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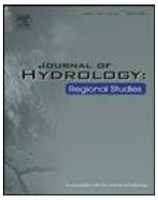

Continental mapping of groundwater dependent ecosystems: A methodological framework to integrate diverse data and expert opinion

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ABSTRACT

Study region: Australian continent.
Study focus: With increasing groundwater development around the world, a method is required to identify and map groundwater dependent ecosystems (GDEs) across broad landscape scales. Identifying the location of GDEs, will ensure that the environmental impacts of increasing water development are understood and will lead to better management of water resources to protect GDEs. In this study, a method is demonstrated that underpinned the development of an online national GDE mapping tool in Australia (GDE Atlas; http://www.bom.gov.au/water/groundwater/gde/map.shtml). Known GDEs and their locations were extrapolated to regional scales using a process that relied on the integration of expert opinion, remote sensing data obtained between 2000 and 2010 and GIS analysis.
New hydrological insights: It was identified that 34% of Australia's landscape potentially contains GDEs of which 5% are classified with a high GDE potential. In addition, new continental scale insights into landscape processes where provided by the derivation and integration of remote sensing products using MODIS and Landsat. These products identify landscapes which are 'wetter' or 'greener' than surrounding areas, indicating these landscapes are accessing additional water, such as groundwater, supplementary to rainfall. The method reported also demonstrates the importance of expert knowledge, obtained through literature and expert elicitation, in order to provide a conceptual understanding of regional ecohydrological processes to develop rules of GDE dependency that would guide the extrapolation of known GDEs.

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1. Introduction

As societal demands for water resources continue to intensify under a changing climate and water scarcity increases globally, attention continues to be heavily focussed on groundwater to meet abstraction requirements (Siebert et al., 2010; Gleeson and Wada, 2013; Arnell and Gosling, 2013; Haddeland et al., 2014). In the United States for example, groundwater pumping more than doubled in the period from 1965 to 1995 to supply domestic consumption, with substantially larger groundwater abstraction occurring to support industry such as mining and irrigated crops (Glennon, 2002). Recently, 43% of total global irrigation water was extracted from groundwater sources, with America and Asia extracting 48% and 45% respectively (Siebert et al., 2010). Furthermore, approximately 25% of the world's population depend on groundwater pumping for drinking water, many of these in semi-arid and arid zones (Glennon, 2002). Groundwater is a finite resource, reliant on seepage from the surface via diffuse recharge from rainfall and surface water leakage from adjacent water bodies to replenish aquifers (Taylor et al., 2013). Understandably, unsustainable extraction of groundwater has been reported at both regional and global scales (Famiglietti et al., 2011; Gleeson et al., 2012; Wada et al., 2012).

There are vast environmental impacts related to groundwater over-extraction. Of environmental significance is local and regional groundwater level decline, which reduces groundwater supply to rivers, springs, lakes and wetlands causing water body contraction and if unmanaged, eventual desiccation as groundwater continues to decline. The outcome is ecosystem and environmental degradation and a significant loss of ecosystem services (Tomlinson and Boulton, 2008; Kløve et al., 2014; Eamus et al., 2015; Pérez Hoyos et al., 2016). Hence, there is an increasing risk to the future persistence of groundwater dependent ecosystems around the world due to increases in groundwater and surface water abstraction to meet irrigation, industrial, urban and domestic water supplies (Hoogland et al., 2010; Eamus et al., 2015; Pérez Hoyos et al., 2016).

It is imperative the environmental impacts of water development are monitored and where necessary mitigated to protect groundwater dependent ecosystems (GDEs; Eamus and Froend, 2006). This can only be achieved by understanding the broad scale distribution of GDEs and assessing and meeting their water requirements within water allocation and management plans (Pérez Hoyos et al., 2016).

1.1. *Groundwater dependent ecosystems*

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). These diverse ecosystems are primarily driven by temporal groundwater flow variability contingent on climate, geology and landuse (Alfaro and Wallace, 1994; Bertrand et al., 2012; Kløve et al., 2014).

Groundwater as reported here, is defined as (i) water naturally occurring below ground level (i.e aquifer) 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 the capillary zone but water held within the soil above this zone is not included. Water within caves that is sourced from groundwater is also included. GDEs include;

- *wetland, lake, remnant terrestrial forest/shrubland and riparian ecosystems* where groundwater discharge forms a component of the hydrological environment (Eamus et al., 2006; O'Grady et al., 2006a,b);
- *springs* where there is a surface expression of groundwater (i.e. artesian mound springs; Eamus et al., 2006);
- *cave and aquifer aquatic ecosystems* which rely on groundwater including aquifer dwelling metazoans referred to as stygofauna (Humphreys, 2006).
- *Estuarine and marine* which rely on submarine discharge of water for nutrients (Paytan et al., 2006)

GDEs provide many ecological and socio-economical values (Boulton, 2005; Tomlinson and Boulton, 2008; Bertrand et al., 2012; Pérez Hoyos et al., 2016) and insufficient supply of groundwater can threaten the variety of ecosystem services and associated values provided. Ecosystem services include ecological (biodiversity), environmental (filtration; flood mitigation; erosion prevention), economic (production of fish, forestry, agriculture) and social values (recreation and tourism). GDEs are impacted when groundwater regime changes (seasonal fluctuation, depth to groundwater, flow rate or groundwater pressure) to exceed the natural bounds of variation (Boulton, 2005). Impacts come not only from abstraction for irrigation and human consumption but also reduced groundwater recharge resulting from land use change where shallow rooted vegetation is replaced by deep rooted vegetation (Schenk and Jackson, 2002; Scott et al., 2014). Furthermore, land clearing for urban or farm development can induce groundwater level rise, waterlogging and where saline water tables are present, this may lead to salinisation or other water chemistry changes associated with anthropogenic interaction (Boulton, 2005).

GDE research and mapping is predominantly undertaken at local scales, involving time consuming and lengthy field studies to quantify vegetation access to a groundwater resource (Hatton and Evans, 1998; Eamus et al., 2006). A number of broad scale studies (>50 km^2) employing Geographic Information Systems (GIS) and spatial analysis and/or satellite imagery such as Landsat, have been undertaken in California (Howard and Merrifield, 2010; Elmore et al., 2003), Oregon (Brown et al., 2005), Colorado and Nevada (Werstack et al., 2012), Netherlands (Hoogland et al., 2010), Ireland (Kilroy et al., 2008), South Africa (Münch and Conrad, 2007) and Spain (Lubczynski and Gurwin, 2005). More recently, new methods employing spatial data have been developed in Australia to identify GDEs at catchment scales (Gow et al., 2016; Glanville et al., 2016).

Continental scale mapping of GDEs has not been undertaken anywhere around the world to date, resulting in large regional knowledge gaps which hinder the future protection of GDEs, especially in Australia. Since water reform began in Australia in 1994, the environment has been recognised as a legitimate user of water where provision of formal water entitlements require prioritisation by the states (Tomlinson and Davis, 2010). An understanding of GDE water requirements and allocations of water are therefore required to maintain riparian, terrestrial, wetland, marine and subterranean ecosystems that depend on groundwater (Murray et al., 2003; Davis et al., 2015; Eamus et al., 2015; Pérez Hoyos et al., 2016). However, the regional identification of GDE types (forest and riparian ecosystems, rivers, wetlands and springs) and mapping of GDEs, has been highlighted as a critical knowledge gap preventing water reform objectives from being met (NGC, 2004).

The broad scale application of remote sensing and the integrative ability of a GIS are well known in terrestrial science. It has been suggested by Pérez Hoyos et al. (2016) that integration of fine spatial scale field studies with these geospatial technologies form an ideal approach to identify and characterise GDEs across large areas. The inclusion of field studies provides validation of GDEs when determined from remote sensing. We suggest within, that the inclusion of expert opinion is also a critical validation tool when remote sensing is employed.

The purpose of this manuscript is to (1) demonstrate a pragmatic approach to enable upscaling of known, fine scale GDEs across broader regions; (2) to highlight that a combination of expert participation, remote sensing and GIS geospatial analysis can identify GDE type and classify their potential for groundwater interaction; (3) present a framework to map GDEs at a continental scale. The outcome is a national scale interactive online mapping platform (National Atlas of Groundwater Dependent Ecosystems; 'GDE Atlas') to aid the protection of GDEs and decisions related to water resource management in the future. GDEs are classified within as subsurface (vegetation) and surface (rivers, lakes, wetlands and springs). MODIS satellite time series data and Landsat imagery were used to develop new continental scale knowledge to assist GDE identification by calculating water balance dynamics and greenness of vegetated land, respectively (van Dijk et al., 2015; Barron et al., 2014). We believe the approach taken is broadly applicable worldwide, although effort may initially be required to quantify GDEs at local scales if such background knowledge is lacking. Deriving marine and subterranean GDEs however, was beyond the scope of the project that was undertaken due to the priorities determined by the funding body and hence these remain a challenge for future research.

2. Methods

2.1. Study extent

Mainland Australia is composed of a landmass of 7.7 M km^2. Climate is diverse, ranging (north to south) from equatorial, tropical, subtropical, desert, grassland to temperate regions. Rainfall is summer dominant in the northern equatorial, tropical, subtropical regions and winter dominant in the southern grassland and temperate regions. As a result, there are diverse ecosystems, consisting of subtropical and tropical rainforest, semi-arid and arid floodplains, desert and alpine mountainous regions. The geology and groundwater systems in Australia are also complex. Major Australian groundwater resources are associated with large sedimentary basins, such as the Great Artesian Basin (GAB) or Perth Basin limestone formations and alluvial systems (shown in blue and yellow respectively in Fig. 1). These systems are known to support multiple GDEs in groundwater discharge zones (e.g. Gnangara in Western Australia; Parsons et al., 2008; artesian springs in GAB; White et al., 2015). Many GDEs also coincide with areas of intensive expanding mining operations across Australia.

