.9.10					na	50	16	47	32	2	32	100
11.10.1					na	35	22	60	na	4	38	100
11.10.7a												100
11.10.9												100
11.10.11					na	30	3	38	16	20	38	100

5 Conclusion

This report describes a desktop method to assess impacts of groundwater drawdown on terrestrial groundwater-dependent ecosystems. It presents a desktop method to identify and prioritise terrestrial GDE regional ecosystems in areas of predicted groundwater drawdown, and to select locations for field investigations. Candidate variables are proposed for three categories of hypothesised ecological response.

The desktop method will be tested and further developed through detailed field investigations in selected priority areas. Following analysis of data and validation and revision of the proposed ecohydrological relationships, hypotheses and conceptual models, the method to assess impacts of groundwater drawdown on terrestrial groundwater-dependent ecosystems will be published. Over time, results from ongoing monitoring will inform refinement of the method. It is intended that future versions of the method with include techniques for upscaling from point measurement, such as individual tree water use, to estimate ecosystem-level characteristics such as transpiration.

In the medium and longer terms, analysis of monitoring results will aid understanding of vegetation responses to groundwater drawdown, contribute to updates of the Queensland GDE mapping, and help inform mitigation, recovery and restoration programs.

Appendix A Literature review

A.1 Obligate and facultative groundwater dependency

Much of the pioneering international research on terrestrial GDEs was carried out in the south-west United States (for example, Robinson 1952, Robinson 1958) where a number of arid-zone species from four genera (*Tamarix, Populus, Salix* and *Prosopsis*) (Lewis 2012) are identified as “obligate phreatophytes” or plants that must be in contact with groundwater at all times (Smith et al. 1998). Very few species of Australian flora have been designated as obligate phreatophytes (Zencich et al. 2002, Canham, Froend & Stock 2009). Instead, it is more commonly recognised that plants are opportunistic in their use of water sources, reflecting local conditions such as availability of soil water. Many species may be considered to be facultative phreatophytes, defined by Pfautsch et al. (2015) as species that depend on groundwater or water from the capillary fringe when soil water originating from surface recharge is limited. The blurred line between obligate and facultative phreatophytes (Lewis 2012) means that there is limited value in assigning a species to one or the other category based on its water use characteristics in a particular location (Canham, Froend & Stock 2009).

Groundwater use by Australian flora varies spatially and temporally, within and between species. Ability to switch water sources is a key adaptation in areas of highly variable rainfall and soil moisture conditions such as those that characterise most of Australia. Reliability of water sources is important; a tree may preferentially access saline groundwater rather than adjacent water from an intermittent stream (Mensforth et al. 1994). In a study of water sources for tree species sampled in transects across the riparian zone in the wet–dry tropics of the Northern Territory, O’Grady et al. (2006) found that for *Acacia auriculiformis* and *Casuarina cunninghamiana* – both of which occurred across the gradient – use of groundwater varied with location. At low elevations, both species used groundwater. At higher elevations in the landscape, both species used soil water.

Groundwater use may occur only for short periods or opportunistically during dry periods (Mensforth et al. 1994), but this may be crucial for the persistence of the community (Bacon et al. 1993). Therefore, a species can be regarded as groundwater-dependent even if groundwater represents only a small proportion of total water use, or is only used infrequently (O'Grady et al. 2006). Vegetation communities may include suites of species with differing degrees of groundwater dependency, and the proportion of groundwater dependency of each species may shift in response to gradual changes in groundwater availability (Sommer & Froend 2014).

The potential for a species to use groundwater can be estimated from literature and expert knowledge (Doody et al. 2017), but actual use of groundwater by a species in a particular location depends on a number of site-specific factors including depth-to–water (DTW), position in the landscape, climate, soil type and geology. Individuals of a species may exhibit differing vulnerability to water stress depending on position in the landscape and the related availability of groundwater (Challis et al. 2016).

A.2 Root architecture and rooting depth

The ability to access groundwater is conferred by the root architecture and rooting depth. Processes affecting root architecture are complex and depend on a high number of variables (Tron et al. 2015) including site-specific characteristics. Eucalypt species that typically grow in coarse-textured soil tend to have more lateral roots compared to those typically found in fine-textured soils (Hamer et al. 2016). The baseline groundwater regime also influences root architecture. Where fluctuations in DTW are highly variable, root profiles tend to be shallower in order to avoid low oxygen conditions where the water table is shallow. Where there is low variability in DTW, root growth profiles are deeper (Tron, Laio & Ridolfi 2014).

