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Methods for the identification of high probability groundwater dependent vegetation ecosystems

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Foreword

The identification and monitoring of groundwater dependent ecosystems (GDEs) are required to meet DPI Water's legislative requirements under the *Water Management Act 2000* and associated Water Sharing Plans (WSPs), and the Basin Plan 2012. To fulfil these requirements DPI Water has put in place a program to identify and monitor groundwater dependent ecosystems (GDEs).

DPI Water defines ecosystems that depend on groundwater as those '*ecosystems that require access to groundwater to meet all or some of their water requirements so as to maintain their communities of plants and animals, ecological processes and ecosystem services'* (modified from Richardson et al. 2011).

The development of a broad scale catchment spatial model has been attempted by various state governments (Rutherford et al. 2005; Dresel et al. 2010; Harding and O'Connor 2012; QLD Department of Science, Information Technology and Innovation 2015) and nationally, in the GDE Atlas (SKM 2012).

This project has aimed to build upon the previous methods used by other states and the National GDE Atlas to provide more rigor and confidence in the final modelled GDEs mapped within NSW. The process adopted here has used various data sets and scientific knowledge to build a complex model based around certain assumptions and conservative decision matrices.

The purpose of this report is to provide the methods used to develop and refine the spatial model for the identification and mapping of high probability GDEs.

This report focuses on terrestrial vegetation GDEs, and does not cover other potential GDEs such as wetlands, stygofauna, and baseflow. Although some wetlands are included here, it is important to note that only those mapped as vegetation units were considered. Additional analysis of wetland mapping is required to identify all types of groundwater dependent wetlands.

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1 Introduction

Knowledge of the relationship between groundwater and their dependent ecosystems is presently limited in Australia (Tomlinson 2011). Current research has largely concentrated on the identification of site specific GDEs and water use requirements. Some broad scale mapping of GDEs has been completed using remote sensing, and supporting information, in Victoria (Dresel et al. 2010), Queensland (QLD Department of Science, Information Technology and Innovation 2015), Western Australia (Rutherford et al. 2005), South Australia (Harding and O'Connor 2012) and, nationally, in the GDE Atlas (SKM 2012). A detailed literature review is presented in Section 2.

The identification of broad scale GDEs is challenging (Eamus et al. 2015; Eamus and Froend 2006), largely due to limited spatial information available with respect to landscape data sets such as vegetation/wetland types, geology, soil information and water table mapping. Additionally, the use of remote sensing to capture data on groundwater dependence probability is an emerging field (Eamus et al. 2015).

The ability to directly measure groundwater use by vegetation requires site specific information on various indicators such as plant physiology information on water use, groundwater depth and identification of source water. At a regional scale this is both impractical and cost prohibitive.

This project has therefore used various data sources as indirect indicators of groundwater use by vegetation. Published scientific knowledge has also been used to identify communities that potentially have a reliance on groundwater.

Data sources used in identifying potential groundwater dependent terrestrial and wetland ecosystems included existing vegetation mapping data sets, monitored real time groundwater level data for the shallowest water levels to create contours and remote sensing analysis of where vegetation might use a water source other than soil moisture.Using these data sources, the identification of potential GDEs was based on a number of probability matrices. These matrices were developed to allow the spatial model to provide outcomes that separated the vegetation into high, medium and low probability of being groundwater dependent.

1.1 Legislation

The protection and enhancement of all water dependent ecosystems, including GDEs, falls under the legislative requirements of the *Water Management Act 2000* (WMA). This legislation provides for the management of water resources in a sustainable and integrated manner for the benefit of both present and future generations. In regards to water dependent ecosystems, the WMA provides for the following sub-surface requirements in particular:

a. Applying the principles of ecologically sustainable development;
b. To protect, enhance and restore water sources, their associated ecosystems, ecological processes, biological diversity and their water quality;
c. To recognise and foster the significant social and economic benefits to the State that result from the sustainable and efficient use of water; and
d. To integrate the management of water sources with the management of other aspects of the environment, including the land, its soils, its native vegetation and its native fauna.

The NSW State Groundwater Dependent Ecosystems Policy (Department of Land and Water Conservation 2002) implements the WMA by providing guidance on the protection and management of GDEs. The policy sets out management objectives and principles to:

a. Ensure that the most vulnerable and valuable ecosystems are protected;
b. Manage groundwater extraction within defined limits thereby providing flow sufficient to sustain ecological processes and maintain biodiversity;

c. Ensure that sufficient groundwater of suitable quality is available to ecosystems when needed;
d. Ensure that the precautionary principle is applied to protect groundwater dependent ecosystems, particularly the dynamics of flow and availability and the species reliant on these attributes; and
e. Ensure that land use activities aim to minimise adverse impacts on groundwater dependent ecosystems.

Water Sharing Plans (WSPs) for each area include provisions for the protection of GDEs from current and future groundwater extraction via distance rules. GDEs are listed and/or mapped in the Plan's schedule.

The Basin Plan identifies water resource planning as one of the strategies for managing or addressing risks to the condition, or continued availability, of water resources. Section 10.18 of the Basin Plan requires that a water resource plan (WRP) for groundwater to be prepared with regard to priority environmental assets dependent on groundwater. The identification of GDEs and an assessment of risk to GDEs from groundwater extraction are required to inform the management rules within the WRP which are prepared for each groundwater source in the Murray-Darling Basin (MDB).

1.2 Groundwater dependent ecosystems defined

DPI Water defines ecosystems that depend on groundwater as those '*ecosystems that require access to groundwater to meet all or some of their water requirements so as to maintain their communities of plants and animals, ecological processes and ecosystem services'* (modified from Richardson et al. 2011).

Groundwater dependent ecosystems (GDEs) require groundwater to maintain their composition and functioning. The removal or change in groundwater availability or quality will influence the composition, structure and function of these ecosystems (Eamus et al. 2006b). Groundwater dependent vegetation do not rely on the surface expression of water to maintain ecosystem function. Instead, the vegetation depends on the sub-surface presence of groundwater, often accessed via the capillary fringe or vadose zone (i.e. the subsurface water just above the water table that is not completely saturated) (Naumburg et al. 2005; Eamus et al. 2006a). Plant species within a community may exhibit differing degrees of groundwater dependency (Hatton and Evans 1998) and can range from obligate (total/entire) to facultative (partial and infrequent (i.e. seasonal/episodic)) (Zencich et al. 2002; Eamus et al. 2006b; Froend and Drake 2006).

Wetlands identified as being groundwater dependent can be either ephemeral or permanent systems that have a continuous or seasonal connection with groundwater (Howe et al. 2007). Wetlands are considered dependent on groundwater if the presence of groundwater is essential to the biota and ecological processes of that wetland (Howe et al. 2007).

Many factors influence an ecosystem's ability to access and use groundwater (Figure 1). A strong relationship between groundwater use, topography, and available soil moisture, rooting depth/root system distribution, depth to water table, water quality and climate has been demonstrated in various studies (e.g. Cresswell and Bridgewater 1985; Dodd and Heddle 1989; Griffith and Wilson 2007). Where possible, these factors were considered in formulating the decision rules used to identify those ecosystems that are likely to be dependent on groundwater.

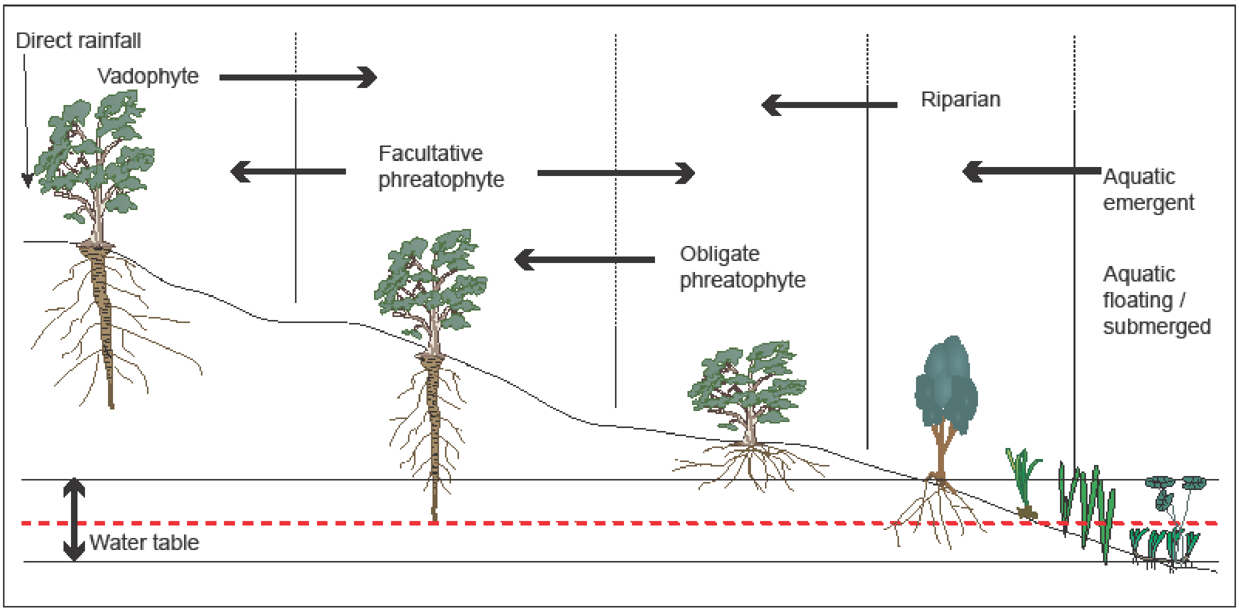

Figure 1: Relationship between vegetation and access to groundwater (from Pettit et al. 2007).

Where (a) refers to species that rely on soil moisture within the vadose zone; (b) refers to species for which groundwater dependence is opportunistic; (c) refers to species that rely totally on groundwater.

NB: Most symbols for diagrams courtesy of the Integration and Application Network (ian.umces.edu/symbols), University of Maryland Center for Environmental Science

1.3 Structure of report

This report details the methods used in the development of the spatial model for the identification of probable GDE locations, as per the following sections:

- Section 2 - Literature review.
- Section 3 - Information on the data sets used and information on the decision rules developed for the development of the model.

  The datasets included:

  1. Remote sensing derived data providing information on potential groundwater use by vegetation over a ten year period;
  2. Vegetation community mapping data; and
  3. Groundwater level data.
- Section 4 - Results of the model.
- Section 5 – Limitations.
- Section 6 - Discussion and recommendations for further work.
- Section 7 - References.

Additional information is included in Appendix 1 on level 3 decision rules.

2 Literature review

2.1 Types of GDEs identified in this report

Phreatophytes are terrestrial vegetation that are dependent on the sub-surface presence of groundwater and is often accessed via the capillary fringe or vadose zone (i.e. the sub-surface water just above the water table that is not completely saturated [Naumburg et al. 2005; Eamus et al. 2006a]). Wetlands identified as being groundwater dependent can be either ephemeral or permanent systems that have a continuous or seasonal connection with groundwater (Howe et al. 2007). Wetlands are considered dependent on groundwater if the presence of groundwater is essential to the biota of that wetland and their ecological processes (Howe et al. 2007). This report only identifies wetlands as groundwater dependent, where they are mapped as a vegetation community.