2.2. Process undertaken to map continental GDEs

2.2.1. Overview

An iterative approach which combined literature reviews, expert consultation and review, remote sensing and GIS analysis (Fig. 2) was undertaken. The reported method was derived from collation of Australia wide GDE research, to provide a conceptual understanding of how groundwater and various ecosystems interact across contrasting Australian landscapes. The final map GDE products relied on the availability of existing polygons which delineate surface water and vegetation landscape features or 'assets' (referred to as asset 'feature layers'). Resource and time constraints prevented the creation of new line mapping (vegetation and river, wetland, spring polygons) prior to GIS analysis, however new remote sensing analysis was undertaken to develop national data to aid GDE identification. GDEs reliant on the subsurface presence of water (vegetation) and surface presence of water (rivers, wetlands, springs) were derived using the aforementioned vegetation and surface water feature layers along with 'rules of GDE dependency'. These rules were developed and guided by information relating to 'known' GDEs, expert opinion and the availability of GIS 'rule dataset' spatial layers (polygons). Integrative analysis of remote sensing, feature layers, 'rule datasets' and expert knowledge, provided a framework to extrapolate local known GDEs to create a national scale atlas.

A. Literature review and expert consultation

A national review of literature was undertaken to identify GDEs derived from scientific research (field data collection and desk-top studies), their location and environmental setting (Fig. 2A). Approximately 200 items were reviewed from across Australia (see Fig. 9 in SKM and CSIRO, 2012).

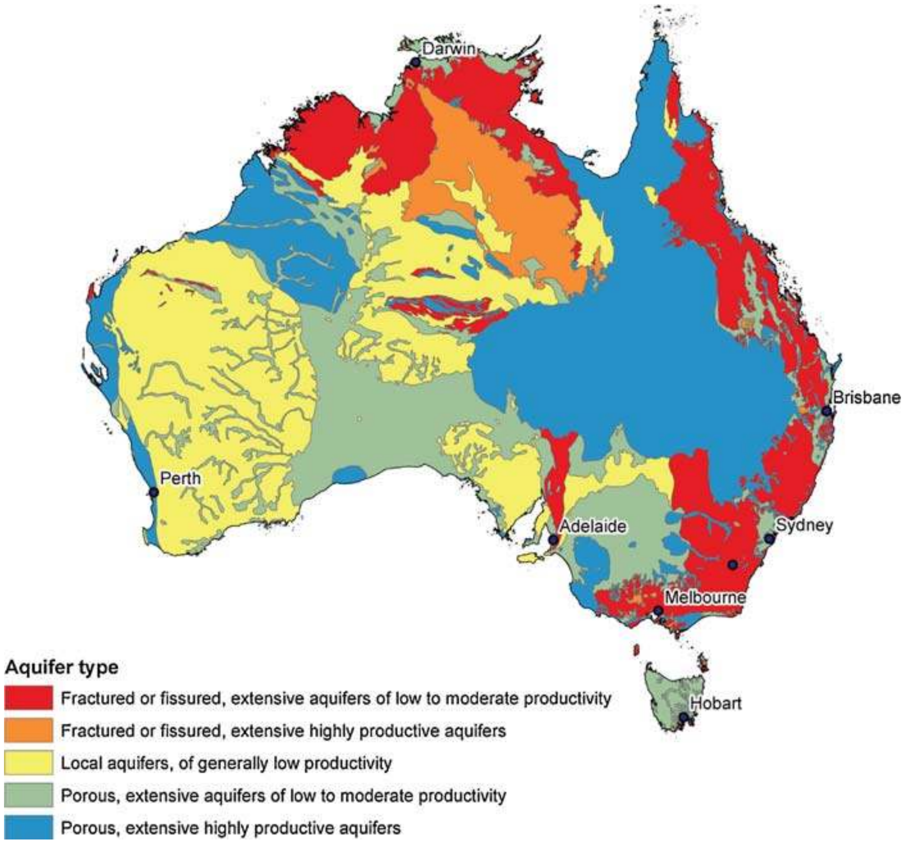

Fig. 1. Aquifer types and their productivity across Australia (adapted from GA, 2000).

B. Collation of continental spatial data and development of ecohydrogeological zones

To expedite GIS analysis, the nation was divided into 57 ecohydrogeological zones (EHZs) within which GDEs were determined (Fig. 3). EHZs were developed by collating continental spatial layers (e.g. climate, geology, groundwater flow systems; Fig. 2B) to identify regions where similar processes are likely to determine the interaction between groundwater and ecology, due to similar climate, ecology, geology and groundwater-surface water connections (see SKM and CSIRO, 2012 for detailed methods).

Existing spatial layers which map vegetation and surface water features such as rivers and wetlands were identified within each Australian state through consultation with experts from both research and government departments (Fig. 2B; Appendix A). The intent was to determine the potential of each polygon within these feature layers of being a GDE (see Section E below).

C. Rules of groundwater dependency

Collated literature and expert consultation (Fig. 2A) provided a conceptual understanding of how groundwater and various ecosystems interact across contrasting Australian landscapes (Fig. 2B). From this, a number of criteria that suggest groundwater dependence were identified (Table 1). For example, a forest ecosystem's potential of being a GDE can depend on how deep the groundwater is. Groundwater less than 10 m is often indicative of an ability to access the water table if the soil conditions are conducive to tree root penetration to that depth (Canadell et al., 1996). These criteria indicate when assets are likely to be GDEs and thus, form not only the basis for the development of 'rules of GDE dependency' but the linkage between the conceptual processes and the method reported (Fig. 2). For detailed description of the rules of GDE dependency, see SKM and CSIRO (2012).

The rules of GDE dependency describe the processes that influence groundwater dependence, and hence, the likelihood of an asset being groundwater dependent (Fig. 2C). The purpose of the rules was to extrapolate the criteria that indicate groundwater dependence to other 'like' assets within each EHZ. For example, it is assumed that similar rules will apply to the same tree species, irrespective of its location in an EHZ. Application of the rules therefore allowed for regional analysis and identification of GDEs based on knowledge of the processes or criteria that describe groundwater dependence for known local GDEs.

D. Collation of regional spatial data and remote sensing derivation of inflow dependent landscapes

To identify GDEs within ecohydrogeological zones, a number of spatial layers were required for intersection with the vegetation and surface water feature layers (see Section E below), in order to apply the developed 'rules of GDE dependency'

Table 1
The conceptual linkages of how groundwater and various ecosystem's interact in order to understand the rationale between conceptual processes identified from literature and the rules of GDE dependency that were subsequently derived. ET is evapotranspiration; GDE is groundwater dependent ecosystem. (see attached file).

Subsurface GDEs	Conceptual processes	Indicator of system recharge	Groundwater availability	Soil characteristics	Biological/ecological indicators	Presence of surface water
Groundwater dependent vegetated land	*Rule(s)*	○ IDE ≤ 5 ○ Evapotranspiration is lower than rainfall ○ Seasonal change in greenness of vegetated land (especially greenness reduction in summer)	○ Depth to water table is shallow (<10 m) ○ IDE>5 (High ET all year) ○ Topography indicates shallow groundwater when depth maps not available ○ Groundwater discharge occurs with the presence of faults	○ Low water holding capacity indicates groundwater access in some instances ○ Presence of cracking clay indicates low chance of groundwater access ○ Presence of Holocene muds in coastal floodplains indicates low chance of groundwater access	○ Vegetation type with known groundwater dependence (i.e. *E. camaldulesis*) ○ Vegetation surrounding 'known' GDEs are likely to be GDEs ○ IDE of 8–10 indicates constant greenness all year	○ Vegetation adjacent permanent water ○ High potential river or wetland GDE identified
	Normalisation *Weightings* *GDE potential*	[a] [a] [b]	[a] [a] [b]	[a] [a] [b]	[a] [a] [b]	[a] [a] [b]
Surface GDEs	Conceptual processes	Indicator of system recharge	Groundwater outlet	Soil characteristics	Biological/ecological indicators of groundwater dependence	Presence of surface water
Groundwater dependent wetlands	*Rule(s)*	○ IDE of surrounding vegetation ≤5 ○ Persistence of water (or permanent water regime) indicates groundwater input	○ Depth to water table is shallow <5 m, 5–10 m ○ Wetlands where dominant water source is known as groundwater ○ IDE>5 (High ET all year) of surrounding vegetation ○ Wetlands adjacent losing rivers ○ Baseflow contributed by fractured rock aquifers, limestone and alluvium	○ High water holding capacity indicates water retention ○ Presence of peaty soils in wetlands indicates groundwater ○ Presence of Holocene muds in coastal floodplains indicates low chance of groundwater presence ○ Presence of cracking clay indicates low chance of groundwater input	○ Wetland type indicates groundwater connection (I.e. deep marsh) ○ Presence of subsurface GDEs ○ Wetlands west of the Great Dividing range receive less rainfall – permanent wetlands have likely groundwater inputs ○ Vegetation type with known groundwater dependence (i.e. minerotroph species) ○ Wetlands in the vicinity of springs	
	Normalisation *Weightings* *GDE potential*	[a] [a] [b]	[a] [a] [b]	[a] [a] [b]	[a] [a] [b]	

Table 1 (*Continued*)

Surface GDEs	Conceptual processes	Indicator of system recharge	Groundwater outlet	Soil characteristics	Biological/ecological indicators of groundwater dependence	Presence of a stream
Groundwater dependent river ecosystems	*Rule(s)*	○ Persistence of water (or permanent water regime) indicates groundwater inputs	○ Depth to water table is shallow <5 m, 5–10 m ○ Baseflow contributed by fractured rock aquifers, limestone and alluvium ○ Fractured rock aquifer of the Adelaide geosyncline and Great Artesian Basin ○ Losing rivers unlikely to have groundwater baseflow ○ Rivers where dominant water source is known to be groundwater	○ Presence of cracking clay nearby indicates low chance of groundwater input ○ Presence of Holocene muds in coastal floodplains indicates low chance of groundwater presence	○ Presence of subsurface GDEs ○ Vegetation type with known groundwater dependence (i.e. Stygobionts) ○ Rivers west of the Great Dividing range receive less rainfall – permanent wetlands have likely groundwater inputs ○ Rivers in the vicinity of springs	○ Geological/geomorphological maps
Surface GDEs	Conceptual processes	Indicator of system recharge	Groundwater outlet	Soil characteristics	Biological/ecological indicators of groundwater dependence	Presence of a stream
Spring ecosystems	*Rule(s)*	○ Persistence of water (or permanent water regime) indicates groundwater inputs	○ Location of known springs ○ IDE > 5 (High ET all year) of surrounding vegetation ○ Fractured rock aquifer of the Adelaide geosyncline and Great Artesian Basin	○ No rule	○ Presence of subsurface GDEs	
	Normalisation	[a]	[a]	[a]	[a]	[a]
	Weightings	[a]	[a]	[a]	[a]	[a]
	GDE potential	[b]	[b]	[b]	[b]	[b]

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[a] Normalisation assigns a rating of 0–3 for each attribute to reflect the likelihood of the attribute accessing groundwater. The weighting of each rule reflects the reliability with which each rule identifies GDEs. Values for both normalisation and weighting vary between ecohydrogeological zones and are determined via expert opinion and interactive assessment of results against ‘known’ GDEs.