Many Australian tree species have a dimorphic root architecture consisting of shallower lateral roots and deeper tap or sinker roots. Lateral roots may extend up to 20 m from the trunk in *E. camaldulensis* (Bacon et al. 1993, Burgess et al. 2001). Tap or sinker roots may extend 10–20 m below ground level (Bacon et al. 1993, Steggles et al. 2017) to reach the water table (Fig. 5). Broadly, it may be speculated that phreatophytic vegetation with dimorphic roots is resilient to water stress because the root architecture allows trees to access water from different parts of the soil profile, thus maintaining transpiration during dry periods (Verma et al. 2014).

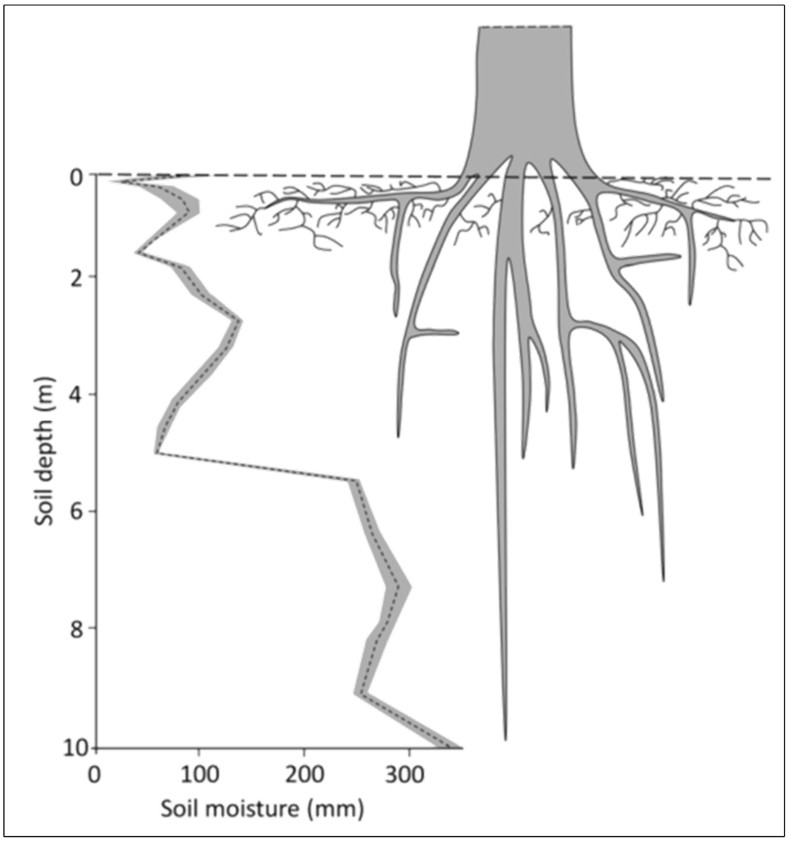

Figure 5 Conceptualisation of root structure in E. camaldulensis (Doody et al. 2015); dashed line indicates mean soil moisture; range over two years of measurements shaded in grey

Documented rooting depths for Australian trees are rare in the literature. As a rule of thumb, all eucalypts could be considered deep-rooted due to their capacity for a dimorphic root architecture. Fine roots of *Eucalyptus marginata* (jarrah) have been recorded at 40 m (Dell, Bartle & Tacey 1983). Eucalypt roots have been recorded from caves at 60 mbgl (Stone & Kalisz 1991). Hill and Hore (2009) inferred a capacity for rooting depths of at least 50 m for *E. camaldulensis* and the gum-barked coolabah (*E. intertexta*) based on elevated uranium and associated trace element content of leaves in trees overlying mineralised settings. Similarly, Lintern et al. (2013) proposed that gold concentrations in eucalypt foliage were derived from an underlying deposit at 35 mbgl. Roots of a mallee community in Western Australia were encountered in a bore at 28 m (Nulsen et al. 1986).

White cypress-pine (*Callitris glaucophylla*) can produce roots that penetrate deep in the soil profile (Harris, Lamb & Erskine 2003). On the basis of stable isotope data, Anderson and Hodgkinson (1997) conclude that poplar box *E. populnea* seedlings have the ability to grow down to groundwater below the soil zone. Bloodwoods (*Corymbia* spp.) are characterised by a deep tap root structure, while the root system of ironbarks (e.g. *E. crebra, E. melanophloia*) is dominated by a series of shallower, lateral roots, making *E. crebra* and *E. melanophloia* more susceptible to drought-induced dieback than bloodwoods (Rice et al. 2004, Fensham & Fairfax 2007). Brigalow (*Acacia harpophylla*) is a clonal species with stems arising from shallow horizontal roots (Thorburn, Cowie & Lawrence 1991, Johnson et al. 2016) and could be considered predominantly shallow-rooted, although roots are recorded as reaching more than 3 mbgl (Coaldrake 1967). It is clear that many species have an inherent capacity to develop deep roots, but actual root extent must be evaluated on a site-specific basis (Stone & Kalisz 1991).