2.1.1 Groundwater dependent terrestrial vegetation

Trees mostly take up groundwater from the capillary fringe as oxygen is required for plant respiration. The direct uptake from the water table is difficult for roots to grow and function under saturated conditions (Naumburg et al. 2005; Eamus et al. 2006a).

As water is removed by transpiration it is continually replenished from the water table through capillary rise. The rise and fall of the capillary zone reflects the rise and fall of the water table. The height of the capillary zone depends largely on soil type; ranging between 40 and 50 cm in sandy soils and between 1.5 – 2 m in heavy clay soils (Eamus et al. 2006a).

Groundwater, for many terrestrial plants, forms only part of the overall water requirement, particularly where rainfall is seasonal and soil water is regularly replenished (Howe et al. 2007). Vegetation will extract water from sources where the combination of soil moisture content, root density and hydraulic connectivity requires the least amount of energy. This means that vegetation will use shallow soil water first before seeking deeper soil water or groundwater (Eamus and Froend 2006). Where there is insufficient soil water for plant physiological requirements, plants will become increasingly dependent on available groundwater as soil water is depleted (Howe et al. 2007).

Some plants can adapt to changes in groundwater levels by extending root networks to greater depths. The ability of how well root systems can transport water will depend on the relative change in depth of the accessible groundwater. If the maximum rooting depth of a species is shallower than the groundwater depth then, groundwater cannot be accessed as a water source. Groundwater may still be available via hydraulic lift, particularly for deeper-rooted species (Eamus and Froend 2006).

When groundwater levels decline at a rate that exceeds the capability for root growth, the plant will be stranded and then must rely on other sources of water such as rainfall and residual soil moisture (Dillon et al. 2009). '*Differences between species can however limit the capacity of plants to rapidly switch to shallower soil water (if it is there), meaning that each species will be uniquely affected by declines in groundwater levels*' (Naumburg et al. 2005). Therefore, even if a species can still access groundwater, there are transport limitations (which vary between species) which may reduce water availability and cause a decrease canopy cover (Naumburg et al. 2005).

2.1.2 Groundwater dependent wetlands, including estuarine wetlands

As an ecosystem, wetlands can be difficult to define and for the purposes of this literature review, only wetlands which have a vegetation classification are considered. Typically, wetlands have seasonal or perennially saturated soil profiles. This saturation may be caused by ponding of surface flows, flooding or by groundwater discharge (Le Maitre et al. 1999). Although rainfall is considered to be the dominant source of water for nearly all wetland systems, groundwater plays a role in many of Australia's wetlands (Hatton and Evans 1998). This role can vary from minor to essential (Hatton and Evans 1998) but is not well understood (Howe et al. 2007).

Some wetlands may be completely dependent on groundwater discharge, whilst others may have limited dependence, such as only under dry conditions (Thorburn et al. 1994a&b; Thorburn and Walker 1994; Mudd 2000). However, even small amounts of groundwater can have important ecological implications, with small seepages supporting unique plant and animal communities. For example, the discharge of nutrient rich groundwater can determine the type and abundance of macrophytes such as seagrasses, although the specific chemical or physical processes determining macrophyte distribution are uncertain (Hayashi and Rosenberry 2002).

Groundwater can play a role in estuarine wetlands such as mangroves and salt marsh. While seawater is the primary water source, mangroves can occupy freshwater discharge areas (Wolanski 1992; Wolanski et al. 1992; Adam 1994; Ridd 1996; Hughes et al. 1998). Although the exact nature of groundwater dependency is unknown (SKM 2001), salt marsh ecosystems appear to make limited or opportunistic use of groundwater. Investigation by Bornman et al. (2002) of salt marsh within the Western Cape, South Africa indicated that *S pillansii*, the dominant salt marsh plant, used saline groundwater during the dry months of the year. Seagrass communities can also be proportionately or highly dependent on sub-surface groundwater discharge (SGD) in that these communities rely on the nutrients contributed by the sub-surface groundwater discharge (Rutkowski et al. 1999; Kamermans et al. 2002).

Groundwater interactions that focus on the movement of water between wetlands and goundwater can be grouped into three categories. These categories, as defined by McEwan et al. (2006) and Jolly et al. (2008) are:

- Discharge systems (‘*water leaves the groundwater system and enters the surface waters of a wetland’*); and
- Flow-through systems (‘*water seeps through the upslope side and base of the wetland, and seeps back to the groundwater from the down slope side of the wetland’*); or
- Recharge systems (‘*water seeps from a wetland into the groundwater’*).

Individual wetlands can change categories. Surface water levels in a wetland and underlying groundwater levels can change over time in response to climate, catchment and river management and groundwater extraction (McEwan et al. 2006).

It is important to note that the dominance of shallow rooted vegetation in wetlands means that wetlands are more susceptible to water table declines than phreatophytic vegetation (Dillon et al. 2009). A decline in water tables can result in the loss of water tolerant species and their gradual replacement by terrestrial species with broader ecohydrological ranges. Investigations of the impact of water table decline suggests that many wetlands display a proportional response to drawdown and conclude that the magnitude and rate of water level change is critical in determining potential impact on a wetland (Froend et al. 2004; Dillon et al. 2009).

2.2 Variables that infer a relationship between ecosystems and groundwater (and used to determine decision rules)

Plants have the ability to use water from a variety of water sources simultaneously when available which includes groundwater, soil water, stream water or recent rainfall (Dawson and Pate 1996; Zencich et al. 2002).

The decision rules used in the identification of potential GDEs are based on a fundamental tenet of ecology in ‘*that ecosystems will generally use resources in proportion to their availability and the availability of different resources will be a significant determinant of structure and composition’* (Eamus et al. 2006a). It is assumed that if an ecosystem can access groundwater then that ecosystem will (generally) develop some degree of dependence and that dependence will likely increase with increasing aridity (Hatton and Evans 1998).

Where possible, decision rules used as part of the methods considered the following factors that influence an ecosystem's ability to access groundwater: These factors included:

- Proximity to groundwater;
- Root system distribution and depth;
- Location or position in the landscape; and
- Species traits.

The relationship between the above factors and groundwater use is acknowledged in the literature (Cresswell and Bridgewater 1985; Dodd and Heddle 1989; Griffith and Wilson 2007).

2.2.1 Proximity to groundwater

Depth to groundwater can have a significant impact on plant water use and growth (Brownlow et al. 1994; Thorburn et al. 1995; Hatton and Evans 1998; Cramer et al. 1999; Morris 1999; Silberstein et al. 1999; Eamus et al. 2006a; Froend and Loomes 2006).

Studies undertaken in Pioneer Valley, Queensland (Howe et al. 2005) indicate that plants occurring in areas of shallow water tables are more likely to exhibit a higher degree of dependence on groundwater than vegetation occurring in areas where water tables are deep. Froend & Zencich (2001) suggest that vegetation located in areas where the depth to groundwater is greater, the more tolerant vegetation is to water table decline due to a corresponding reliance on alternative water sources such as soil moisture. Froend & Loomes (2005) report that groundwater becomes less important to terrestrial vegetation when depths to groundwater exceed 10m while Froend and Zencich (2001) note that the probability of accessing groundwater at depths of greater than 20m is low. While it possible that vegetation might use groundwater at depths of 10 to 20 metres (e.g. Jarrah trees – Dell et al. 1983), Froend and Loomes (2006) suggest that groundwater use at those depths is negligible in terms of total plant water use.

Griffith and Wilson (2007) and Griffith et al. (2008) divide vegetation into facultative and obligate GDEs. This division is based predominantly on depth to the water table and generalised topographic location. Swamp sclerophyll shrublands, wet heathlands and sedgelands growing in swales and swamps and subject to shallow water table levels were classified as obligate GDEs whereas dry sclerophyll tree mallee, dry sclerophyll shrublands and dry heathland occurring on beach ridges and dunes and subject to deeper water table levels were classified as facultative GDEs.

Driscoll and Bell (2006a&b) also established that the distribution of facultative and obligate species within the Tomago Sandbeds (NSW) could be correlated with various water table levels:

- Obligate wetlands species occurred generally in areas where depths varied between 0 to 1 m.
- Obligate terrestrial species occurred generally in areas where depths varied between 1 and 2 m.
- Obligate/facultative mixed assemblages occurred generally in areas where depth varied between 2 and 3 m.
- Facultative GDEs species occurred generally in areas greater than 3 m.

While depth to groundwater is often the most important attribute for vegetation relying on the sub-surface provision of groundwater, for ecosystems which rely on surface expression of groundwater and flooding of surface water sources, the depth of inundation and frequency of inundation that appears most important (Griffith and Wilson 2007; Griffith et al. 2008).

2.2.2 Plant rooting distribution and depths

Vegetation with a dimorphic root structure are capable of using (if available) unsaturated soil moisture (both shallow and at depth) and groundwater (at depth), either derived from the capillary fringe or directly from the water table due extensive tap and lateral root zones (Froend and Loomes 2005). The root systems of many tree and shrub species typically extend vertically and laterally to access available water and nutrients. Rooting depths can increase if water is available at depth or if there is transpirational demand for it (Schenk and Jackson 2002). In general, shallow root systems are favoured over deep root systems (Schenk and Jackson 2002) because (a) energy costs for construction, maintenance and resource uptake are lower for shallower roots (Adiku et al. 2000) and (b) nutrient concentrations are often higher in the shallow soil layers (Jobbágy and Jackson 2001).

The depth to which plant roots can grow is a key constraint in their ability to exploit groundwater. Cannadell et al. (1996) established that root biomass not only occupies the top 0.5 m of the soil profile, but can also extended to much greater depths and penetrate various substrates (e.g. compact clay soils, rocky soils and hard pans). Roots have the ability to follow cracks, fissures or channels to access groundwater at depth (e.g. Dell et al. 1983; Crombie et al. 1988; Poot and Lambers 2008).

Various studies have reviewed rooting depths of different types of vegetation. These studies found that different above-ground plant growth forms were correlated to their maximum rooting depths and lateral root spreads (e.g. trees had the largest root systems and annuals the smallest). Root systems of smaller plants also tended to be shallower and wider in dry and hot climates and deeper and narrower in cold and wet climates (Schenk and Jackson 2002).

For shrubs and herbaceous species various studies have shown rooting depths are generally less than 5 m. For example; the average rooting depth of sclerophyllous forest species was approximately 4 m and around 3 m for grasslands and herbaceous plants; arid and semi-arid species tended to have shallow, spreading root systems <1.5 m; roots tended to be deeper >5 m) in higher precipitation areas (>125 mm) (Canadell et al. 1996; Le Maitre et al. 1999; Schenk and Jackson 2002).

However, an exception has been found within sand-plains, with rooting depths exceeding 10 m. Griffith (2004) recorded roots up to 15 m deep, root to shoot ratios of 5:1 for plants less than 1.5 m tall on high sand dunes. This means that a 1m shrub is capable of extending root growth to 5 m.

Investigating Wallum vegetation along the east coast of Australia, Griffith et al. (2008) reported that plant roots were present in shallower aquifers, that is, at depths of up to 10.5 m, suggesting that some wallum species are capable of developing deeper root systems.