[b] Formula to calculate GDE potential. Formula can be adapted to match any number of rules. $GDE\ \ potential = \frac{(Rule\ \ 1\ x\ weighting)+(Rule\ \ 2\ x\ weighting)+(Rule\ \ 3\ x\ weighting)+(Rule\ \ 4\ x\ weighting)}{Sum\ \ of\ \ total\ \ weightings}$.

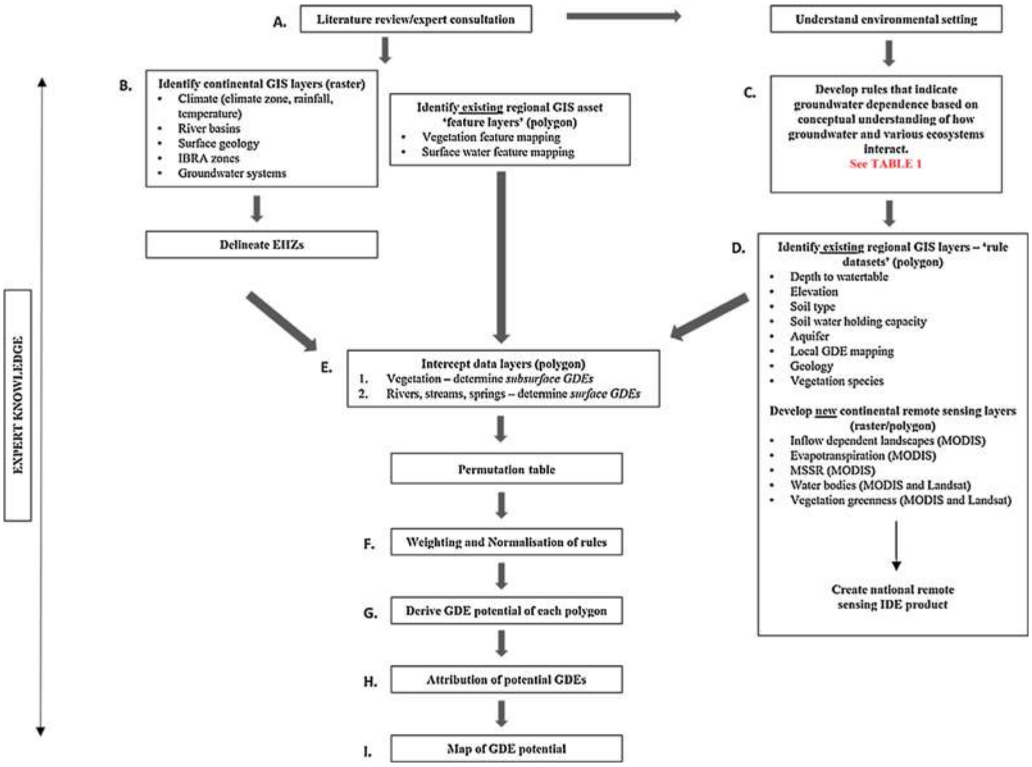


Fig. 2. Framework developed to scale up known GDEs across Australia.

Table 2
The thresholds which create the probability of inflow dependence.

ET/rainfall ratio	pIDE
0.49	0%
0.79	10%
0.90	20%
0.95	30%
0.99	40%
1.04	50%
1.10	60%
1.17	70%
1.22	80%
1.38	90%
3.14	100%

(Table 1) within a GIS analysis framework. Expert elicitation was undertaken to identify relevant GIS datasets that reflect the rules which aid GDE identification such as depth to watertable (Table 1). The available GIS datasets were referred to as 'rule datasets' (Fig. 2D). Remote sensing was employed to develop semi-quantitative inflow dependence layers, to ensure that in data poor regions, there was at least one rule of GDE dependency that could be used to help GDE identification. Inflow dependence (ID) describes landscapes in Australia which are 'wetter' or 'greener' than surrounding areas either seasonally or permanently, as water is accessed from inflows (such as groundwater) supplementary to rainfall.

2.2.2. Remote sensing

MODIS satellite imagery (250 m resolution) estimates of average annual evapotranspiration (ET) from the land surface between 2000 and 2010 were utilised. For detailed methods see van Dijk et al. (2015). In summary, the algorithm developed by Guerschman et al. (2009) was employed to derive ET (in mm) of each pixel nationally, in eight-day time steps. ET estimates were validated against flux tower observations Australia-wide and catchment water balance analysis and then scaled to calculate average annual ET. Inflow dependence was identified when average annual ET from the land surface exceeded annual average rainfall for a pixel. The degree of exceedance was given as a probability derived from a ratio of ET to rainfall and referred to as the potential inflow dependent landscape ('pID') layer (Table 2). This product best represents landscapes which predominately use groundwater during dry seasons such as temperate and arid climates.

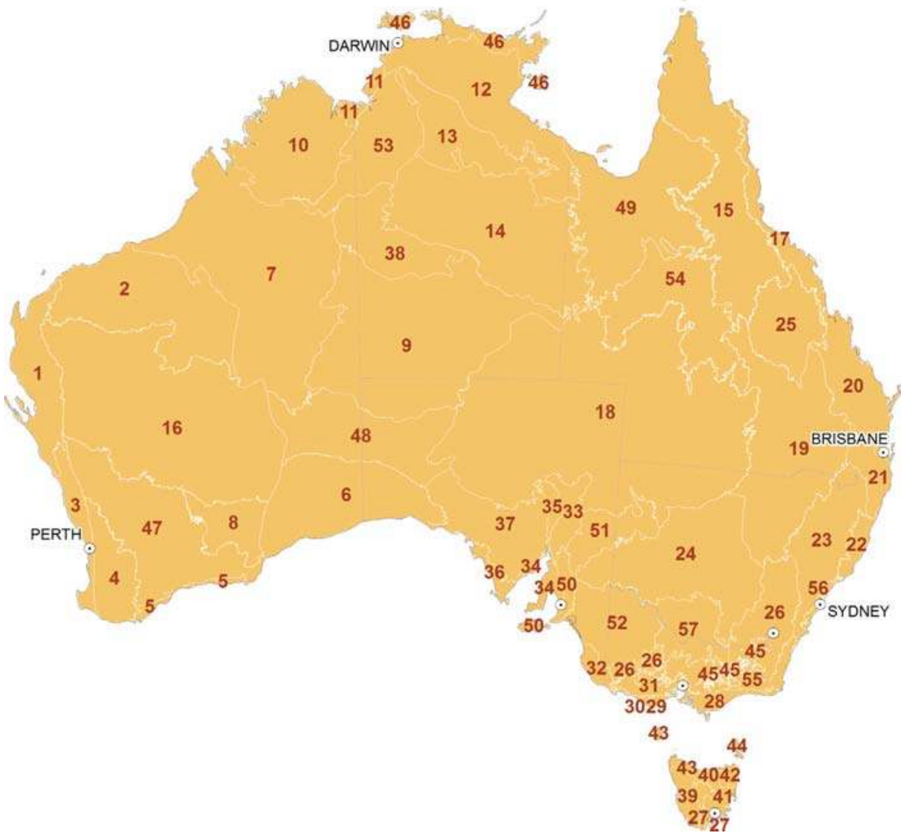


Fig. 3. Eco-hydrogeological zones used in the creation of the GDE Atlas.

An ancillary dataset generated from MODIS, expresses the estimated mean seasonal storage range (MSSR) of water in all water stores in mm of ET (surface, soil and groundwater). An extended range indicates significant water extraction from stored supplies during low rainfall periods which is especially useful in tropical regions where the ratio of ET to rainfall is not always indicative of groundwater dependence due to high monsoonal rainfall during summer periods with high evaporation.

Continental Landsat TM (30 m resolution) analysis identified vegetation greenness, highlighting potential groundwater dependence as areas maintaining greenness throughout prolonged dry periods. For detailed methods see Barron et al., 2014. In summary, between 2000 and 2010, an extended wet and dry period image was selected for each Landsat scene across Australia (a total of 720 scenes). Imagery selection was guided by meteorological data (SILO Climate Data, Queensland Government) highlighting periods of prolonged high and low rainfall. Two remote sensing indices, normalised difference vegetation index (NDVI) and normalised difference water index (NDWI) classified vegetation in each pixel as either 'no drying', 'slow drying' or 'fast drying' during an extended dry period. The 'slow drying' and 'no drying' class identified potential GDEs as areas where greenness and wetness slowly decline or show little change, respectively. The method was validated in the Ellen Brook region of Western Australia (Barron et al., 2014). Permanent surface water was also identified by both MODIS and Landsat methods.

2.2.3. Creation of a national remote sensing inflow dependent ecosystem product

To develop a national inflow dependent ecosystem (IDE) layer with 25 m pixel resolution, MODIS pID and MSSR products were normalised to represent the likelihood that water in excess of rainfall was being used at a given location, with values between 1 and 10 (low to high). Landsat greenness was reclassified to 'slow drying', 'no change', 'water', 'forest and non-forest'. The products of the two sensor types were combined to form one inflow dependence likelihood layer which best characterised the landscape using either Landsat or MODIS data (referred to as a mosaic product). For the majority of Australia, most landscapes were represented by the pID, however this product was not reliable in wet tropical regions. MSSR data was thus included, to help identify GDEs where ET is not higher than rainfall as identified from previous research (O'Grady et al., 2006a,b). Landsat results were not reliable in forested regions due to NDVI insensitivity at high canopy densities. Therefore, rules were developed and applied to each pixel, dependent on climate, to determine the final IDE probability for each pixel. For example, vegetation classified as 'slow drying' was assigned a high inflow dependence probability between 1 and 10 (i.e.