The ability of roots to maintain access to the capillary zone depends on the rate of groundwater drawdown (Froend & Sommer 2010). Rapid root elongation (up to 0.55 m per month) after germination of *E. grandis* seedlings has been observed (Christina et al. 2011), but growth ceased after the roots reached the water table. The ability for rapid root growth in seedlings does not necessarily imply tolerance of water table decline in established individuals (Canham, Froend & Stock 2015). Once connection has been made with the water table, roots show limited capacity to respond to water table drawdown. Therefore, rapid groundwater decline may strand roots above a soil depth that was previously within the capillary fringe of the water table, leading to reduced tree productivity and, in some cases, mortality (Lite & Stromberg 2005). In any case, investment in root growth reduces the resources available to support above-ground biomass (Decuyper et al. 2016, Li et al. 2015), so groundwater drawdown may be associated with loss of condition and impaired growth even if connection with groundwater is maintained.

A.3 Hydraulic redistribution

A dimorphic root architecture facilitates hydraulic redistribution (Orellana et al. 2012) by which water is transported via roots along water potential gradients from wetter to drier parts of the soil profile. Hydraulic redistribution allows maintenance of the shallow roots during dry periods (Zencich et al. 2002), facilitates water use efficiency by redistributing soil water from the shallow subsurface (thus reducing water loss through evaporation, runoff and lateral flow) and enables rapid switching between shallow and deep water sources.

Water lifted to shallower soil layers may contribute up to half of the following day's transpiration (Naumburg et al. 2005). Hydraulic redistribution has been observed in a range of Australian tree species (Dawson & Pate 1996) including eucalypts (Burgess et al. 2001) and banksias (Burgess et al. 2000). Brooksbank et al. (2011) demonstrated the redistribution of substantial quantities of groundwater to the soil surrounding the surface roots of the mallee species *Eucalyptus kochii* subsp. *borealis*, and downward flow of water in the tap root following a rainfall event.

Hydraulic redistribution of groundwater to the soil surrounding surface roots not only aids the persistence of the individual but may also be important for the establishment of young plants whose roots have not reached the water table (Burgess et al. 2001). It also aids the establishment and persistence of understory species including grasses (Caldwell, Dawson & Richards 1998) and shallow-rooted herbaceous species (Naumburg et al. 2005). Hydraulic redistribution of water absorbed by deep roots and released into the upper soil profile indicates that groundwater use is not only ecologically relevant for deep-rooted species but is an important driver of the hydrology of dryland ecosystems (Bleby, Mcelrone & Jackson 2010) and arguably contributes to community productivity, diversity and ecosystem services (Maeght, Rewald & Pierret 2013). The ecological value of groundwater extends even beyond phreatophytic communities; through consumption of groundwater-fed leaves by terrestrial insect herbivores, groundwater sustains food webs in linked ecosystems (Sabo et al. 2008).

A.4 Mapping groundwater-dependent terrestrial vegetation

The need for mapping of GDEs in Australia arose from the requirement in the national water reforms that water plans should contain an allocation for the environment. For water plans that include groundwater, this means identifying GDEs in the plan area and quantifying or at least estimating their water needs (termed “ecological water requirements”). The need for GDE mapping prompted the development of the web-based National Atlas of Groundwater Dependent Ecosystems (National Atlas). The National Atlas provides broad-scale mapping of GDEs for the Australian continent, drawing on national datasets – including remote sensing products – available for the period 2000 to 2010. Mapping of terrestrial vegetation GDEs in the National Atlas is determined by the availability and scale of mapped vegetation communities.

In Queensland, vegetation communities are grouped into regional ecosystems (REs) (Sattler & Williams 1999) which are defined as vegetation communities in one of 13 bioregions that are consistently associated with a particular combination of geology, landform and soil. The Regional Ecosystem Description Database (REDD) (Queensland Herbarium 2016b) contains detailed descriptions of REs. There are currently 1539 REs in the REDD. Technical descriptions provide further details of the structural and floristic composition of REs; for example, Pollock et al. (2015) for the Brigalow Belt.

The Queensland RE mapping was not used in the National Atlas because vegetation mapping at the scale of the RE mapping was not available consistently across Australia. The National Atlas incorporates the Queensland RE mapping via a field in the RE mapping (Dowsley et al. 2012) which indicates one of 35 categories of broad vegetation group for the whole state at a scale of 1:2,000,000.