Studies on woodland and woody tree species found that they are likely to target deeper aquifers with woodland species having rooting depths <17 m and larger, taller trees generally having deeper root systems (up to 30 m) (Le Maitre et al. 1999; Smith 2006). Studies on eucalyptus species have recorded rooting depths of between 10 and 40 m meaning that they are accessing water from depths normally out of reach by grasses and shrubs (Dell et al. 1983; Le Maitre et al. 1999; Stirzaker et al.1999; Stirzaker and Vertessy 2000). Studies for *Corymbia sp.* showed that this species appeared to be accessing groundwater between 12 and 20m (O'Grady et al. 2006; Howe et al. 2007). The rooting depth of predominant Mallee trees (*Eucalyptus*, *Acacia* and *Casuarina*) was found to be in the range of 20-30 m (Nulsen et al. 1986; Allison et al. 1990). Research on *Banksia* woodlands have been found to have both nutrient acquiring lateral roots within the top 40 cm of the soil profile and deeper tap roots that reached between 2 and 9 m (Dawson and Pate 1996; Jackson et al. 1996; Groom et al. 2000a; Groom 2004). Other

Australian native species found in the Swan Coastal Plain have been known to access groundwater at various shallow depths from <1 m to2 m (Groom et al. 2000b; Veneklaas and Poot 2003).

Wetlands that depend on groundwater require that the water table be at or near the ground surface and that groundwater levels be episodically or periodically within the root zone for use when soil water availability is low. Wetlands usually have shallow groundwater, allowing plant roots to reach the groundwater, if necessary, and satisfy demands for water and nutrients (Groom et al. 2000a&b). Many of the species common to wetlands have shallow roots systems and are relatively intolerant of drying out. In general however, little is known about the rooting depths of wetland plants and their reliance on groundwater when surface water is unavailable.

2.2.3 Location or position in the landscape

The majority of ecosystems are groundwater dependent due to their location in the landscape, whilst some ecosystems (such as permanent springs and geothermal springs) are groundwater dependent due to upwelling of groundwater under pressure (Dillon et al. 2009).

Some plants will only inhabit areas where they can access groundwater while other plants will only use groundwater if it is available i.e. inhabit areas where their water requirements can be met mostly by soil moisture reserves. Groundwater use can therefore be a function of the hydrogeologic setting that determines whether or not a shallow water table exists that species can access (Dillon et al. 2009).

Zencich et al. (2002) found groundwater use by several *Banksia* species to be a function of their position in the landscape. *Banksia attenuate* and *B. menziesii* are able to survive and co-dominate various topographic locations on the Swan coastal plains (Western Australia) because of their ability to use more than one water source. *B. ilicifolia* and *B. littoralis* are restricted to lower lying locations and depend on groundwater during summer (Groom 2004). *B. attenuata* trees, growing on dune crests do not use groundwater, even late in summer but will access groundwater if located on lower slopes (Groom 2004).

Wallum vegetation along the coast of eastern Australia is associated with Quaternary dune fields and beach ridge plains. *Banksia aemula* is found on ridges where the water table is deep while *Banksia ericifolia* subsp. *macrantha* is located on the flats and in open depressions where the water table depth ranges between 0 and 1.3 m (Griffith et al. 2008).

O'Grady et al. (2006) and Lamontagne et al. (2005) also found groundwater use by trees close to rivers to be a function of position in the landscape. Lamontagne et al. (2005) found that species such as *Melaleuca argentea* and *Barringtonia acutangula* that occurred close to the river were highly dependent on river water or shallow groundwater. Species opportunistically accessed groundwater depending on the time of year were located at higher positions such as on the river levees. Similarly, O'Grady et al. (2006) observed that *Corymbia bella*, used progressively deeper water sources as the dry season progressed due to their location on the top of levee banks. This relationship between distance from a river and access to groundwater depends upon topography that can affect the depth to the water table. Large, flat floodplains generally have shallow water tables, providing access to groundwater for several kilometres from river channels.

Geology and lithology control groundwater flow and impose aquifer boundaries. Fractures, faults, folds and intrusive dykes may form preferred pathways or barriers to groundwater flow, affecting availability of groundwater for terrestrial and wetland ecosystems (Le Maitre et al. 1999).

Coastal floodplain forests and swamps can be located in areas of shallow groundwater on alluvial floodplains. Some will rely totally on groundwater while others rely on a combination of surface and groundwater and some only on surface water. Swamp forests can be highly dependent on groundwater and many swamp forests exhibit an obligate dependency on groundwater (Eamus and Froend 2006). Obligate dependency does not mean a total dependence on groundwater or that continuous access to groundwater is required. It does however mean that groundwater forms an important water source at some point of the ecosystems hydrological regime (Eamus and Froend 2006).

2.2.3.1 Wetland landscape position

Groundwater dependent wetlands, for example, occur where geology, topography and landform allow groundwater discharge to concentrate (Semeniuk and Semeniuk 1997; Mitsch and Gosselink 2000; Stein et al*.* 2004). Landscape settings that favour wetland formation include topographic depressions, gullies, steeply dissected hills and break of slopes (Stein et al. 2004; Dear and Svensson 2007; Ramsar Convention Secretariat 2007). Table 1 provides descriptions of wetland types based upon landscape settings. The information in Table 1 was sourced from Semeniuk and Semeniuk (1997), Mitsch and Gosselink (2000), Stein et al. (2004), Dear and Svensson (2007), Ramsar Convention Secretariat (2007).

Table 1: Wetland types

Wetland type	Water Source	
Slope wetland	Groundwater seepage, supplemented by surface runoff and rainfall	Wetland is in direct contact with underlying aquifer. Examples include: break of slope wetlands which occur where groundwater reaches the surface. Constant groundwater seepage along topographic or stratigraphic breaks maintains soil saturation and wetland plant communities. Groundwater discharge originates from recharge that occurs either near the wetland or at some distance away from the point of ultimate discharge in the slope wetland (Stein et al. 2004). Other examples include upland swamps which occur on slopes where groundwater seeps out of a porous layer of rock (which is underlain by a non-porous layer, such as shale, which restricts further downward infiltration). These wetlands are known to occur in areas of high water tables (Pressey and Harris 1988). They may hold water permanently, or may fill on a seasonal or intermittent basis. The seepage area is often permanently wet and supports vegetation dominated by sedges, ferns and heath shrubs.
Depression wetlands	Surface runoff, rainfall and occasionally groundwater fed	Wetland is separated from underlying aquifer by lower permeability layer that restricts groundwater input. Input from groundwater discharge occurs when groundwater table is high.
	Groundwater fed	Wetland in direct contact with underlying aquifer. Input is dominated by groundwater discharge when water table is high
Valley bottom	Surface (over bank	Wetland is separated from underlying aquifer by

wetlands	flow, rainfall) and groundwater discharge	lower permeability layer. Groundwater flow may be restricted by a low permeability
	Groundwater fed	Wetland in direct contact with underlying aquifer. These wetland types often occur along river floodplains and lake margins. Groundwater is discharged through these into streams or lakes. Wetland may become recharge areas when water levels are higher than the water table due to heavy precipitation, saturated soils, and low evaporation rates.

In general, wetlands occurring in depressions are maintained predominantly by overland flow, groundwater and precipitation while wetlands adjacent to rivers are maintained predominantly by periodic pulses of water from over bank flows as well as occasional or seasonal dependency on groundwater between flood events. Wetlands (and lakes) located higher in the landscape receive a larger percentage of their incoming water from precipitation than wetlands/lakes located lower in the landscape. Some upland creeks can flow for a few weeks after sustained heavy rains. This is assumed to be from recharged shallow aquifers discharging directly along the creek channels (Semeniuk and Semeniuk 1997; Mitsch and Gosselink 2000; Stein et al*.* 2004).

Wetland communities (e.g. coastal dune lakes, dunal wetlands, or window lakes) that are located within coastal sand aquifers are groundwater dependent. Coastal sand dunes and sand masses hold vast quantities of freshwater in aquifers (Saenger 1996). Wetlands form wherever depressions are deep enough to intersect the water table (e.g. water table-window wetlands). Water within these wetlands is acidic and often crystal clear indicating that it has arisen from regional groundwater aquifers (Saenger 1996). The Gnangara Mound (located on the Swan Coastal Plain) supports some 400 wetlands, which most often occur in depressions between the dominant dune systems of the coastal plain and have some degree of groundwater dependence (Yesertener 2002). Some wetlands within these environments will not be groundwater dependent. Perched wetlands form within deflation hollows in elevated dunes where organic material has accumulated and sealed the basin floor (Timms 1982). Perched wetlands/lakes are hydrologically closed systems and rely on rainfall and runoff.

In conclusion, it follows that where wetlands and terrestrial vegetation occur in certain landscape positions and can be linked to shallow groundwater or areas of groundwater discharge, they are more likely to be groundwater dependent (Richardson et al. 2011).

2.2.4 Availability of soil moisture

Soil water is an important source of water for plants as less energy is required to draw on water from the vadose zone than from the water table (Howe et al. 2007). Trees and shrubs mostly access water from the upper unsaturated soil profile.

After rainfall, soil can hold water for months. The amount that can be stored depends on a number of factors including soil hydraulic properties and the amount and timing of the rainfall. The available water holding capacity (i.e. the amount of water in the soil that is available to plants) of sandier soils is much lower than loams or clays. Clays have higher water holding capacity than loams but less is available to plants as the water tends to be held tightly by the clay. Soils with low water holding capacity can store only limited amounts of water that can be extracted by plants (Howe et al. 2007).

2.2.5 Soil characteristics

Soils that are deep and well drained provide no apparent impediment to rooting depth. Many species develop larger, deeper root systems within coarse textured soils than in finer textured soils (Martre et al. 2002; Xu and Li 2008). Root systems with a deep and large surface area facilitate greater soil water uptake and allows extraction of water from a larger soil volume (Xu and Li 2008). Deeper roots allow plants to shift water uptake to deeper layers during drought and avoid hydraulic failure (Hacke et al. 2000). Lower water entry, restricted root growth and water availability occurs in finer textured sub-soils due to low permeability and high soil strength, (Xu and Li 2008). Plants with a larger canopy may also need larger root systems in coarse textured soils, due to smaller water-holding capacities and deeper infiltration depths (Schenk and Jackson 2002).

To be dependent on groundwater, wetlands must have a hydraulic connection with shallow (unconfined) aquifer systems. This connection depends on local geological conditions (McEwan, et al. 2006). Where wetlands overlie impermeable soil or rock there is little (if any) interaction with groundwater (Rassam and Werner 2008). Many wetlands occur at low points in the terrain where heavy textured soils are common place due to alluvial depositional processes (i.e. groundwater interaction can be limited). Roberts et al. (2000) notes that unlike many coastal wetlands or wetlands on sandy soils, groundwater exchange is rarely dominant on floodplains with surface flows, losses via evaporation and plant water use, the dominant ecosystem functions. Within alluvial aquifers, groundwater is stored in the pore spaces in the unconsolidated floodplain material in which floodplain vegetation grows and wetlands are situated. Significant interaction between ground and surface water can occur where alluvial aquifers occur in up-river situations and are composed of coarse materials such as sand and gravel. In the lower catchment areas (i.e. coastal floodplain alluvium) where alluvial materials tend to be finer, there is less inter-play between ground and surface water (Department of Water and Energy 2008)

2.3 Known groundwater dependent species and communities

When a vegetation community has identified groundwater dependent species present, the community is usually attributed to being groundwater dependent. However the term ‘groundwater dependent community’ does not imply that all species making up that community are dependent on groundwater (Eamus et al. 2006a). However, such a community can consist of herbaceous and grass species that rely on recent rainfall, as well as deep-rooted species that, in the absence of rainfall, rely directly on groundwater (Sommer and Froend 2010a&b).