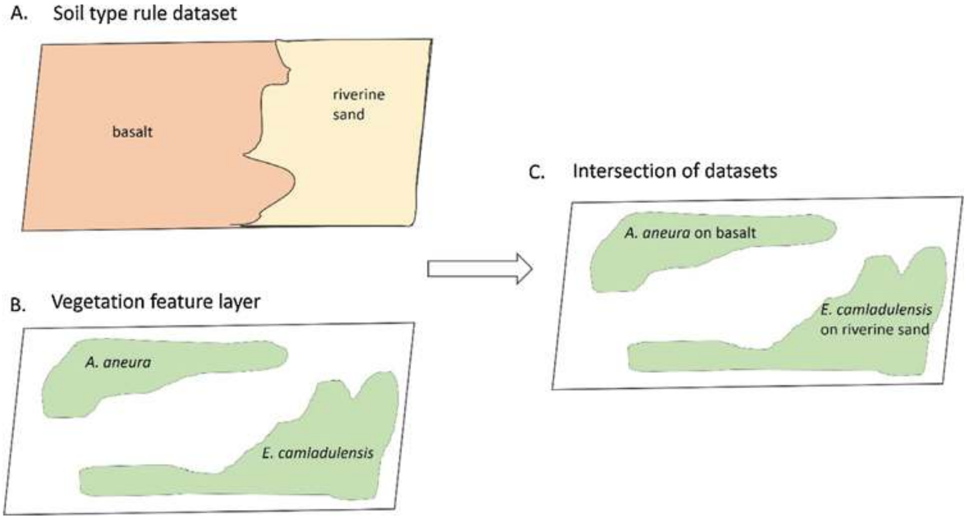


Fig. 4. Attributes from a 'soil type' rule dataset (A) were added to the vegetation asset feature layer (B) they intersect with. The result is the vegetation feature polygons gain the attribute which describes the potential for groundwater interaction.

Landsat results were used). Where vegetation remains seasonally green or moist ('no change') the pID values were assigned (i.e. use MODIS pID results). The resulting layer is called the inflow dependent ecosystem (IDE) layer.

E. Intersection of spatial layers to classify potential presence of GDEs

GIS analysis involved intersecting both vegetation and surface water asset 'feature layers' (Fig. 2B) with collated datasets that represent the rules of GDE dependency ('rule datasets'; Fig. 2D). Where a polygon from a rule dataset intersected (or overlapped) with a vegetation or surface water asset polygon from the feature layer datasets, the asset polygon gained an attribute that described the potential for groundwater interaction from each 'rule dataset' intersected (Fig. 4). A 'majority rules' approach was used to assign the attribute.

The number of rule datasets attached to each vegetation asset polygon (for example) was dependent on the availability of spatial data (see Table 3 – four rule datasets were available in that example). Many rule datasets were regional in extent rather than national, limiting the number of rules which could aid GDE identification. In some regions, there were no available rule datasets besides the national scale IDE product that was developed. As such, all asset 'feature layers' (Fig. 2B) were intersected with the IDE product (Fig. 2D), to add an inflow dependence probability to each asset feature polygon to ensure at least one rule dataset was available Australia wide. Complex permutation tables presenting unique combinations of 'rules of GDE dependency' (Table 1) for each asset polygon (from 'rule datasets') resulted from the spatial intersections between 'feature layers' and 'rule dataset' layers. Attributes of rule datasets in either text or number format were added to each asset polygon after intersection (see example in Table 3).

F. Normalisation and weighting of rules

The rules of GDE dependency were applied through a process of weighting of rules to prioritise the importance of some rules over others for each EHZ, and normalisation of attributes within each rule dataset (Fig. 2F). Normalisation and weighting decisions were made in consultation with regional experts, and recorded in each permutation table for each unique combination of rules (Table 3).

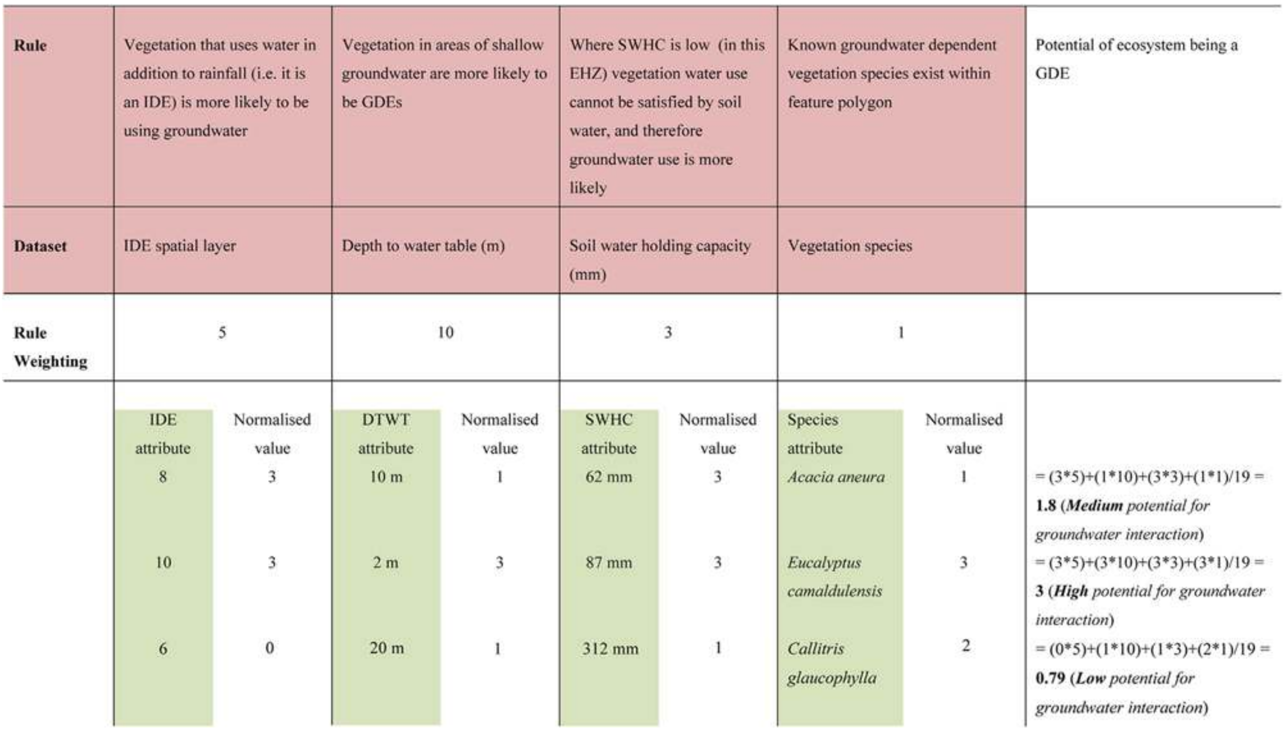
2.2.4. Normalisation

Normalisation of the attributes in each rule dataset involved assigning a rating of 0–3 to each attribute to represent the likelihood that the attribute indicates groundwater dependency. The rankings were assigned as 3, 2 and 1 where the attribute indicates a high, medium or low likelihood of groundwater interaction, respectively. A 0 ranking represented no data available.

To clarify the method undertaken, we provide an example from a vegetation asset feature layer intersection with four rule datasets available for an EHZ. Example rule datasets are inflow dependent ecosystem (IDE); depth to water table (DTWT); soil water holding capacity (SWHC); vegetation species (Table 3). The attributes within each rule dataset were normalised to indicate the likelihood of groundwater use. For example, the vegetation species *Acacia aneura* is unlikely to use groundwater (obtained from literature; O'Grady et al., 2009 where *A. aneura* only uses rainfall as a water source) and so was assigned a value of 1. *Eucalyptus camaldulensis* however, only maintains vigour when it can access groundwater, especially in the absence of other water sources (obtained from literature; Mensforth et al., 1994; Doody et al., 2009, 2015) and is thus normalized to 3, indicating a high likelihood of groundwater interaction. Similarly, shallow watertable, low soil water holding capacity and high IDE in this examples location (Murray-Darling Basin) indicate a high likelihood of groundwater interaction and were thus assigned values of 3. Deep watertable, high SWHC suggest that assets use alternative sources of water (e.g. soil water), while low IDE suggests that no additional water source is used other than rainfall. Hence, these attributes were assigned

Table 3

Example permutation table for derivation of GDE potential of hypothetical vegetation ecosystems. Red denotes the 'rules of GDE dependency' and associated 'rule datasets' being applied. Green denotes the GIS analysis attribute from the rule dataset that was assigned to each ecosystem polygon in the feature layer. The attribute indicates likelihood of groundwater dependency, and was normalised by assigning a value of between 0 and 3, where 3 indicates a high likelihood of groundwater dependence, and 1 indicates a low likelihood of groundwater dependence. Rule datasets were weighted so the most 'reliable' rules have the most influence on the derivation of GDE potential for each polygon. IDE is inflow dependent ecosystem, DTWT is depth to water table, SWHC is soil water holding capacity. In this example, the ecosystem polygon containing Eucalyptus camaldulensis, with lower soil water holding capacity, a shallow watertable and high IDE has the greatest potential of being a GDE. This final potential value (between 0 and 3) was divided into high, moderate and low categories by reviewing the data spatially and matching GDE likelihood to the occurrence of known GDEs and with the understanding of regional experts. The permutation table demonstrates the combination of attributes from rule datasets for each ecosystem polygon in the feature dataset being analysed. Thus, the permutation table contained as many combinations as there were ecosystem polygons in the feature dataset (For interpretation of the references to colour in this Table legend, the reader is referred to the web version of this article.).



