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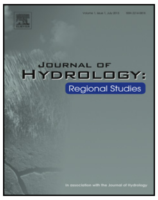

# Continental mapping of groundwater dependent ecosystems: A methodological framework to integrate diverse data and expert opinion

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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),