Although there is much uncertainty as to which species within a given ecosystem depend on groundwater (fully or partially), certain plants can indicate the presence or absence of shallow groundwater. Species which occur in association with discharge areas, such as topographic low points or along dykes or fault lines can be used as indicators of the presence of groundwater (Le Maitre et al. 1999). Zoete (2001) noted that the type of ground layer vegetation can often reflect surface or shallow groundwater hydrology. The presence of Swamp *Banksia* (*Banksia robur)*, for example, can suggest the existence of shallow groundwater for periods sufficiently long to allow for its proliferation (Finlayson 2005). Harding (2005) found swamps comprising communities typical of waterlogged and/or peat soils occurring in areas of low rainfall and high summer evaporation rates to be potentially groundwater dependent.

Much of the vegetation associated with Quaternary dune fields and beach ridge plains along the coast of eastern Australia can be considered to have some dependency on groundwater. Coastal heath swamps are scattered along most of the NSW Coast. They are generally restricted to poorly drained depressions associated with swales on coastal sand sheets or the headwaters of creeks on coastal sandstone plateaus up to 600 m altitude (Keith 2004). The most extensive areas of coastal heath swamps occur on the coastal sandstone plateau of the Sydney area (Keith 2004). High rainfall, generating surface water flow and groundwater seepage into depressions, maintains a water table perched above the impermeable sandstone bedrock or hard sand dune-sub-soil (Keith 2004). Vegetation within these swamps is related to gradients in soil moisture. Along the drainage lines of the swamps where the water table remains within a few centimetres of the soil surface during winter, the soil form a mixture of peat and mineral sand. Within these areas, large shrubs, fern and tall sedges occur while on the outer sedges of the swamp, where inundation occurs less frequently and the soil contain less organic matter and nutrients, the vegetation is shorter and more open (Keith 2004).

Sedgelands that occupy environments that have shallow groundwater (e.g. coastal, floodplain and valley floors) are likely dependent on that groundwater (SKM 2001). Sedgelands within the Tomago and Tomaree sandbeds have been classified as either obligate or facultative (*Chorizandra* Sedgeland and *Philydrum* Sedgeland) GDEs (Driscoll and Bell 2006a&b). Shrub swamps are known to occur in areas of shallow groundwater and can be considered to be groundwater dependent. Shrub swamps located at the Tomago and Tomaree Sandbeds are classified by Driscoll and Bell (2006a&b) as obligate GDEs. The relationship between shallow water tables and the occurrence of swamp forests is well identified (Winning and Clarke 1996). Within the Tomago and Tomaree sand beds (NSW) Paperbark Swamp Forest, Swamp Mahogany forest, Paperbark-Mahogany Low Swamp Forest, Paperbark-Apple-Mahogany Dry Swamp Forest and Fringing Paperbark Forest are classified as obligate GDEs (Driscoll and Bell 2006a&b). These communities occur on sand beds where the depth to water is less than 10m (Driscoll and Bell 2006a&b).

Typically, swamp forests are either seasonally inundated or occur at the margins of rivers or lakes that are partly groundwater derived. These forests are relatively common along the eastern seaboard of NSW and are particularly associated with coastal sand masses often occurring in swamps behind fore dunes and sporadically around the perched swamps and lakes (Green 1997). A number of species and communities were identified as being dependent on surface and/or shallow groundwater systems within the Saltwater Creek catchment within NSW (Kendall and Kendall Pty Ltd 2003). Saltwater Creek Catchment is an intermittently open coastal creek/lagoon system entering the ocean at the western end of front beach at South West Rocks and is located between South West Rocks and the Smoky Cape Range. Species that depended on a high water table included *Eucalyptus robusta.* Species and communities that depended on both periodic inundation as well as high water table included: *Casuarina glauca*; *Melaleuca quinquenervia*; wet heath/sedgelands; *Baumea juncea* sedgeland; *Leptocarpus tenax Restio pallens Schoenus brevifolius* sedgeland. Species and communities that dependent on periodic high water tables included: Heath; *Banksia ericifolia*; *Leptospernum juniperinum s*hrubland and heath; *B. oblongifolia; L. liversidgei*; *Lepyrodia interupta*; *Sprengelia sprengelioides* X fulva heath. *Juncus krausii* rushland depended on both tidal inundation and high water tables (Kendall and Kendall Pty Ltd 2003).

In various sites throughout Australia, woodland species that occur on sandy soils (e.g. Scribbly Gum (*Eucalyptus haemastoma)*, Sydney Red Gum (*Angophora costata,)* Old Man Banksia (*Banksia serrata*), Red Bloodwood (*Eucalyptus gummifera*)) often depend on groundwater (e.g. Zencich et al. 2002; Driscoll and Bell 2006a&b; Griffith and Wilson 2007; Loomes et al. 2007). Open forests that occur along drainage lines or in places with deeper sandy soils (e.g. Smooth-barked Apple (*Angophora costata*)*,* Sydney Peppermint (*Eucalyptus piperita*) Grey Gum (*Eucalyptus punctata*), Bangalay (*Eucalyptus botryoides*)) are also known to use groundwater. Littoral rainforest and sub tropical rainforests that occur in moister coastal areas and in moist protected gullies can depend on groundwater. Dunal communities that occur on the sand dune and sand sheets {e.g. She-Oak (*Casuarina glauca*), Red Bloodwood (*Eucalyptus gummifera*), Scribbly Gum (*Eucalyptus haemastoma)*, Smooth- barked Apple (*Angophora costata*) Coastal Banksia (*Banksia integrifolia)} are* known to use groundwater (e.g. Zencich et al. 2002).

On the Chowilla floodplain in South Australia, *Eucalyptus camaldulensis* and *E. largiflorens* trees often use small amounts of saline groundwater to maintain ecosystem function between large flooding events (Cramer et al. 1999, Mensforth et al. 1994).

Drake and Franks (2003) indicated that several riparian rainforest species (e.g. *Doryphora aromatica* and *Canstanopora alphandii)* within the Atherton Tablelands used groundwater during the dry season. During the wet season, water from the upper 1 m of the soil profile was used instead. Groundwater dependent vegetation and wetlands are reported on the Alstonville Plateau, mostly associated with springs and base flow streams (Brodie et al. 2002). Springs are surface expressions of groundwater and vegetation associated with springs are likely to depend on that groundwater. The GAB Mound springs support a diverse group of ecosystems that are entirely groundwater dependent. The most common vegetation associations are grasslands and sedgelands, although some larger spring pools support *Melaleuca glomerata* swamp woodlands or scrublands.

A limited review of the literature found groundwater use to be associated with the following species:

- *E. camaldulensis,* Chowilla SA, Riparian (Mensforth et al. 1994; Thorburn et al. 1994a&b; Thorburn and Walker 1994).
- *E.camaldulensis* and *E.largiflorens, NSW,* floodplains of the Murray and Darling Rivers (Mensforth et al. 1994)
- *B. prionotes,* South West WA, Woodland; *E. globulus and E. camaldulensis* South West WA plantation; *B. grandis,* South West WA woodland (Dawson and Pate 1996).
- *E. camaldulensis and C. glauca* Darling Downes, QLD Plantation, (Cramer et al. 1999).
- *B. prionotes,* Woodland, (Burgess et al. 2000).
- *B. prionotes and B. ilicifolia,* Gnangara mound *Woodland,* (Zencich et al. 2002).
- *Doryphora aromatica and Castonospora alphandii,* Atherton tablelands, QLD, *Dry Rainforest,* (Drake and Franks 2003).
- *Melaleuca argentea and Barringtonia acutangulata,* Daly River, NT Riparian forest, (Lamontagne et al. 2005).
- *Corymbia clarksoniana,* Pioneer Valley, QLD Woodland (O'Grady et al. 2006).
- *Corymbia opaca and E. victrix* ,Ti Tree, NT Open woodland (Howe et al. 2007).
- *E. victrix and M. glomerata,* Pilbara WA, Riparian (Pritchard et al. 2010).
- *E. coolabah,* Lake Eyre Basin, SA Riparian (Costelloe et al. 2008).
- *Melaleuca quinquenervia,* east coast of NSW (Zoete 2001).
- *Eucalyptus robusta, Casuarina glauca*; *Melaleuca quinquenervia*; wet heath/sedgelands; *Baumea juncea* sedgeland; *Leptocarpus tenax Restio pallens Schoenus brevifolius* sedgeland. Heath; *Banksia ericifolia*; *Leptospernum juniperinum* shrubland and heath; *B. oblongifolia; L. liversidgei*; *Lepyrodia interupta*; *Sprengelia sprengelioides* X fulva heath. *Juncus krausii* rushland; Open coastal lagoon system, NSW, (Kendall and Kendall Pty Ltd 2003).

2.4 Remote Sensing

Terrestrial vegetation communities are complex ecological systems and identification of their dependency on ground water is an even more complex task. Over three decades, there has been large amount of interest devoted to the research and application of remotely sensed data for vegetation monitoring (Jackson et al. 1979; Benedetti and Rossini 1993; Quarmby et al. 1993; Wardlow et al. 2007). Application of remote sensing to the identification of GDEs however appears limited (Munch and Conrad 2007; Dresel et al. 2010; Yang et al. 2011; Eamus et al. 2015).

The main advantage of using remotely sensed data is that satellite systems provide spatially and temporally continuous data with global coverage and decent resolution. Timely acquisition of such data is available and mostly inexpensive through several online portals and archives. For example, MODIS data exhibit features considered valuable for operational vegetation condition and stress assessments, such as high temporal and world-wide coverage, and real-time availability at low cost to the user.

MODIS Enhanced Vegetation Index (EVI) is sensitive to changes in plant biomass, vigour, and leaf size, which varied according to land cover types and management practices (Chen et al. 2014). For example, Figure 2 shows the range of annual standard deviation variations of greenness of different cover types as observed during 2000-2008 in NSW. Figure 2 shows the EVI ranges for various vegetation structure classes. The EVI range for woodlands is generally narrow when this is measured across all woodland sites. Individual woodland sites could have a larger EVI range (Eamus 2016).