Rule	Vegetation that uses water in addition to rainfall (i.e. it is an IDE) is more likely to be using groundwater		Vegetation in areas of shallow groundwater are more likely to be GDEs		Where SWHC is low (in this EHZ) vegetation water use cannot be satisfied by soil water, and therefore groundwater use is more likely		Known groundwater dependent vegetation species exist within feature polygon		Potential of ecosystem being a GDE
Dataset	IDE spatial layer		Depth to water table (m)		Soil water holding capacity (mm)		Vegetation species		
Rule Weighting	5		10		3		1		
	IDE attribute	Normalised value	DTWT attribute	Normalised value	SWHC attribute	Normalised value	Species attribute	Normalised value	
	8	3	10 m	1	62 mm	3	*Acacia aneura*	1	= (3*5)+(1*10)+(3*3)+(1*1)/19 = **1.8** (***Medium*** *potential for groundwater interaction*)
	10	3	2 m	3	87 mm	3	*Eucalyptus camaldulensis*	3	= (3*5)+(3*10)+(3*3)+(3*1)/19 = **3** (***High*** *potential for groundwater interaction*)
	6	0	20 m	1	312 mm	1	*Callitris glaucophylla*	2	= (0*5)+(1*10)+(1*3)+(2*1)/19 = **0.79** (***Low*** *potential for groundwater interaction*)

a normalised value of 1 to indicate a low likelihood of groundwater interaction. The process of normalization provides a means to convert all attributes within the rule datasets to a meaningful number for GDE determination.

2.2.5. *Weighting*

Weighting of each rule (Table 3) reflects the reliability of each rule (e.g. depth to groundwater) to identify GDEs as well as the accuracy of the rule dataset used in the analysis. Literature suggests that vegetation assets located over shallow groundwater (0–2 m) are highly likely to access groundwater at some stage over their life cycle and are thus GDEs (Canadell et al., 1996). As a result, the highest weighting in Table 3 is given to the 'depth to watertable rule'. Less reliable rules receive a lower relative weighting, such as soil water holding capacity (weighted 3 in Table 3) Depending on the processes that control groundwater interaction in each EHZ, the same rule may have a different weighting in individual EHZs.

Weighting the rules is an iterative process that uses ***known GDEs*** (i.e. GDEs identified in the literature) to calibrate the results. When the results identify ecosystems that are known GDEs as having 'high potential for groundwater interaction', the weighting was considered to be appropriate. Where known GDEs do not occur in an EHZ, the correct weighting was inferred from surrounding EHZs, logic, and expert opinion.

G. Calculation of GDE potential

Determination of GDE potential (Fig. 2G) employed the following formula;

$$GDE\ \ potential = \frac{(Rule\ \ 1\ x\ \ weighting) + (Rule\ \ 2\ x\ weighting) + (Rule\ \ 3\ x\ weighting) + (Rule\ \ 4\ x\ weighting)}{Sum\ \ of\ \ total\ \ weightings} \tag{1}$$

where Rule 1–4 are individual rule datasets for a vegetation or surface water ecosystem (Fig. 2D). The number of rules employed, is related to the number of rule datasets intersected with vegetation or surface water features. For example, four rule datasets are available in Table 3.

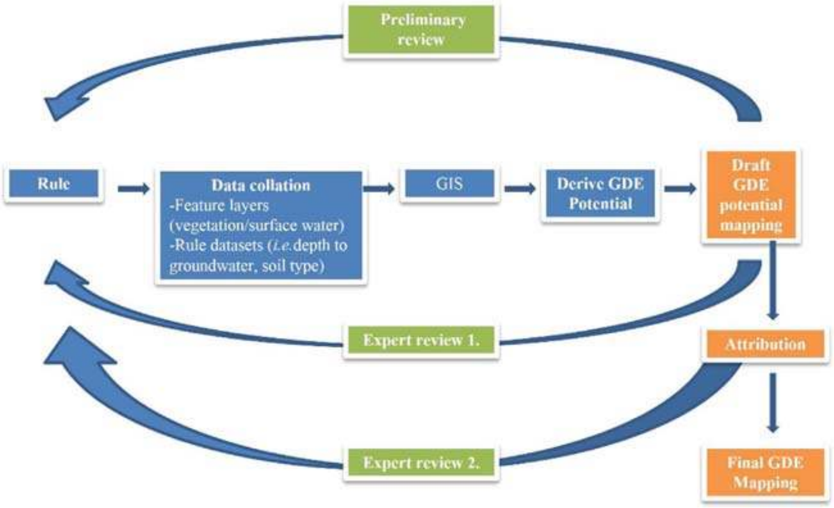


Fig. 5. Process undertaken to derive GDE potential of surface and subsurface GDEs incorporating rules of GDE dependency ('rule' in the above diagram), spatial data and expert knowledge.

Calculation of GDE potential for each unique combination of attributes (Table 3) was undertaken using Eq. (1) and 'rules of GDE dependency'. Eq. (2) expresses the calculation in relation to the example above (Table 3);

$$GDE\ \ potential = \frac{(IDE\ \ norm\ x\ weight) + (DTWT\ \ norm\ x\ weight) + (SWHC\ \ norm\ x\ weight) + (Species\ \ norm\ x\ weight)}{Sum\ \ of\ \ total\ \ weightings} \tag{2}$$

Where *IDE norm* is the normalised inflow dependent ecosystem potential, *DTWT norm* is the normalised depth to watertable, *SWHC norm* is the normalised soil water holding capacity and *species norm* is the normalisation of vegetation species based on literature and expert knowledge and its tendency to extract groundwater to meet its water requirements over its lifetime.

Example calculations of GDE potential are given in Table 3. *A. aneura*, *E. camaldulensis* and *Callitris glaucophylla* potential was determined as 1.8, 3.0 and 0.8 respectively. A GDE likelihood of 3, 2 or 1 represents a high, medium or low potential for groundwater interaction, respectively. This process was undertaken for derivation of both ecosystems that rely on the surface expressions of groundwater (rivers, springs, wetlands) and ecosystems that rely on the subsurface presence of groundwater (vegetation).

2.3. Validation of GDE potential and mapping of GDEs

Field validation could not be undertaken due to fiscal restrictions, however, GDEs identified in previous studies ('*known GDEs*') provided a level of validation, as all previous studies were assumed to be highly accurate. Maps identifying GDE potential of both surface water and vegetation GDEs were produced, after which substantial iteration was undertaken with expert opinion sought to critique rules, normalisation, weighting and final derivation of GDE potential in each EHZ (Fig. 5). Whilst known GDEs guided the development of the method reported to predict the location of GDEs, the method was also used to predict the location of the known GDEs to offer a level of validation of the process undertaken. In general, the method was accurate 90–95% of the time in predicting the location of known GDEs.

Expert opinion was critical to allow final mapping and also played an important validation role throughout development of the Atlas (Fig. 2). In addition, both the MODIS and Landsat methods were validated with field data prior to scaling up. For example, validation with flux towers and water balance estimates across Australia identified that there was a 10% chance that actual ET is more than 25% greater than the MODIS calculated ET and a 20% chance that it was more than 25% lower (van Dijk et al., 2015).

A number of attributes were assigned to describe the climate, landscape setting, water regime, and temporal and spatial nature of groundwater interaction for each ecosystem polygon within the GDE Atlas (Fig. 2H). These descriptive attributes also included: the number of rules used to derive results referred to as 'lines of evidence'; the IDE value; scientific references; geologic setting; rule dataset attributes such as depth to water and vegetation species; and finally GDE potential.

3. Results

A number of innovative continental scale products were developed within the reported development of the GDE Atlas. Key outputs include the development of rules of groundwater dependence, national potential GDE layer and additional national remote sensing products to help identify potential GDEs at finer resolution.

Table 4
Area of surface (rivers, lake, springs) and subsurface (vegetation) GDEs across Australia.

GDE likelihood	Area (km^2)	Area of Australia (%)
Ecosystems that rely on surface expression of groundwater		
Identified in previous study	12,714	0.16
High potential for groundwater interaction	86,110	1.12
Moderate potential for groundwater interaction	66,774	0.87
Low potential for groundwater interaction	52,748	0.69
Total	**218,346**	**2.84**
Ecosystems that rely on the subsurface presence of groundwater[a]		
Identified in previous study	2,015	0.03
High potential for groundwater interaction	302,144	4.00
Moderate potential for groundwater interaction	629,104	8.19
Low potential for groundwater interaction	1,467,779	19.08
Total	**2,401,042**	**31.00**

Total areas are indicated in bold text.
[a] Subsurface GDEs were not mapped in the Northern Territory due to lack of data.

3.1. Rules of groundwater dependence to aid GDE identification

Conceptual rules of groundwater dependence were developed for both vegetation and surface water features, based on literature and expert knowledge (Table 1). Development of these rules was instrumental in providing a method to allow integration of field knowledge with spatial analysis followed by regional scaling. Rules were specific to each EHZ and provide only guidelines relevant to Australian landscapes. Independent rule development would be required for other continents, however, the general theory behind each rule is likely to be applicable. Detailed logic for each rule can be obtained from SKM and CSIRO, 2012.

3.2. Potential groundwater dependent ecosystems

The Atlas presents two mapped groundwater dependent ecosystem products which indicate ecosystems which rely on both the subsurface (Fig. 6A) and surface (Fig. 6B) expression of groundwater and known subterranean GDEs (data not shown).

Within these maps, derived GDEs were classified in order of their potential for groundwater interaction in five classes. GDEs identified through field and/or desktop research represent a greater potential for groundwater interaction since detailed work at the local scale has identified groundwater interaction for these ecosystems. Remaining classes include high, medium and low potential for groundwater interaction.

An attribute table accompanies the classification, describing the ecosystem setting and groundwater interaction. The attribute table is consistent with the Australian National Aquatic Ecosystem framework (Auricht, 2010) and was created as a living document for future update. The attribute table is available within the online GDE Atlas platform.

The product results are available online via the Bureau of Meteorology (http://www.bom.gov.au/water/groundwater/gde/map.shtml), using an interactive interface which allows fine scale observation and data extraction. It must be noted here, that the estimates of national GDE coverage do not include vegetation GDEs in the Northern Territory as regional scale vegetation mapping (feature layer) was not available for that State at the time of development.