In Queensland, the availability of state-wide RE and wetland mapping at a minimum scale of 1:100,000 supported a different GDE mapping method based on the integration of these detailed spatial datasets with local expert knowledge (Glanville et al. 2016). Each mapped GDE in the Queensland GDE mapping is linked to a pictorial conceptual model and rule-set developed from structured multidisciplinary technical workshops with local experts. Details of the REs within each GDE polygon and attributes of the connected aquifer are also available through a link. Further detail on the methods, conceptual understanding and technical outputs of the Queensland GDE mapping is available in drainage sub-basin handbooks (for example, Department of Science, Information Technology and Innovation 2016).

For New South Wales, Kugunis et al. (2016) present a method to identify terrestrial vegetation with a high, medium and low probability of being groundwater-dependent based on existing vegetation datasets, groundwater level data and remote sensing analyses.

A.5 Methods to assess condition of terrestrial vegetation

The concept of vegetation condition or ‘health’ may be interpreted in different ways depending on the management intent. Harwood et al. (2016) define ‘condition’, as it applies to maintenance of habitat for biodiversity, as “a measure of the difference between two sets of dynamic ecological states: one resulting from the natural regime of disturbance and recovery processes, and the other consisting of modified states resulting from anthropogenic perturbations”.

In Queensland, an assessment framework (BioCondition) has been developed to assess terrestrial ecosystem condition for biodiversity (Eyre et al. 2015). In this framework, ‘condition’ is defined as the similarity in key features of the regional ecosystem being assessed with those of the same regional ecosystem in its reference state, where the reference state refers to the natural variability in attributes of an ecosystem relatively unmodified since the time of European settlement, or the ‘best on offer’.

BioCondition is a simple, rapid assessment approach that uses a suite of condition attributes that are readily measureable in the field. BioCondition site condition attributes include measures of native plant species richness for each layer in the community, the median height and percentage cover of each layer, and characteristics of the coarse woody debris. For each site condition attribute assessed in BioCondition, quantitative values – or BioCondition Benchmarks – have been derived for reference sites in eight Queensland bioregions. BioCondition Benchmarks are compiled from quantitative site data and expert opinion. The method described in this document preferentially uses the BioCondition framework. For the Surat CMA, the BioCondition Benchmarks for the Brigalow Belt (Queensland Herbarium 2016a) apply.

A.6 Methods to identify and measure groundwater use by terrestrial vegetation

Natural ecosystems are inherently variable. Spatial patterns of species diversity are determined by many ecological factors (Zhu et al. 2013). Environmental characteristics vary along gradients and may exhibit patchiness depending on local topography, geology, soil type and climate. Controls on groundwater use by vegetation are a combination of a host of factors that vary across sites and species (Eamus et al. 2015, Evaristo & McDonnell 2017) and are influenced by interactions between factors such as grazing pressure (Kath, Le Brocque & Maron 2016) and species composition. This natural variability may occur at fine spatial and temporal scales. Therefore, multiple lines of evidence at more than one scale are needed to establish groundwater use by vegetation and to understand the ecosystem-scale response to changes in the groundwater regime (Eamus et al. 2015).

The Australian Groundwater-Dependent Ecosystem Toolbox (Richardson et al. 2011b) (GDE Toolbox) presents a suite of methods to identify GDEs and estimate their ecological water requirements. Although the GDE Toolbox was primarily aimed at a water planning audience, it presents a sound approach that is applicable to any investigation of the groundwater needs of GDEs. The first steps are landscape mapping and conceptual modelling to gain a broad understanding of the biophysical setting, including groundwater hydrology of the area of interest. For the Surat CMA, the first steps have been covered by the Queensland GDE mapping. The subsequent steps described in the GDE Toolbox are specific techniques which identify, infer and/or quantify groundwater use by ecosystems.

Methods to identify groundwater use by vegetation include:

- Consideration of rooting depths and DTW, including analysis of diurnal groundwater fluctuations (Devitt & Bird 2016). As a rule of thumb for treed ecosystems, groundwater use is considered to be of lesser importance, but still possible, at DTW of 10–20 mbgl, and has a low probability at depths of >20 m (Eamus et al. 2006b). Where DTW data are not available, position in the landscape may be a surrogate for DTW. In general, the water table is a subdued reflection of topography (Fetter 1980), so the water table may be shallower in valleys and at the bases of slopes compared with upslope or ridge locations.

Further, valley geomorphology promotes the accumulation, rather than shedding, of soil moisture (Cadol & Wine 2017).