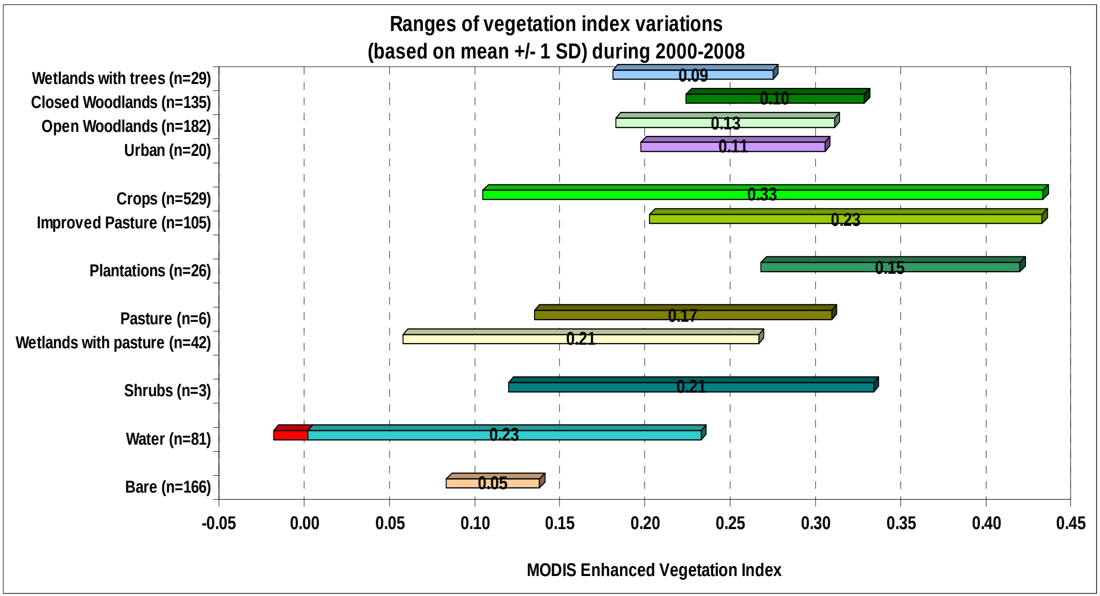

Figure 2: Long-term vegetation greenness variation pattern for selected cover types in NSW area.

NOTE: Each bar chart represents range of +/- 1 SD of the annual EVI values during 2000-2008 for each vegetation structure class.

Longer-term index values of trees, as well as the changes during every season, indirectly measure the health and growing condition of trees. This can be a measure of water availability because in order to maintain a healthy condition, a tree requires ample supply of water else the tree may show stress signs. Vegetated areas that maintain high EVI during dry seasons or during prolonged drought months can indicate that the vegetation is potentially groundwater dependant vegetation (Groeneveld and Baugh 2007; Eamus et al. 2015).

The temporal evolution pattern of greenness and wetness during a particular season and/or over many years is useful in identifying periods of water stress. By analysing the behaviour of these indices during a season or during a year, it is possible to derive key statistics related to tree health and/or periods with limited water availability (Groeneveld and Baugh 2007; Eamus et al. 2015).

2.4.1 Vegetation indices

Remotely sensed spectral vegetation indices (VIs) are widely used and have been of benefit for numerous disciplines interested in the assessment of vegetation biomass, water use, plant stress, plant health, crop production, and identification of biome types. Vegetation indices are optical measures of vegetation canopy “greenness”, a composite property of leaf chlorophyll, leaf area, canopy cover, and canopy architecture (Chen & Cihlar 1996; Gutman and Ignatov 1998; Boegh et al. 2002; Gitelson et al. 2005; Jiang et al. 2006). Although VIs are used as proxies in the assessment of many biophysical and biochemical variables, including canopy chlorophyll content (Gitelson et al. 2005), leaf area index (LAI) (Chen & Cihlar 1996; Boegh et al. 2002), green vegetation fraction (Gutman and Ignatov 1998; Jiang et al. 2006), gross primary productivity (GPP) (Rahman et al. 2005; Sims et al. 2006) and fraction of photosynthetically active radiation absorbed by the vegetation (FAPAR) (Myneni et al. 1997).

The main capability of VIs is their ability to respond to subtle changes in plant health status for variable view, illumination and atmospheric conditions. Therefore, examination of spatial distribution and temporal trends of the vegetation indices over longer periods is useful and provides significant insight into a regional scale vegetation pattern.

The amount of radiation reflected from a vegetation surface is determined by solar irradiance (amount and composition that strikes the vegetation), and the reflectance properties of the vegetation surface. Solar irradiance varies with time and atmospheric conditions. A simple measure of reflected light is therefore not sufficient to characterize the surface in a repeatable manner (Nagler et al. 2013). For this reason, often, data from two or more spectral bands are used to form a vegetation index. VIs can be calculated by ratioing, differencing, ratioing differences and sums, and by forming linear combinations of spectral band data. These techniques used to minimize solar irradiance and soil background effects to enable detection of the vegetation signal (McCabe and Wood 2006; Groeneveld and Baugh 2007; Nagler et al. 2013).

2.4.1.1 Enhanced Vegetation Index (EVI)

EVI was developed as a standard satellite vegetation product for the MODIS. The EVI was calculated as follows:

$$EVI = \mathrm{G}\frac{\rho_{\mathrm{NIR}} - \rho_{\mathrm{Red}}}{\rho_{\mathrm{NIR}} + C_1\rho_{\mathrm{Red}} - C_2\rho_{\mathrm{Blue}} + L}$$

Where $\rho_{\mathrm{NIR},}$ ρ_{Red} and ρ_{Blue} are reflectances in the near infrared, red and blue bands respectively; C_1 and C_2 are aerosol resistance coefficients; *G* is a gain factor, and *L* is the canopy background adjustment that addresses nonlinear, differential NIR and red radiant transfer through a canopy. The coefficients used in the MODIS-EVI algorithm are L=1, C1=6, C2=7.5 and G=2.5 (Huete et al. 2002). EVI provides improved sensitivity in high biomass regions while minimizing soil and atmosphere influences. EVI has been used variety of studies, including those on land cover/land cover change (Wardlow et al. 2007), estimation of vegetation biophysical parameters (Chen et al. 2004; Houborg et al. 2007), phenology (Zhang et al. 2003; Xiao et al. 2006), evapotranspiration (Nagler et al. 2005), biodiversity (Waring et al. 2006) and the estimation of gross primary production (GPP) (Rahman et al. 2005; Sims et al. 2008).

MODIS data provides both Normialised Difference Vegetation Index (NDVI) and EVI as standard products and they provide consistent, spatial and temporal comparisons of global vegetation conditions. The level 3 gridded vegetation indices are the standard products available to the science community. The level 3, spatial and temporal gridded vegetation index products are composites of daily bidirectional reflectances. The 16-day VI product is designed to provide a cloud-free, atmospherically corrected and nadir-adjusted vegetation maps at nominal resolutions of 250 m.

2.4.1.2 Normalized Difference Wetness Index (NDWI)

Wetness indices aim at combining water status of the plants and ambient meteorological conditions and will yield a measure of plant water stress. Furthermore, such wetness indices reflect the soil moisture status across the entire root zone depth rather than a particular soil layer (Nagler et al. 2013; Eamus et al. 2015).

Physically based models and laboratory studies have shown that changes in vegetation water content have a large effect on the leaf reflectance in several regions of the 0.4 – 2.5 µm spectrum (Fensholt & Sandholt 2003). It is widely accepted that large absorption by leaf water occurs in these wavelengths and therefore reflectance of the shortwave infrared (SWIR) region is negatively related to leaf water content (Tucker 1980). Also, increased reflectance in these wavelengths is a promising and consistent leaf reflectance response to vegetation stress in general, including water stress (Carter 1994).

Gao (1996) proposed the NDWI by the equation

$$NDWI = \frac{NIR - MIR_{1.24}}{NIR + MIR_{1.24}}$$

Where the surface reflectance in Band-2 for NIR (841–876 nm) and Band-5 for MIR (1230–1250 nm) reflectance.

Gao's (1996) NDWI uses the band combination of 2 and 5 where the reflectance signal of vegetation is the highest. However this band combination is not available as a standard package through the MODIS data. However different combination was available (Bands 2 and 7), and is also termed Land Surface Water Index (LSWI) to allow differentiation between the bands used. This LSWI utilizes surface reflectance in the farther regions of MIR spectrum and can be defined as below (Fensholt and Sandholt 2003).

$$NDWI = \frac{NIR - MIR_{2.13}}{NIR + MIR_{2.13.}}$$

Where NDWI represents LSWI, NIR and MIR represents MODIS surface reflectance in Band-2 (841–876 nm) and Band-7 (2105–2155 nm).

To determine if the use of the LSWI was adequate for the purposes of this project, remote sensing experts at the University of Technology Sydney were engaged to provide a comparison between the band combinations. The results of this work showed that the derived datasets for the MODIS resolution at 250m and 500m showed a strong correlation with native 500m NDWI which indicated that using band 7 in applications may provide higher resolution NDWI data series. This will need to have field verification to determine the extent it applicability (Huete & Devadas 2016).

2.4.1.3 Regionally Normalized Temperature Index (RNTI)

The most widely established method for detecting vegetation water stress remotely is through the measurement of the surface temperature of the vegetation. The correlation between surface temperature and water stress is based on the assumption that as vegetation transpires evaporative cooling cools the leaves below that of air temperature. Under water stress, plant transpiration decreases, and leaf temperature increases. Other factor that needs to be accounted for to enable a good measure of actual stress levels is leaf temperature. Leaf temperature is one of the most important and it is easily measured with remote observations (Moran et al. 1994; Bastiaanssen et al. 1997; McVicar and Jupp 1999; Wan et al. 2004).

The most useful land surface variable that can be derived from thermal remote sensing is the land surface temperature (LST). Land surface temperatures play an important role in land-surface processes. They are of fundamental importance to the net radiation budget at the Earth's surface and to monitoring the state of vegetation (Moran et al. 1994; Bastiaanssen et al. 1997; McVicar and Jupp 1999; Wan et al. 2004). Furthermore, many other modelling applications such as in hydrology, geology, vegetation monitoring, and global circulation models rely on the knowledge of land surface temperature. Remotely sensed LST have been used in number of applications including moisture availability to vegetation (Moran et al. 1994; Bastiaanssen et al. 1997; McVicar and Jupp 1999; Wan et al. 2004). Other LST applications include modelling of regional scale evapotranspiration (McCabe & Wood 2006) and land surface turbulent flux prediction (Diak and Stewart 1989).

Accurate retrieval of LST is a complex process and requires enormous effort. The accuracy of satellite LST measurement is limited mainly by the complexity of land surface types, the atmospheric correction, and sensor performance (Wan et al. 2004). In order to retrieve the LST physically from the satellite derived data, it is necessary to know the atmospheric profile for each pixel, and also the surface emissivity for each band. Because the surface emissivity for each band is different, the number of unknowns is always larger than the number of equations. Without any additional information, it is impossible to recover both LST and emissivity exactly. The availability of MODIS LST products however has paved the way to use LST data for broader applications including vegetation stress studies (Wan et al. 2004).

MODIS LST data over a large region such as NSW provide a range of LST measurements that represent many possible soil water conditions and vegetation stresses within the area (Wan et al. 2004). Thus, it can be argued that space-borne LST data alone will be sufficient for developing a simple index to describe the vegetation stress conditions in a region. This is possible to achieve with the Regionally Normalised Temperature Index (RNTI) for a given pixel is defined as:

$$RNTI = \frac{LST_i - LST_{\min}}{LST_{\max} - LST_{\min}}$$

where the two bounding temperatures, LST_{min} and LST_{max}, are derived from the LST measurements over the entire region and LST_i is the measured temperature in a given pixel.