3.2.1. Potential GDEs across Australia

Of Australia's area (7.7 M km^2), a total of 218, 346 km^2 (~3% of Australia's land area) of surface water assets have been analysed for groundwater dependence using the framework and methods presented. The majority of these were classified as having a medium to low potential for groundwater interaction (Table 4) with 1% identified as high probablilty. A large proportion of the potential GDEs reside in south eastern Australia and Queensland, indicative of extensive river and wetland systems throughout those regions (Fig. 6A). A further 31% of Australia's land surface is occupied by vegetation assets, with a large proportion of those having a high potential for groundwater interaction (4%) occupying an area of over 300,000 km^2 (Table 4; Fig. 6B). The majority of the vegetation assets are however classified as having a low potential for groundwater interaction, and are therefore unlikely to be GDEs.

3.3. Additional remote sensing products

3.3.1. MODIS potential inflow dependent (ID) landscapes

A national 250 × 250 m MODIS remote sensing layer was produced to identify where inflow in excess of rainfall occur across the landscape, as determined by the ratio of ET to rainfall (Fig. 7A). In tropical regions however, rainfall often exceeds ET due to monsoon rain volumes however, some monsoonal rivers in tropical Australia would not permanently flow without groundwater inputs during the dry season, indicating the presence of GDEs (Eamus and Froend, 2006; Lamontagne et al.,

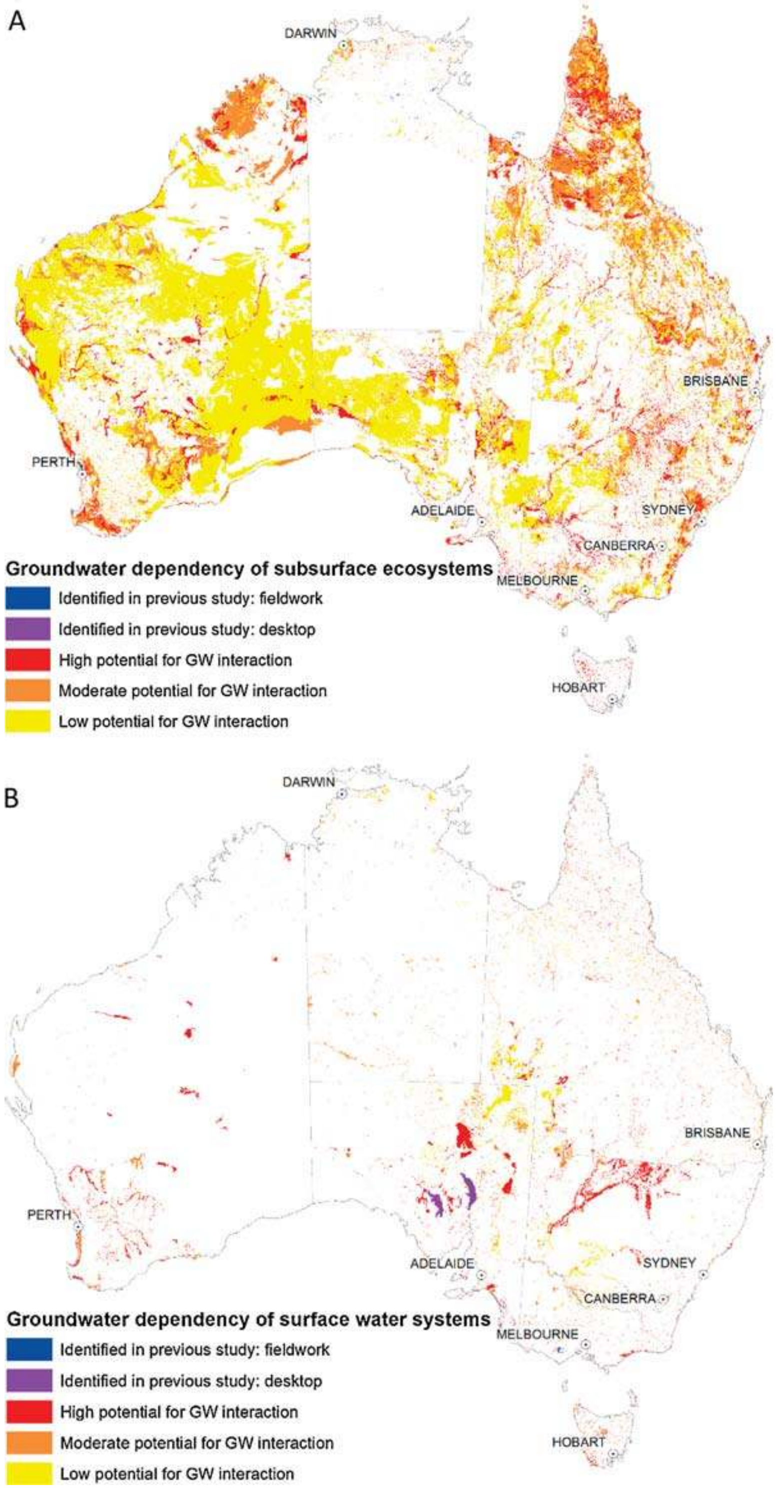


Fig. 6. Final map products demonstrating potential (A) ecosystems that rely on the subsurface presence of groundwater including vegetation and (B) ecosystems that rely on surface expression of groundwater such as rivers, lakes, wetlands and springs. Ecosystems are classified as known or those with a high, medium and low potential for groundwater (GW) interaction. Images are 25 m pixel resolution.

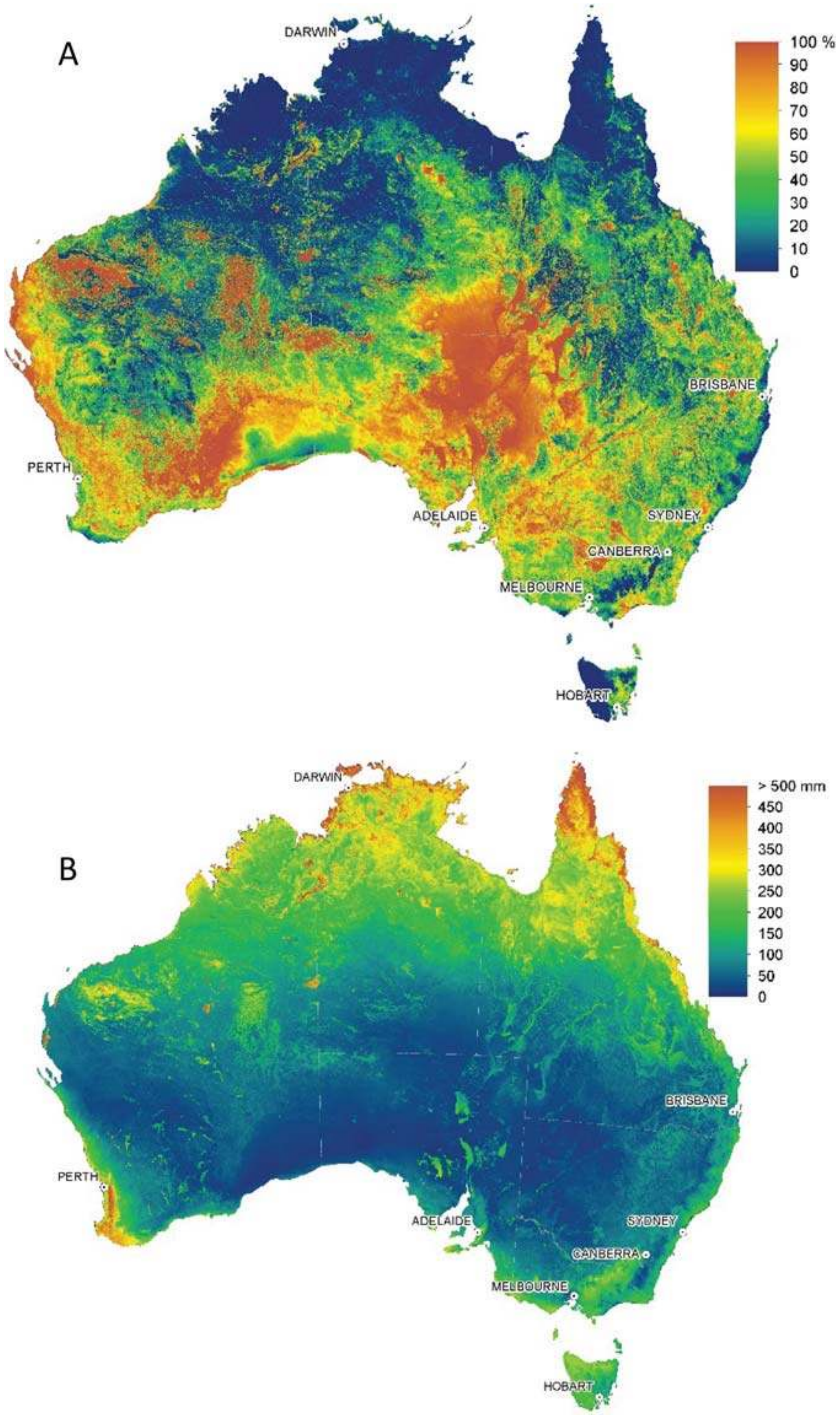


Fig. 7. (A) Estimated inflow dependence probability (ID Product). The higher the probability, the higher the chance a landscape accesses water from an alternate source from rainfall. (B) Estimated mean seasonal storage range (MSSR). Large storage range is indicative of an additional water source other than rainfall. Images are 250 m pixel resolution.