- Analysis of plant water stable isotopes to identify sources of water and estimate rates of groundwater use (e.g. Costelloe et al. 2008).
- Sapflow meters to measure rates of water use relative to groundwater availability (Pfautsch et al. 2015).
- Dendrometers to infer groundwater use over short time scales (hourly to daily) (Andersen et al. 2016).
- Remote sensing techniques (e.g. NDWI, NDVI) to measure canopy ‘greenness’; higher and relatively stable NDVI values during low-rainfall periods infer groundwater use. NDVI typically increases with decreasing DTW but approaches a constant value where DTW reaches a threshold (Liu et al. 2017).
- Comparison of pre-dawn leaf water potential with soil water potential and plant height across seasons.
- Analysis of combination datasets, for example Aridity index, AET (Cooper et al. 2006, Sommer et al. 2016) and land surface temperatures (Gow et al. 2016).

These methods vary in their spatial and temporal scales. There is very little guidance available for selecting and combining the methods or interpreting their output – for example, in upscaling from the tree to catchment scale, and downscaling from remotely sensed data to gain an accurate understanding of finer-scale groundwater use by vegetation. Lawley et al. (2016) review recent literature on integration of site-based and remote sensing methods for monitoring vegetation condition.

These methods identify and to some degree quantify groundwater use by vegetation. A different set of methods, discussed in the next section, are appropriate for monitoring the impacts of groundwater drawdown on terrestrial GDEs.

A.7 Impacts of groundwater drawdown on terrestrial GDEs

As methods to identify GDEs have become established, research attention has turned to predicting and measuring the impacts of groundwater drawdown on specific terrestrial GDEs. It has become apparent that communities of terrestrial phreatophytes do not respond similarly to groundwater declines (Cooper et al. 2006, Froend & Sommer 2010, Cunningham et al. 2011). Instead, groundwater drawdown may trigger complex ecological responses (Cooper et al. 2006) that may be gradual or non-linear as thresholds in groundwater level are reached (Eamus et al. 2006a). The rate of change in groundwater depth relative to a previous condition or regime may be more important than absolute DTW (Naumburg et al. 2005, Shafroth, Stromberg & Patten 2000). Vulnerability to water stress may be influenced by the thickness of the capillary zone and the water-holding capacity of the soil. Vulnerability of terrestrial GDEs to groundwater drawdown is considered to be greatest where the capillary zone is least thick and pore size is larger (Naumburg et al. 2005). Ecological responses will be influenced by other factors such as rainfall regime, soil type and potential root growth rate (6).