2.4.1.3 Limitations of remotely-sensed land surface indices

Land surface vegetation indices are sensitive to changes in vegetation biomass, vigour, and leaf size, which varies for forest structural and crop types (Pedroni 2003). Therefore, VI values of vegetation as well as the changes during the growing season indirectly measure vegetation health and growing condition. For example, as growing season progresses, crops become greener and bigger in size, and that translates to increasing average in VI. Conversely, trees can exhibit a fairly consistent VI value across different seasons. Any increases of seasonal VI vary depending on how healthy and dense tree covers are developing and vegetation condition could plunge in a situation where access to soil or ground water is limited (Pedroni 2003).

Vegetation indices have some limitations that can affect the accuracy of image classifications. These include:

- Objects that obscure the satellite such as clouds, fog, aerosols and water vapour (Chahine 1983; Holben & Fraser 1984; Holben 1986; Henderson-Sellers et al. 1987; Kaufman 1987).
- A reduction in the measured VI as the light has to pass through more atmosphere before reaching the sensor (Holben & Fraser 1984; Holben 1986).

- The VI value can increase with increasing view angle. This is due to the geometric effect of the soil or water being hidden by the vegetation, which, in turn, takes up a higher proportion of the field of view (Robinson 1996).
- The spectral response of vegetation depends on the instantaneous angle of view of the sensor relative to the sun and the target (Graetz & Gentle 1982). For example, the visible wavelengths are more affected by shading than the near-infrared (Graetz & Gentle 1982). That influence is not normalised by the NDVI (Robinson 1996). Large zenith solar angles, directional reflectance and shading tend to reduce the measured NDVI values (Holben & Fraser 1984; Holben 1996).

Although it is not an inherent limitation, tree canopies in different ecological regions are not homogeneous in composition, space and time, and therefore vegetation index values can vary greatly within each particular type of ecological region at a particular time (Groeneveld and Baugh 2007). Vegetation index values of many non-woody varieties can influence the greenness of trees particularly in sparse-tree canopies, hence make it difficult to separate the signature patterns of ground-cover plants from the trees by simple approaches. Consequently, sparse-tree area requires meticulous analysis of the available images in order to accurately identify the trees (Eamus et al. 2015).

A major limitation of LST retrieval is that it can only be done under clear sky conditions. Therefore, LST values computed during partially overcast days may not necessarily represent true canopy temperature (Groeneveld and Baugh 2007; Eamus et al. 2015). Furthermore, it is difficult to obtain true canopy temperature values over the full range of land surface types. Typically, LST varies significantly on a sub-pixel scale, and over short timescales. The satellite retrieved LST represents a snap-shot pixel-averaged measurement at a point in time. MODIS LST values are available at approximately 1 km pixel scale; use of such data for vegetation stress monitoring does not provide the ideal conditions for accurate estimates (Groeneveld and Baugh 2007).

3 Methods

The spatial model developed for the identification of potential vegetation GDEs uses information from three major data sources of remote sensing, vegetation community mapping and associated data, and groundwater level data. Information from published scientific literature has been used to inform the assumptions made for all data used and in the development of the spatial model. Figure 3 shows the flow pathways for the model process (further information for each of the data sources see sections 3.1 to 3.3 for remote sensing, vegetation and groundwater, respectively).

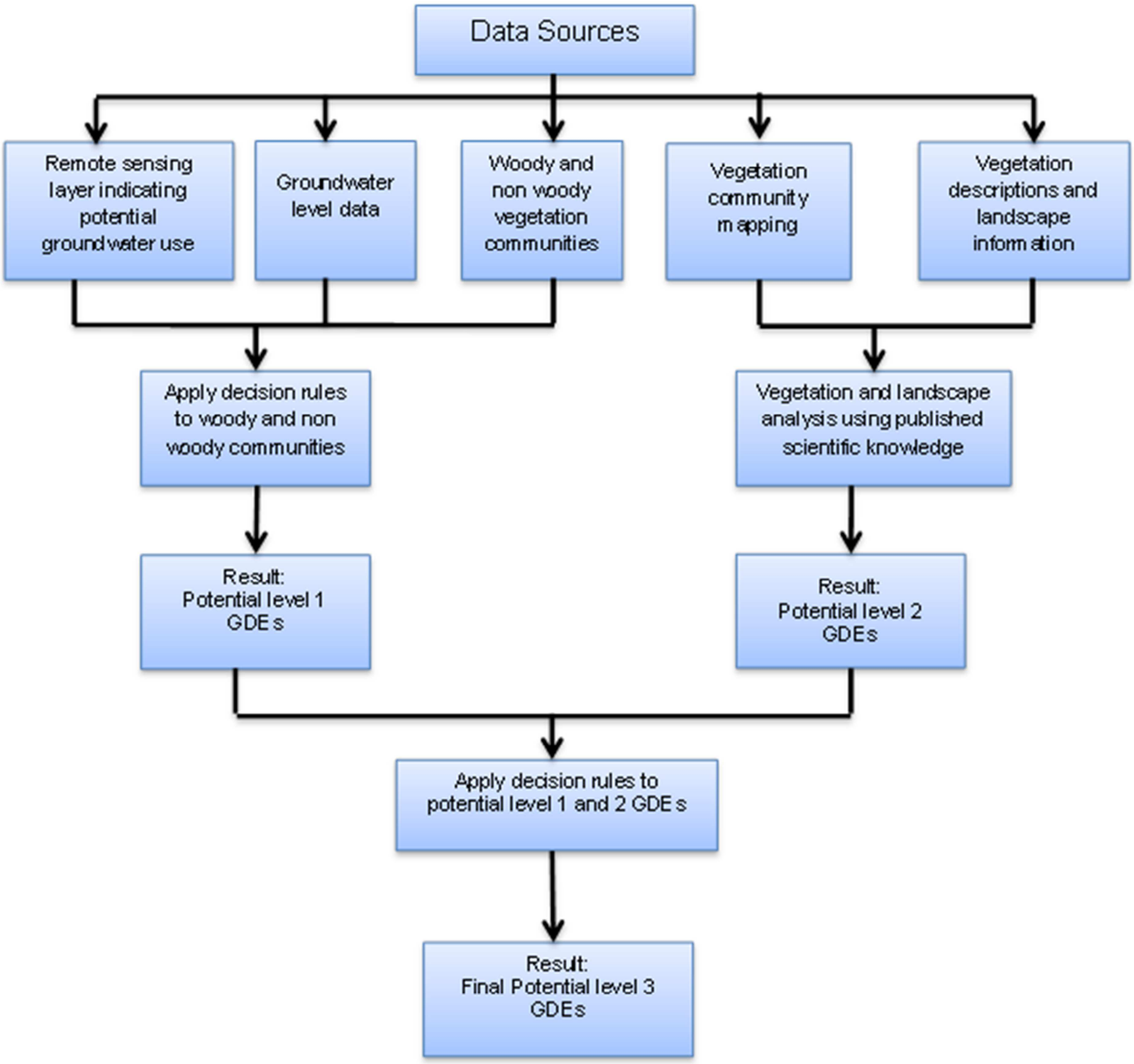

Figure 3: Sources of data and their use in identifying potential GDEs at different points in the process.

A number of spatial models were developed to automate the various GIS processes involved in determining the final derived data sets.

Three different cartographic models (Levels 1, 2 and 3) were developed for GIS analysis and processing of spatial datasets (see Figure 3). The Level 1 model was used to automate the GIS process for selecting possible GDEs within all WSP areas. This model combined remote sensing generated data, existing vegetation mapping and groundwater level data. Results generated from the Level 1 model were either a high, medium, low or not dependent on groundwater. Level 2 model used the information and associated data for assigning each vegetation community a probability of groundwater use a ranking of 1 (highest) to 3 (lowest). The combination of Level 1 model and Level 2 model results provide Level 3 model results.

Potential probability of groundwater use was ranked based on the combination and analysis of three sets of data e.g. existing vegetation map, groundwater depth and a remote sensing data set (that identified the groundwater use by the existing vegetation). The following steps were undertaken for deriving final data sets for potential probability of groundwater use.

a) **Map sheet grid creation:** A WSP area was divided into number of map sheets based on 1: 50, 000 map grid. Splitting the entire WSP area into small grids simplifies and eases GIS processes. The data set is recombined once processing has been complete

b) **Preparing base data:** The three main datasets (remote sensing data, vegetation communities and groundwater levels) were clipped as an extent of an individual map sheet grid of the WSP. Therefore, each of the grid datasets have the same scale of 1:50,000.

c) **Creating final layer for probability analysis:** Vegetation extent was considered as a base layer for identifying the GDE probability. Hence, the other two layers were combined with the vegetation layer. The process was done using UNION tool of ArcGIS. The GIS analysis was performed with data of each individual map sheets. The combined output layer is known as GDE probability layer in further discussion.

d) **Probability of groundwater use:** A probability ranking was assigned (1 to 4 in LEVEL 3 in the attribute table of the probability layer) to each individual vegetation community. This was based on the application of decision matrices using the attribute information within all three datasets and four levels of probability results generated in the Level 1 model for potential groundwater use (1 – high, 2 – medium, 3 – low and 4 other water source).

3.1 Remote sensing

The identification of potentially groundwater dependent terrestrial vegetation for this project has been based on the analysis of three indices: 1) the Normalised Difference Water Index (NDWI), 2) the Enhanced Vegetation Index (EVI) and 3) Regionally Normalised Temperature Index (RNTI).

The hypothesis for using the three indices in conjunction is based upon the notion that landscapes that are groundwater dependent will have both wetness and greenness parameters consistently at higher level with lower stress conditions in comparison to landscapes with low wetness and greenness conditions with frequent high stress conditions. The likelihood of terrestrial vegetation being groundwater dependent will be between these two limits as shown in Figure 4.

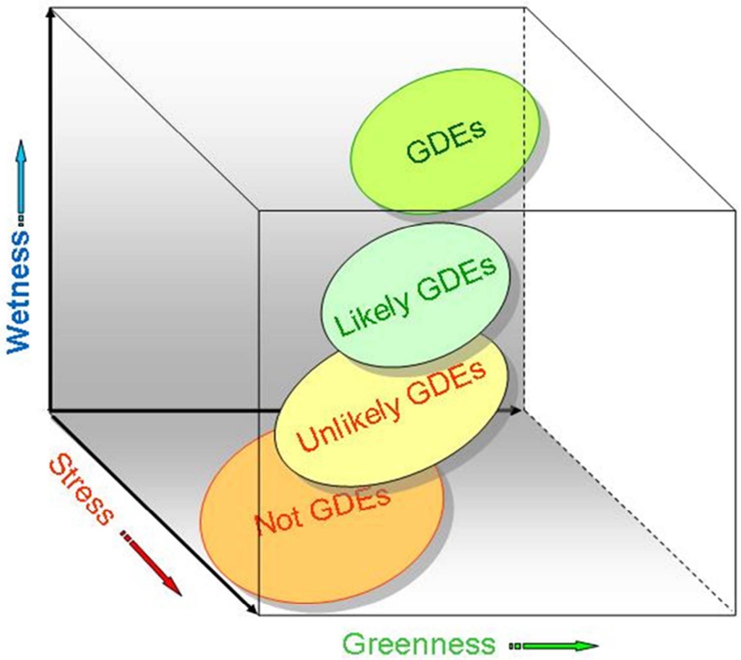

Figure 4: Hypothetical contribution patterns of vegetation greenness, wetness and stress indicators for classifying a landscape as potentially groundwater dependent.