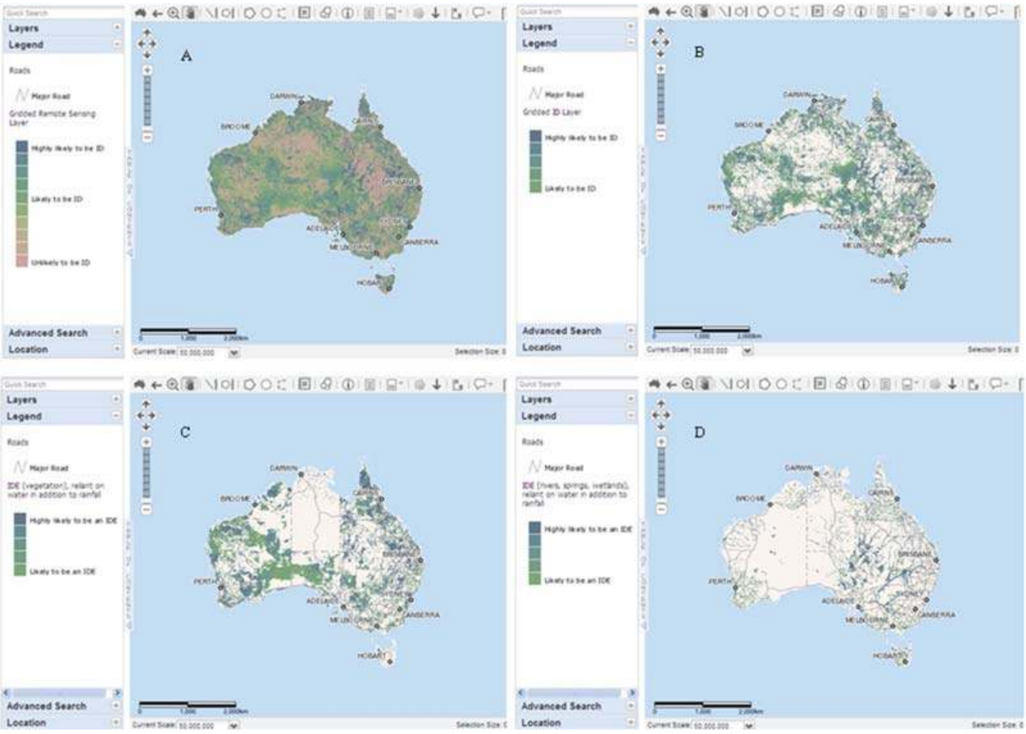


Fig. 8. The Atlas of Groundwater Dependent Ecosystems screen snapshots showing integration of MODIS and Landsat remote sensing to create (A) gridded remote sensing layer – likelihood of 1–10; (B) gridded inflow dependent landscape layer – likelihood of 6–10; (C) Inflow dependent ecosystem (IDE) polygons with a majority rules IDE likelihood per ecosystem of 6–10 for vegetation and (D) Inflow dependent ecosystem (IDE) polygons with a majority rules IDE likelihood per ecosystem of 6–10 for rivers, springs and wetlands. Images are 25 m pixel resolution.

2005). The MSSR (mean seasonal storage range) layer was created (Fig. 7B) to indicate areas with a large soil storage range, which is indicative of an additional water source in tropical regions. This product is not available online.

3.3.2. *Landsat and MODIS integration – the ID product*

Vegetation cover across Australia was classified as having either permanent, diminishing or no access to groundwater (data not shown) using Landsat. An additional four remote sensing products were derived from the integration of the Landsat and MODIS products. MODIS was important to provide temporal variability, however its spatial resolution of 250 m could not identify small ecosystems and wetland areas. Conversely, Landsat provides 30 m resolution (resampled to 25 m) with poor temporal resolution indicating integration could harness the strengths of both methods. Of the four layers produced, two are raster layers (25 m pixel resolution) and two are polygon 'ecosystem' layers. All are available within the online GDE Atlas (Fig. 8).

The pID product (Fig. 8A) presents integrated MODIS and Landsat data resampled to 25 m × 25 m. Pixels have a probability rating between 1 and 10, with 10 indicating high probability of inflow dependence by receiving water from an additional source other than rainfall (i.e. groundwater, surface water). Values below 6 indicate a reliance solely on rainwater. The probability rating is based on the following five criteria:

- The volume of evapotranspiration relative to rainfall (MODIS)
- The relative volume of dry season water use (MSSR – MODIS)
- The ephemeral presence of surface water (Landsat and MODIS)
- Vegetation activity during dry periods (Landsat)
- Similarity between spectral response to known alpine GDEs (Landsat)

A second product, generated from the pID layer, displays only landscapes that are likely to be inflow dependent and have a probability between 6 and 10 at 25 m pixel resolution (Fig. 8B).

Inflow dependent ecosystems (IDEs) – ecosystems likely to be accessing an additional water source, were derived after intersection of vegetation and surface water feature layers with the ID product (Fig. 8B). Two layers were created which identify vegetation IDEs (Fig. 8C) and river, spring and wetland IDEs (Fig. 8D).

Although individual MODIS and Landsat products are not available in the online Atlas, the combined national scale remote sensing layers described in this section (Fig. 8), provide pixel by pixel detail in the pID (Fig. 8A and B). As a result of the scaling method to produce the IDE product, large vegetation polygons were used, so much of the pixel level detail was diluted (Fig. 8C and D). The pixel level detail provided in the GDE Atlas (Fig. 8A and B), therefore provides a resource to guide natural resource managers to undertake detailed studies if a potential groundwater threat is identified in a region where GDEs could not formally be identified in the first iteration of the GDE Atlas. This resource is a major advance in terms of fine scale data availability to guide and inform hydrological and natural resource management decisions.

4. Discussion

A pragmatic approach was taken to identify, classify and map GDEs as best as possible nationally in Australia, by integrating knowledge from hydrology, hydrogeology, ecology and participatory expert opinion. The methods and framework presented are potentially applicable worldwide. However, some caution is warranted as Australia has invested significant resources into identifying local GDEs over the preceding two decades whereas there is likely to be a paucity of local GDE knowledge in other parts of the world. The knowledge in relation to these known GDEs, proved instrumental in the scaling process.

As competition for water increases in the future, provision of water to maintain aquatic and terrestrial ecosystem functions, biodiversity and ecosystem services will continue to pose challenges to water resource management. Worldwide, consumptive water use and climate change continues to deplete water resources from natural systems such as the Colorado and Murray-Darling River Basins, with continuing biodiversity losses (Vörösmarty et al., 2010). The GDE Atlas provides a first step in facilitation of GDE protection nationally, providing new information to aid water resource management. An estimated 34% of Australia's landscape is potentially occupied by GDEs, providing strong justification for the need to protect GDEs. Acreman (2005) outlines a two tiered approach to groundwater management, where an understanding of regional and local impacts of groundwater exploitation is required to develop integrated groundwater management plans. Acreman (2005) suggests initial scoping at regional level is required to identify potential GDEs across a target exploration area which may be vulnerable to impacts of groundwater exploitation, followed by focused local-level investigations to elucidate groundwater processes and interactions between ecosystems, geology and hydrology and ecological response functions. Local investigations can highlight how GDEs might be threatened by extraction or changes in water regime to allow development of strategies to aid the understanding of groundwater resource exploitation by water managers and ensure protection. The GDE Atlas framework provides a means to undertake such regional scale assessments, highlighting presence and extent in areas targeted for new, continued or increased groundwater abstraction. Additionally, targeted local to catchment research can then be undertaken to investigate groundwater and surface water processes and ecohydrological interactions as demonstrated by Glanville et al. (2016).

4.1. Role of GDE Atlas in protection of GDEs nationally

It is anticipated the GDE Atlas will play a role in informing users where groundwater requirements of ecosystems should be considered for management and protection purposes by identification of GDEs. However, the degree and timing of groundwater dependency remain important issues as applicable management options are influenced by these factors (Murray et al., 2003). Additionally, groundwater processes and groundwater-surface water interactions may be site specific requiring improved localised knowledge in high risk areas to understand the relationships between the groundwater regime and water requirements of associated GDEs (Boulton, 2005). The GDE Atlas therefore provides a broad overview of GDE location nationally but should only be considered a first step in aiding water resource planning and management. Further local scale field based or desktop research is required employing tools presented in Richardson et al., 2011. This especially important in high risk locations subject to hydrological extraction and/or mining, to understand the links between GDEs, their water requirements and their hydrogeological and ecohydrological setting as suggested by Acreman (2005).

The GDE Toolbox assessment framework (the Toolbox; Richardson et al., 2011) answers local questions such as 'where are ecosystems that use groundwater?' and 'what are the broad GDE types and functional grouping?' The Toolbox provides practical and robust tools to undertake further investigation of local-scale GDEs under approaches such as that suggested by Acreman (2005), to determine local ecosystem reliance on groundwater and develop appropriate ecological water requirements for consideration in environmental water provisions and water resource plans. The Risk Assessment and Decision Making Framework for Managing Groundwater Dependent Ecosystems (Chambers et al., 2013) aims to aid prioritisation to protect GDEs by assessing the risk of potential impacts of proposed groundwater abstraction. Once the hydrology of a system is understood, 'safe' or 'sustainable' groundwater yields which will balance long-term withdrawal of groundwater and recharge to meet both human and environmental water use, can be established (MacKay, 2006). Although these tools have been developed for use in Australia, they are likely to be broadly applicable internationally.

Management of surface water dependent ecosystems, such as rivers, floodplains and lakes, has advanced through the provision of environmental flows based on thresholds and water requirements from surface water measurements. The provision of adequate groundwater resources and protection of GDEs lags due to the predominantly underground nature of the resource, with limited hydrogeological data leading to a lack of confidence in locating and quantifying GDEs. Development of the GDE Atlas aids our understanding of GDE distribution nationally and facilitates further investigation at local scales to improve our understanding of ecosystem water requirements. Providing regional managers and water planners with information on the location and type of GDEs will facilitate the inclusion of associated underground water resources into integrated water resource management plans. Identifying ecosystems such as GDEs improves the ability to manage them by incorporating recharge requirements and abstraction limits.

4.2. Key limitations and contributions

As a consequence of the method employed, there are a number of limitations to the final GDE mapping. In particular, the broad scale approach may not have identified GDEs smaller than 25 × 25 m as highlighted using remote sensing. Wetlands in particular, consist of a range of sizes and are highly distributed across the landscape, supporting various groundwater dependent aquatic and terrestrial species.

The GDE Atlas provides a snapshot in time and whilst the influence of temporal variability is included, it is from 2000 to 2010 as per the remote sensing data collection period. Ecosystems using groundwater outside this period may not have been identified if their groundwater use over the period of spatial data availability within the project was negligible. Additionally, GDEs affected by salinity and drought are unlikely to be identified if their vegetation response was in decline during 2000–2010, unless expert knowledge brought this into consideration. Long-term drought had a significant impact on riparian vegetation condition across south-eastern Australia during the first decade of the 21st Century (van Dijk et al., 2013).