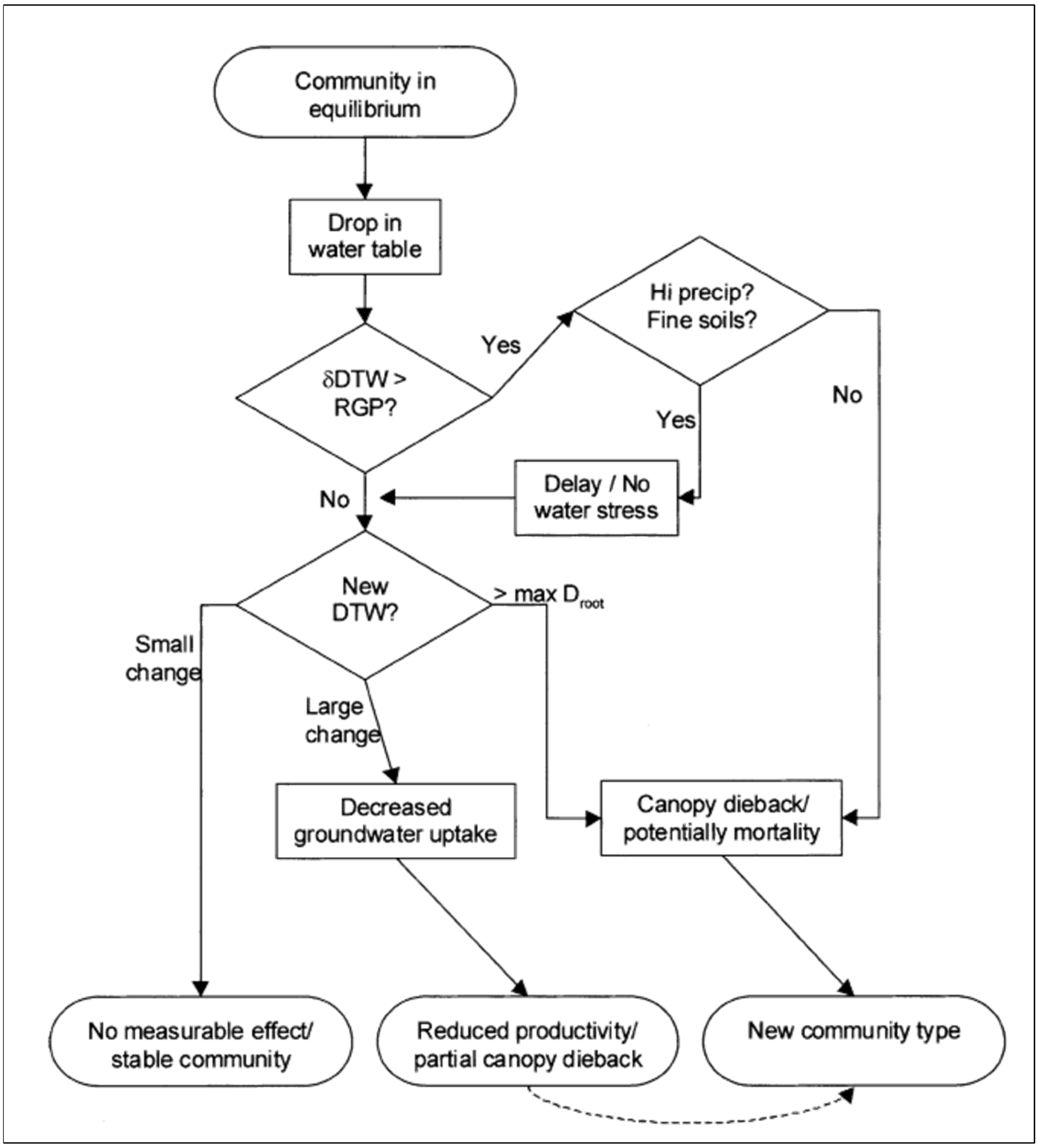

Figure 6 Simplified conceptual model of the effects of a dropping water table on a terrestrial GDE

DTW = depth to groundwater
dDTW = the rate of increase in depth to groundwater
RGP = the potential root growth rate
max Droot = the maximum potential rooting depth
Dashed arrow refers to potential long-term routes (Naumburg et al. 2005)

A generalised understanding of the ecological responses of phreatophytes to groundwater drawdown can be hypothesised (Figure 6). Changes in the hydraulic properties of plant tissues are a key mechanism by which plants adapt to changes in water availability (Zolfaghar et al. 2015). As water availability decreases, stomata close and photosynthesis reduces. Prolonged water deficits can lead to xylem cavitation and eventually to branch and crown mortality (Naumburg et al. 2005). As groundwater availability decreases, productivity and growth decline while reproduction and recruitment decrease. Over time, species abundance and community composition and structure alter, and biodiversity may be lost (Eamus et al. 2006a, Challis et al. 2016, Lite & Stromberg 2005, Groom, Froend & Mattiske 2000).

For riparian *Populus* species in arid eastern Colorado, USA, leaf desiccation and branch dieback occurred within three weeks of sustained drawdown of more than one metre, and significant declines in live crown volume and stem growth, and increased mortality, occurred within three years. Declines in live crown volume were a significant indicator of mortality in the following year. More gradual drawdown of ~0.5 m had no measurable effect on mortality, stem growth or live crown volume and produced significant declines only in annual branch growth increments (Scott, Shafroth & Auble 1999). Changes in composition of a shrubby phreatophyte community in Colorado continued for >20 years after the onset of groundwater drawdown (Cooper et al. 2006).