Other methods for potential GDE identification have incorporated remote sensing derived data (e.g. Munch and Conrad 2007; Dresel 2010; Yang et al. 2011; Eamus et al. 2015). These methods have used limited time series imagery. Additional data sources included potential areas of saturated soil profiles, inferred shallow water tables, areas indicative of inundation and saline mapping (Munch and Conrad 2007; Dresel 2010). Dresel (2010) also used vegetation classes to distinguish differences in responses due to different vegetation classes having different remote sensing responses to continual water use.

This project has investigated the use of an extended time series of remote sensing imagery over a period of ten years and a combination of remote sensing indices to identify potential areas of interest as being potential GDEs.

3.1.1 Data sets used

Global MOD13Q1 data are provided every 16 days at 250-meter spatial resolution as a gridded level-3 product in the Sinusoidal projection. MOD13Q1 product contains two vegetation indices, Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI). Land Processes Distributed Active Archive Centre (LP DAAC) computes these indices from atmospherically corrected bi-directional surface reflectances that have been masked for water, clouds, heavy aerosols, and cloud shadows. The product contains 250-m 16-day EVI and NDVI composites, taking into consideration all images in each 16-day repeat cycle, which were combined into monthly composites. Composites representing longer periods of time appear to be more suitable for the present study than 1-day images. It reduces effects due to cloud contamination and data volume.

For this project, the 16-day composite data were obtained for ten-year period from February 2000 to December 2009. For the coverage of NSW area, five tile of the MODIS data are required, namely h29v12, h30V11, h30v12, h31v11 and h31v12, where h and v denote the horizontal and vertical tile number respectively. Therefore, approximately 1135 image tiles have been used.

This project only considered EVI due to EVI being an optimized vegetation index with improved sensitivity in high-biomass regions and vegetation monitoring characteristics. NDWI was computed with the NIR and MIR reflectance data sets (from the same composited image tiles).

The MODIS Land Surface Temperature and Emissivity (LST/E) product from Aqua-MODIS (e.g. MYD11A2 products) and Terra-MODIS (e.g. MOD11A2 products) provide per-pixel temperature and emissivity values on a daily basis. The project considered version 5 data series from Terra-MODIS LST product.

Following data sets/map layers were also used in the project.

- SPOT mosaic of NSW 2009 version (enabled the separation of woody and non-woody areas. This was achieved due to the spatial resolution of 2.5, 5 and 10 m pixels allowing vegetation community structures to be identified);
- Eco-hydrological zones of NSW (see Figure 5) (initially remote sensing analysis was undertaken statewide, but then stratified based on the eco-hydrological areas. This was because the coastal areas that typically had high soil moisture "swamped" any inland areas (as the analysis score things relative to each other) (SKM 2012); and
- Daily climate data (mainly rainfall and ET) from Silo.

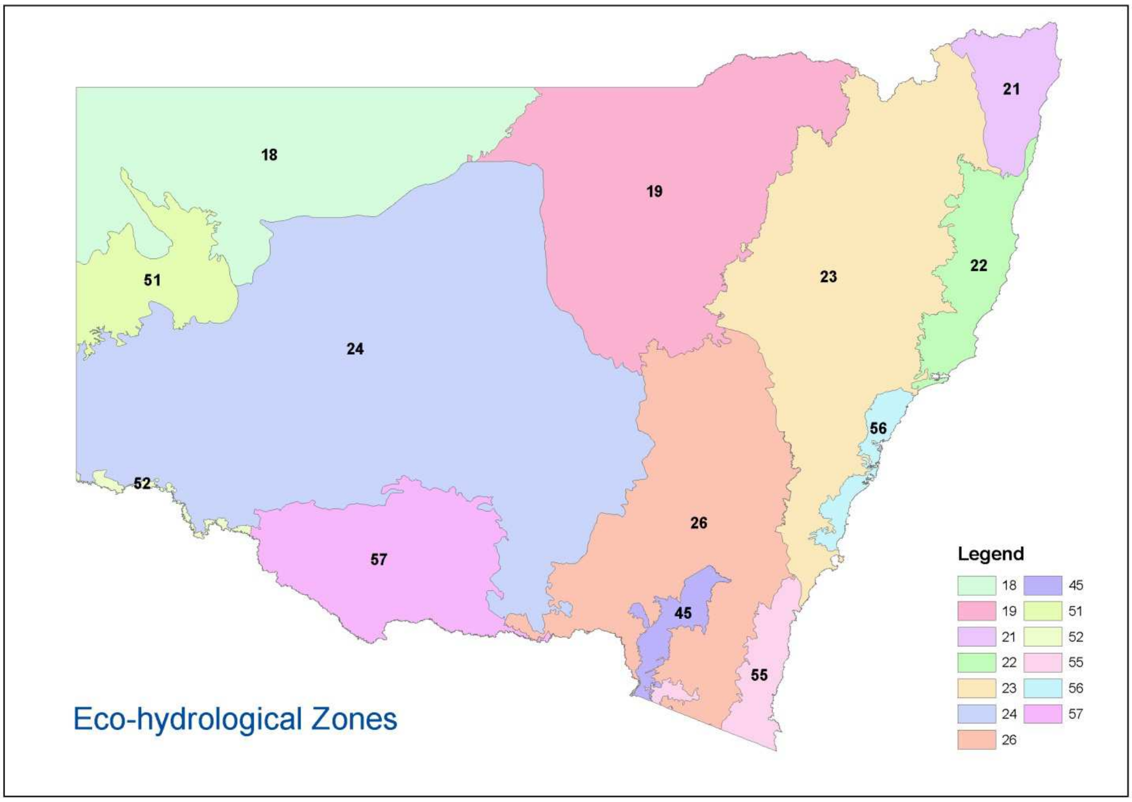

Figure 5: Eco-hydrological zones of NSW (source: SKM 2012)

Note: the legend numbers corresponds to zone names as per SKM (2012).

3.1.2 Sampling site selection and validation database

SPOT mosaic of NSW (2005 version) was used to differentiate and validate the MODIS VI data set into the vegetation cover types (woody and non-woody) due to the spatial resolution of 2.5, 5 and 10 m for SPOT 5.. A database of 7141 field sites of different land cover types were created and collected to represent 31 land use types (Table 2). The main reason for identifying a range of land cover types was to gain a broad understanding of the threshold values for various cover types (e.g. non-woody and woody vegetation).

Sites were selected from almost all major catchments distributed across the NSW area. This was done to ensure that each area had a representative geographic sample that reflected the diverse environmental conditions and management practices. Ideally, a randomly or systematically selected sample of sites would have been preferred because it is the only way to acquire objective, scientifically valid statistics. In Western NSW and most inland catchment areas the majority of the sites were selected in a systematic manner. However, this type of design was not practical in eastern and central NSW due to the fragmented nature of the diverse land cover footprints. This could lead to areas being under represented. To ensure that this did not occur, sites that were spatially distributed across each major catchment were selected.

Whenever possible, a 32 ha field size minimum (i.e. approximately five 250 m pixels) was accepted to ensure that the selected sites were sufficiently large to collect a representative spectral–temporal signal. A single pixel was used rather than a pixel window (e.g. 2×2 pixels) to eliminate mixed edge pixels composed of multiple cover types from being included in the training and validation data (Wardlow and Egbert 2008).

Table 2: Major land use types considered for selecting training samples, land use codes and their characteristics.

Major land use type	LU code	Description	Sample size
Wetland	3	Primarily vegetated, semi-aquatic, largely uncultivated (semi) natural - closed trees	48
	4	Primarily vegetated, semi-aquatic, largely uncultivated (semi) natural - open trees	84
	5	Primarily vegetated, semi-aquatic, largely uncultivated (semi) natural - sparse trees	144
	6	Primarily vegetated, semi-aquatic, largely uncultivated (semi) natural - shrubs - unclassified	53
	8	Primarily vegetated, semi-aquatic, largely uncultivated (semi) natural - shrubs - open	91
	9	Primarily vegetated, semi-aquatic, largely uncultivated (semi) natural - shrubs - sparse	241
	10	Primarily vegetated, semi-aquatic, largely uncultivated (semi) natural - grass/forbs	387
	11	Primarily vegetated, semi-aquatic, largely uncultivated (semi) natural - grass/forbs-closed	29
	12	Primarily vegetated, semi-aquatic, largely uncultivated (semi) natural - grass/forbs-open	40

Major land use type	LU code	Description	Sample size
	13	Primarily vegetated, semi-aquatic, largely uncultivated (semi) natural - grass/forbs-sparse	133
Woody	19	Primarily vegetated, terrestrial, largely uncultivated (semi) natural - closed trees	1203
	20	Primarily vegetated, terrestrial, largely uncultivated (semi) natural - open trees	550
	21	Primarily vegetated, terrestrial, largely uncultivated (semi) natural - sparse trees	494
	23	Primarily vegetated, terrestrial, largely uncultivated (semi) natural - shrubs - closed	71
Woody-modified	31	Primarily vegetated, terrestrial, cultivated/modified lands - plantations	44
	32	Primarily vegetated, terrestrial, cultivated/modified lands - trees	
Non-woody	24	Primarily vegetated, terrestrial, largely uncultivated (semi) natural - shrubs - open	259
	25	Primarily vegetated, terrestrial, largely uncultivated (semi) natural - sparse shrubs	329
	26	Primarily vegetated, terrestrial, largely uncultivated (semi) natural - grass/forbs	199
	27	Primarily vegetated, terrestrial, largely uncultivated (semi) natural - grass/forbs - closed	136
	28	Primarily vegetated, terrestrial, largely uncultivated (semi) natural - grass/forbs - open	74
	29	Primarily vegetated, terrestrial, largely uncultivated (semi) natural - sparse grass/forbs	220
Non-woody modified	34	Primarily vegetated, terrestrial, cultivated/modified lands - herbaceous (e.g. Improved pasture)	752
Crop	30	Primarily vegetated, terrestrial, cultivated/modified lands - crops	1271
Urban	35	Primarily vegetated, terrestrial, cultivated/modified lands - urban vegetated areas	182

Major land use type	LU code	Description	Sample size
Water	37	Non-vegetated aquatic - unclassified	19
Flood zone	38	Non-vegetated, aquatic, natural water features	12
Bare	36	Non-vegetated, terrestrial - unclassified	7
Extraction	64	Non-vegetated, terrestrial, non-built up, extraction sites	13
Built up	65	Non-vegetated, terrestrial, built up - unclassified	8
	71	Non-vegetated, terrestrial, built up, non-linear - industrial	48
		Total number of samples	**7141**

Note: For a complete description of the land cover classification codes refer to 'Classifying Australian land cover' by Atyeo and Thackway (2006)

3.1.3 Analysis of indices for studying vegetation behaviour during drought periods

The study of land cover dynamics during annual drying cycles could potentially identify areas that have access to groundwater by showing a smaller effect in severe dry conditions. In locations where there are GDEs, vegetation water content (NDWI) and greenness (EVI) are expected to be stable during prolonged drying events (Eamus et al. 2015). Similarly, vegetation stress condition (RNTI) should also reflect very low level of fluctuation or no visible change. However, terrestrial vegetation that is reliant on soils with a high water holding capacity could also exhibit similar trends but with a lesser extent (Eamus et al. 2015).