Issues with feature layer datasets (e.g. vegetation) such as limited coverage, large polygons, incomplete datasets and maps that end at state boundaries were also limitations. Where limited coverage and incomplete datasets occur, GDEs were not mapped in the GDE Atlas. An important legacy of the remote sensing of inflow dependence, is an ability to identify areas where an additional water source is likely to be accessed when ecosystem polygons are not available (Fig. 8A and B). Use of the ‘majority rules’ approach is limiting when only large ecosystem polygons were available, as greater landscape variation is expected within larger areas (Fig. 8C and D). It is important to understand that the GDE Atlas displays ecosystem polygons where groundwater interaction may be occurring and while caution related to groundwater changes may be required within that polygon, it does not suggest all vegetation within the polygon depends on groundwater.

A future limitation of the GDE Atlas is likely to develop if regular updating to incorporate new expert knowledge and refined ecosystem mapping is not undertaken. While the Atlas may provide the stimulus to undertake local GDE studies, it will rapidly become outdated if new knowledge is not incorporated to improve reliability. It was decided that a five yearly update may be suitable, for example, if one of the primary contributions of the GDE Atlas is to stimulate research. This timeframe would allow a suitable duration for new local scale studies to be completed and provides a modest period over which income can be sought to fund an update. The literature review and collation of spatial data for this first iteration of the Atlas occurred in 2010 and considerable data is likely to have been generated since. A partial update is planned in 2016–17, to capture new information and the ensure longevity of the online product.

Future research effort should investigate development of a finer scale (sub 10 m) national spring database to address current knowledge gaps in the Atlas and add value to water resource and groundwater management as these areas directly indicate groundwater presence and GDE status. More investment and effort is required to map depth to groundwater nationally and continual improvement in vegetation mapping is required nationally. Vegetation mapping is limited for most of Northern Territory and parts of New South Wales and of poor resolution in other regions. Likewise, field studies and desktop studies have not been undertaken in 13 EHZ’s across Australia (data not shown). Jurisdictions are now aware of areas which may require additional future resource investment to provide mapping or field studies to elucidate GDEs. The impact of these data gaps are currently being acknowledged, especially in New South Wales where significant investment is underway to address vegetation mapping gaps, to then map GDEs at a finer spatial resolution. Overtime, the inclusion of additional fine scale literature and map products will improve the results of the GDE potential mapping products, as GDE calculations undertaken in each EHZ can be refined.

Inclusion of expert opinion and engagement of local experts throughout the process of the GDE Atlas development proved critical to provide valid mapping of ecosystems dependent on groundwater nationally. In the initial stages, experts provided spatial layers and guided access to literature, whilst contributing to robust discussion to derive acceptable definitions pertaining to identification of GDEs. The expert’s knowledge of local processes was invaluable to facilitate development of the ‘rules of GDE dependency’, and feedback from them was essential subsequent to rule analysis and final derivation of GDEs, to ensure that areas of GDEs and their potential were represented appropriately.

5. Conclusion

The GDE Atlas is the first national spatial inventory, which illustrates both known and modelled potential GDEs in Australia, across diverse climates and landscapes. Better management of GDEs is required to improve their current condition worldwide and to protect these vulnerable ecosystems from further exploitation. While consideration of surface water requirements and environmental flows has advanced to manage surface water dependent ecosystems, provision of adequate groundwater resources and protection of GDEs lags. This is attributed largely to the predominantly underground nature of the resource, leading to a lack of confidence in locating and quantifying GDEs.

Development of the National Atlas of Groundwater Dependent Ecosystems for Australia aids our understanding of GDE distribution nationally and facilitates further targeted investigation at local scales to improve our understanding of groundwater regimes and water requirements. Providing regional managers and water planners with information on the location and type of GDEs facilitates the inclusion of these underground water resources into integrated water resource management plans. Identifying GDEs improves the ability to manage them by incorporating recharge requirements and abstraction limits above any surface water requirements already identified. The approach taken here can be broadly used in other countries worldwide, and is especially important for remote locations or areas with low data availability. The Australian Atlas of Groundwater Dependent Ecosystems can be found at http://www.bom.gov.au/water/groundwater/gde/map.shtml.

Conflict of interest

There is no conflict of interest in relation to the manuscript Continental mapping of groundwater dependent ecosystems: a methodological framework to integrate diverse data and expert opinion.

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Appendix A. Collated feature layer datasets (ecosystem layers) and GIS analysis datasets. DECC is Department of Environment and Climate Change; DSE is Department of Sustainability and Environment; DPI is Department of Primary Industries; NTG is Northern Territory Government; DEWNR id Department Environment and Natural Resources; Qld EPA is Queensland Environmental Protection Agency; DERM is Department of Environment; DEC is Department of Environment and Conservation; DoW is Department of Water; DPIPWE is Department of Primary Industries, Parks, Water and Environment.

State	Ecosystem	Description	Custodian
NSW	Vegetation	Vegetation mapping for NSW	NSW Office of Water
NSW	Vegetation	Murray-Darling Basin (VISmap)	DECC
NSW	Vegetation	Namoi region vegetation mapping	NSW Office of Water
NSW	Vegetation	Central west Lachlan vegetation mapping	NSW Office of Water
NSW	Vegetation	South coast vegetation mapping	OEH
NSW	Vegetation	Alstonville vegetation mapping	NSW Office of Water
NSW	Vegetation	Blackville vegetation mapping	NSW Office of Water
NSW	Vegetation	Wollemi vegetation mapping	NSW Office of Water
NSW	Vegetation	West Blue Mountain vegetation mapping	NSW Office of Water
NSW	Wetlands	NSW wetlands mapped in 2006	DECC
NSW	Springs	High priority point GDEs 2011	NSW Office of Water
NSW	Springs	Blue Mountain swamps	Blue Mountain City Council
NSW	Springs	Spring point locations	DECC
NSW	River	Alstonville stream buffer	NSW Office of Water
NSW	River	High priority GDE line 2011	NSW Office of Water
NSW	River	National water courses	Geoscience Australia
Vic	Vegetation	Ecological vegetation classes. Vegetation mapping for Victoria	DSE
Vic	Vegetation	Alpine bog and wetland mapping	DSE
Vic	Wetland	Wetland mapping in 1994 for Victoria	DSE
Vic	Springs	Mapping of mineral springs in Victoria	DSE
Vic	Springs	Springs	DPI
Vic	River	Watercourse mapping Victoria	DSE
Vic	River	National watercourses	DPI
NT	Vegetation	Greater Darwin vegetation mapping	NTG
NT	Vegetation	National Vegetation Information System 2005	NTG
NT	Vegetation	*Livistonia mariae* vegetation distribution	NTG
NT	Wetlands	Wetlands inventory 2000–2001	NTG
NT	Wetlands	Geodata lakes	Geoscience Australia
NT	Wetlands	Geodata flats and swamps	Geoscience Australia

NT	Wetlands	Stirling Swamp mapping	NTG
NT	Wetlands	Unknown description (Dataset name Snt_allwb_g94)	NTG
NT	Wetlands	Unknown description (Dataset name Ground_sites_g94)	NTG
NT	Springs	Springs 2009	NTG
NT	Springs	Geodata springs	Geoscience Australia
NT	Springs	Watersites (Wadeye250)	NTG
NT	Springs	Springs and groundwater fed waterholes	NTG
NT	River	River mapping	NTG
NT	River	Gulf of Carpentaria river mapping	NTG
SA	Vegetation	South Australian vegetation data	DEWNR
SA	Wetland	State-wide wetlands GDE mapping in 2010	DEWNR
SA	Wetland	Wetland GDE classification	DEWNR
SA	Rivers	State-wide wetlands GDE mapping in 2010	DEWNR
SA	Rivers	Watercourse 250k mapping	DEWNR
SA	Springs and waterholes	Gazetteer aquatic ecosystem mapping	DEWNR
SA	Springs	Great Artesian Basin springs	DEWNR
SA	Springs	Springs mapped in Flinders Ranges	DEWNR
QLD	Vegetation	Queensland remnant vegetation mapping	DERM
QLD	Vegetation	CRC tropical vegetation	Qld EPA
QLD	Wetland	Queensland wetland system – 100k	DERM
QLD	Springs	Springs mapping	DERM
QLD	River	National watercourses	Geoscience Australia
WA	Vegetation	Pre-european vegetation mapping	DEC
WA	Vegetation	Vegetation complexes	DEC
WA	Vegetation	Rangeland land system mapping	DEC
WA	Vegetation	Subsystems north	DEC
WA	River	River mapping	DoW
WA	Wetlands	Geomorphic wetlands Swan Coastal Plain	DEC
WA	Wetlands	Geomorphic wetlands Augusta to Walpole	DEC
WA	Wetlands	Geomorphic wetlands Cervantes South	DEC
WA	Wetlands	Geomorphic wetlands Darkin	DEC
WA	Wetlands	Geomorphic wetlands Cervantes Eneabba	DEC
WA	Wetlands	Wheatbelt wetlands	DEC
WA	Wetlands	Directory of Important wetlands	DEC
WA	Wetlands	Southeastern Coast wetlands	DoW
WA	Springs	Potential GDE points	DoW
WA	Pools	Pilbara pools mapping	DoW
Tas	Karst	Mapping of karst regions 2008	DPIPWE
Tas	Wetlands	Mapping of wetland regions 2008	DPIPWE
Tas	Waterbodies	Mapping of waterbodies and streams 2008	DPIPWE
Tas	Vegetation	Tasmanian vegetation mapping	DPIPWE
Tas	Vegetation	World Heritage Area vegetation mapping	DPIPWE
Tas	Springs	Mapping of springs 2008	DPIPWE
Tas	Springs	Mapping Smithton Mound Springs	DPIPWE
Tas	Springs	Northwest incised basalt plateau predicted springs	N/A
Tas	Burrowing Crayfish	Mapped locations of Burrowing Crayfish in Tasmania	DPIPWE

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