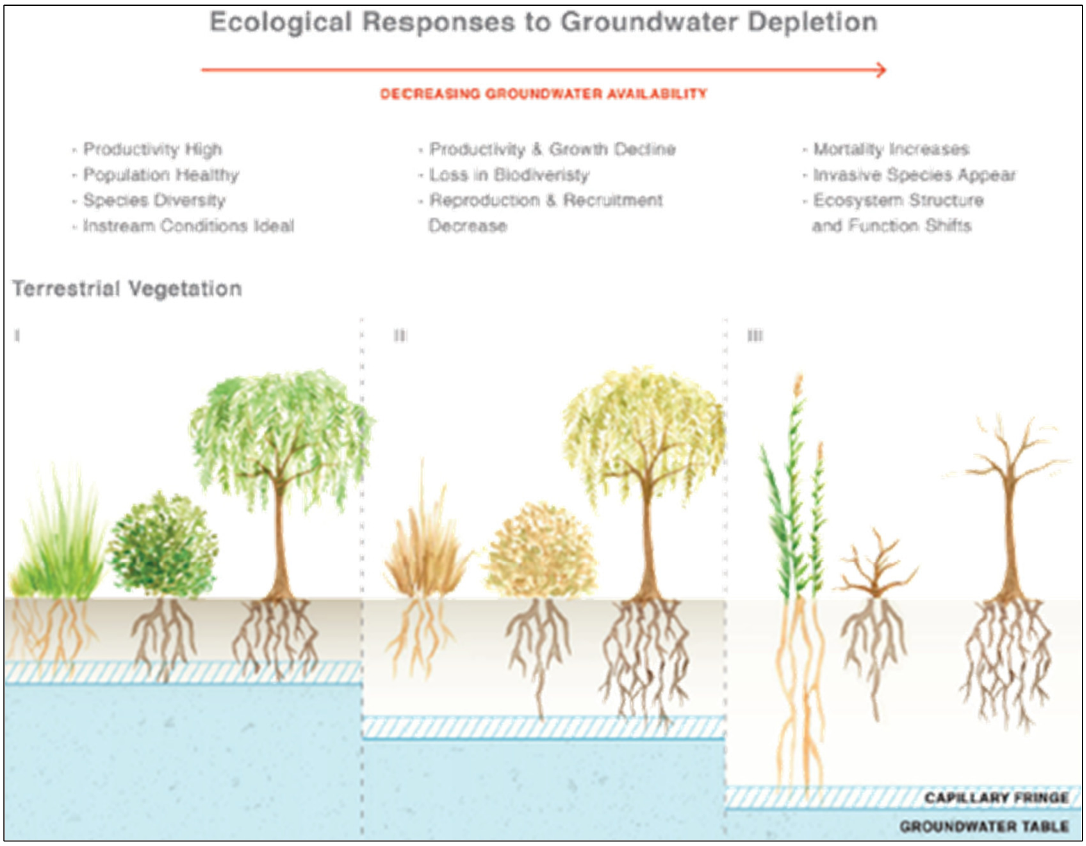

Figure 7 Schematic ecological responses of terrestrial vegetation to groundwater drawdown (Rohde, Froend & Howard 2017)

Zolfagher et al. (2014) showed a stepwise response in leaf area index (LAI), mean tree height and basal area, and above-ground net primary production (ANPP) to increasing DTW in a eucalypt woodland. For example, at sites where groundwater was deeper (>9.8 mbgl), the trees had larger Huber values – that is, a larger ratio of sapwood cross-sectional area to leaf area distal to the point of excision. In other words, the trees at deeper groundwater sites could only sustain a smaller leaf area for a given sapwood area. ANPP can be approximated by litter production (Grigg & Mulligan 1999). Litterfall rates in eucalypt communities decrease with increasing aridity and moisture stress.

The LAI of terrestrial GDEs is generally greater than that of neighbouring non-GDEs. In an analysis of LAI and water balance studies, O'Grady et al. (2011) found that the LAI of ecosystems with access to groundwater was higher than that of ecosystems without access to groundwater, for a given climatic regime. The corollary is that groundwater drawdown may be associated with reduction in LAI in these ecosystems. LAI data can be derived using a variety of techniques including visual estimation and light interception techniques, such as canopy photography or plant canopy analysis (Zolfaghar et al. 2014, Macfarlane & Ogden 2012, Hakamada et al. 2016).

The relationship between groundwater depletion and loss of phreatophyte vigour has also been demonstrated for desert vegetation in Chile (Decuyper et al. 2016). A three-metre groundwater drawdown over 20 years was associated with significantly lower stem growth and reduced crown biomass measured by satellite-derived indicators of canopy greenness at the tree and stand scales. Fritz (2012) found that groundwater depth was a significant factor influencing *Eucalyptus populnea* condition (measured by a foliage index) and seedling density in the Condamine catchment. The association with seedling density was assumed to be due to support of seedlings through hydraulic lift by mature *E. populnea* trees.

Kath et al. (2014) investigated the relationship between tree condition and groundwater depth in the Condamine floodplain and identified distinct DTW thresholds beyond which canopy condition declined abruptly, in the range of 12.1–22.6 m for *E. camaldulensis* and 12.6–26.6 m for *E. populnea*. These authors found that a visual estimate of the proportion of the crown that contained foliage relative to a healthy tree with a full crown was a simple, consistent and reliable indicator of stand condition.

Cunningham et al. (2011) demonstrated a quantitative relationship between widespread dieback of an *E. camaldulensis* floodplain forest and changes in groundwater availability and salinity over a 20-year period. Dieback increased with increasing groundwater depth, particularly at depths below 10 m. However, the authors did not identify a distinct groundwater level threshold below which dieback occurred, noting that the condition of floodplain forests is likely to be driven by the interaction of groundwater with flooding, rainfall and soil type. Lateral recharge through the bank from river channels is especially important in floodplains underlain by saline groundwater (Doody et al. 2014).

The magnitude of response to water stress can be expected to vary within and between species. Greater mortality may be observed in larger trees under water stress compared with trees of the same species with smaller canopies, because large trees require more water to maintain physiological functioning (Challis et al. 2016). Casuarinas generally have greater desiccation tolerance and lower water use requirements than do eucalypts (Cramer, Thorburn & Fraser 1999), so casuarinas could be expected to exhibit a less-marked response to groundwater drawdown. It is therefore important to record site-specific characteristics of a community as a starting benchmark against which to compare future changes in condition.

A.8 Conclusion

Groundwater use by vegetation varies spatially and temporally, within and between species. The impacts of groundwater drawdown can therefore be expected to vary. In the absence of specific data on groundwater use by particular species or evidence of ecological impacts of groundwater drawdown, inferences may be made on the basis of extrapolation from studies of that species at other sites or from data on different species, but the scientific literature indicates that such extrapolations should be made with caution. It may not be valid to assume that a species is not phreatophytic because individuals of that species do not use groundwater in another location, that vegetation can switch to using other water sources if groundwater availability is reduced, or that vegetation can respond by rapid root growth to follow falling water levels. Such assumptions should be made in a precautionary manner, stated explicitly, illustrated conceptually, supported by scientific evidence and tested with field data.

In general, groundwater drawdown potentially results in loss of leaf area and crown vigour of terrestrial GDEs in the short term (within three years). Sustained groundwater drawdown can be expected to lead to a change in community structure and composition in the longer term.

Appendix B Generic method to identify terrestrial GDEs sourced from target formations

Desired outcome: Identify those terrestrial GDEs that may source groundwater, directly or indirectly, from specified target formations.

Step One – Identify terrestrial GDEs in a specified area of interest

Method:

- Perform a geometric intersection (using the 'Intersect' tool) of the following features in ESRI ArcGIS® or similar geographic information system:
  - the latest version of the Queensland GDE Mapping: GDE Terrestrial Areas
  - a customised area of interest dataset delineating the outcrop areas of specified target formations.

Output:

- Derived dataset of terrestrial GDEs that occur in the specified area of interest.

Step Two – Identify terrestrial REs in a specified area of interest that potentially access groundwater from specified target formations

Method:

- Analyse the attribute table (using the 'Frequency' tool) to determine unique field values for the following key fields in ESRI ArcGIS® or similar geographic information system:
  - source aquifer name(s) 'AQ_NAME'
  - groundwater flow system 'AQ_GFS'
  - conceptual model 'C_MODEL'
  - conceptual model (regional) 'C_MODEL_R'
  - conceptual model (local) 'C_MODEL_L'
  - conceptual model (site) 'C_MODEL_S'.
- Select features (i.e. terrestrial GDEs that occur in specified areas of interest identified in step one) in a layer based on an attribute query of the source aquifer name(s) 'AQ_NAME' and groundwater flow system 'AQ_GFS' with consideration of unique field values.

  For example, AQ_NAME may be used to select terrestrial GDEs linked to relevant source aquifers such as 'alluvia', 'consolidated sedimentary rocks', 'sandstone' or 'sedimentary rocks'. AQ_GFS may be used to exclude some terrestrial GDEs linked to irrelevant groundwater flow systems such as 'perched'. In addition, consideration of conceptual model 'C_MODEL' may be useful in guiding the user in determining an appropriate selection attribute query.
- Select features in a layer based on an attribute query of groundwater-dependent REs 'GDE_RE' with consideration for those relevant land zones.

For example, in the Surat CMA, GDE_RE may be used to select those polygons that contain terrestrial GDEs where the RE is located on alluvia (land zone 3) or sedimentary rocks (land zone 9 and land zone 10).

- Export the attribute table from ESRI ArcGIS® as a text file and import the data into Microsoft Excel®.
- Develop a unique list of GDE regional ecosystems using the 'Text to Columns' and 'Remove Duplicates' tools in Microsoft Excel® based on the GDE_RE column. Refine the list of unique REs based on the RE land zone. REs should be excluded where the land zone is not considered to contain groundwater, directly or indirectly, sourced from the target formations.

Output:

- Derived spatial dataset of terrestrial GDE REs that occur in the specified area of interest and potentially access groundwater, directly or indirectly, from the specified target formations.
- Derived list of terrestrial GDE REs that occur in the specified area of interest and potentially access groundwater, directly or indirectly, from the specified target formations.

Step Three – Identify a subset of priority REs for field investigations

Method:

- Use the Regional Ecosystem Descriptions Database to populate a new 'BIOD_STATUS' column listing the biodiversity status for each identified RE.
- Refine the list based on biodiversity status of each RE. For example, REs may be excluded based on a biodiversity status of 'Least concern', if many REs with status 'Endangered' or 'Of concern' occur in the study area.

Output:

- Derived spatial dataset of priority terrestrial GDE REs that occur in the specified area of interest and potentially access groundwater, directly or indirectly, from specified target formations.

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