Careful analysis of vegetation water content pattern during the 10 year period (2000-2009) indicates that the peak water contents usually occur during mid-year and the lowest conditions towards the end of year, indicating a drying cycle of approximately 7 months. There were severe drought conditions across NSW during 2001 to 2003. Considering all these factors, three drying events were focused on for further analysis.

The selected drying periods were:

1. 9 June to 31 December, 2000 – The first half of year 2000 was a reasonably wet period and was used to provide base conditions for comparison;
2. 9- June to 31 December, 2001 – In 2001 state-wide drought was noted; and
3. 9- June to 31 December, 2002 – Drought which commenced on 2001 continued throughout 2002 and hence provided extreme dry conditions which are ideal for identify GDEs.

The results of this analysis indicate:

1. Reasonably good wetness predictions may be obtained for different land types with NDWI;
2. Substantial decrease of wetness is evident in drying events;
3. Drying effect on coastal alluvimum is visible only during severe drought conditions such as in 2002. Under normal conditions, consistent wetness is maintained throughout the drying cycle;
4. In general, nearly consistent level of greenness is maintained during a drying cycle. Under severe drought condition, it can show a slight reduction;

5. However, greenness can be high towards the end of a dry period if water is not a limiting factor (as in coastal alluvial during 2000 and 2001); and
6. Considering 8-day average RNTI values, it can conclude that severity of stress condition vary from cover type to cover type.

An example of the results of the vegetation water content (NDWI) and greenness (EVI) and vegetation stress condition (RNTI) for the severe drying period is shown below in Figures 6 to 8.

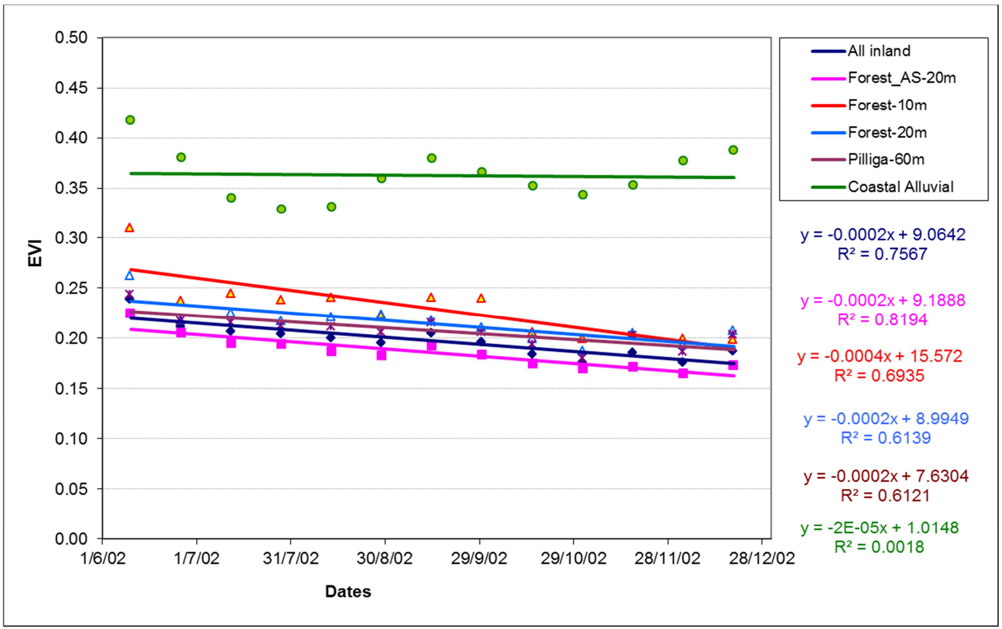

Figure 6: Vegetation greenness during drying period-3 (9 June – 31 December, 2002).

Note: Linear regression lines and associated (colour-coded) equations are to show the strengths of greenness relationships in different ecosystems where the legend indicates soil depth.

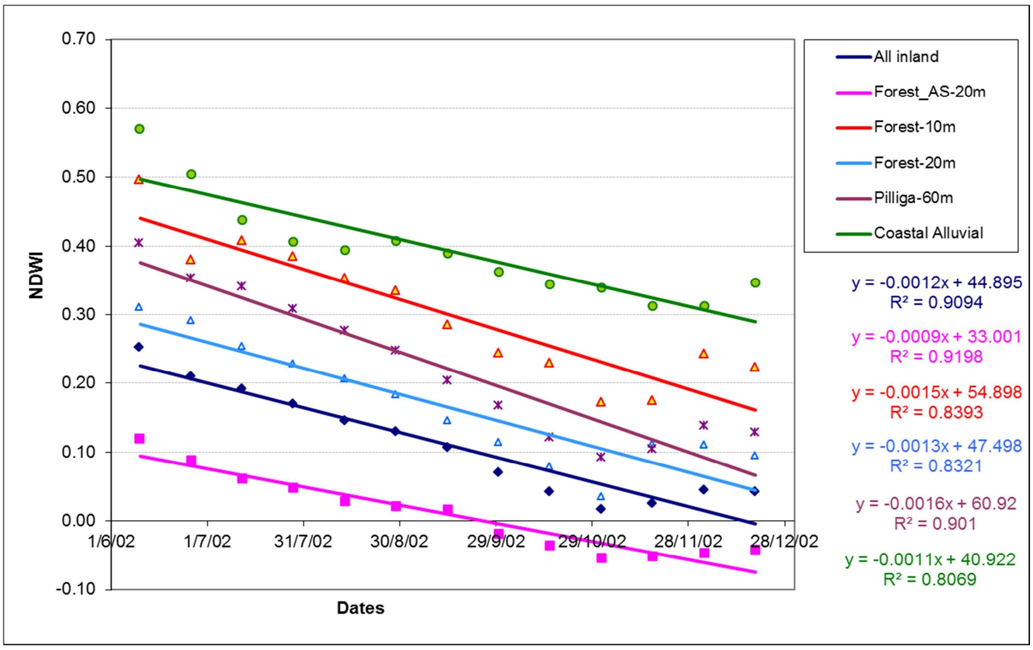

Figure 7: Vegetation water content during drying period -3 (9 June – 31 December, 2002).

Note: Linear regression lines and associated (colour-coded) equations are to show the strengths of wetness relationships in different ecosystems where the legend indicates soil depth.

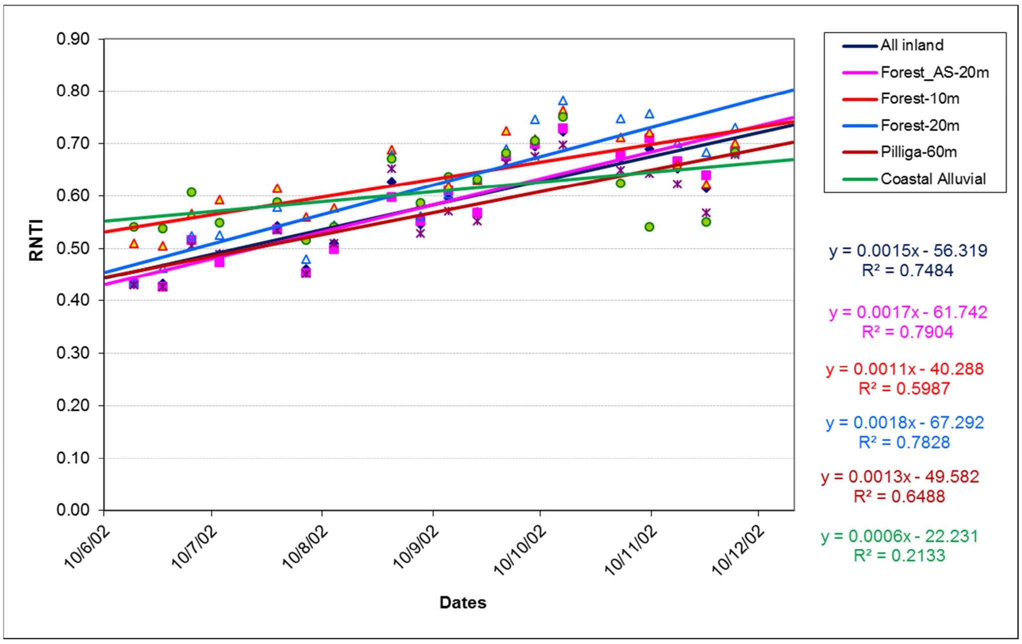

Figure 8: RNTI based vegetation stress pattern during drying period 3 (9 June – 31 December, 2002)

Note: Linear regression lines and associated (colour-coded) equations are to show the strengths of wetness relationships in different ecosystems where the legend indicates soil depth.

3.1.4 Final parameters used in the remote sensing model

A total of ten parameters have been identified for defining threshold limits at each site. Selected parameters and their main function are summarized in Table 3.

Table 3: Key parameters considered in the decision tree model

Item/s	Parameter	Purpose
1	Eco-hydrological zones	Classify image based on hydrological zones
2	EVI - Ten-year mean	Identify terrestrial vegetation
3	EVI - Ten-year standard deviation	Identify long-term stability of vegetation greenness
4	EVI – Annual mean	Identify terrestrial vegetation
5	EVI - Annual standard deviation	Identify annual stability of vegetation greenness
6	EVI – Summer mean	Include vegetation greenness during summer
7	EVI – Winter mean	Include vegetation greenness during winter
8	NDWI – Winter mean	Include wetness during winter season
9	NDWI – Summer mean	Include wetness during summer season
10	RNTI – Annual mean	Include stress information

Based on the entire NSW data set, it was found that long-term mean greenness index (EVI) for perennial vegetation ranges from 0.15 to 0.55. The mean EVI during 2000 to 2009 provides a basis for separating green woody areas from non-green areas. Particularly, long-term mean EVI, annual standard deviation and summer EVI layers are useful to define the spatial areas where terrestrial GDEs will exist. These layers help to exclude landscapes that do not have constant growth or growth similar to identified potential GDE areas.

NDWI during summer, winter and annually delineate landscapes that are actively growing by maintaining vegetation wetness characteristics. NDWI provides information on vegetation community condition. Therefore, seasonal and annual NDWI statistical parameters together with summer/winter and seasonal/annual ratios help further divide the landscapes into subcategories and finally, to identify the potential GDEs, likely GDEs, unlikely GDEs and definitely non-GDE areas. Each layer contains an essential component in defining a candidate GDE.

Figure 9 shows seasonal EVI patterns of a known GDE throughout the year based upon monthy and annual mean observations. While in some years healthy trees usually follow constant path say above 0.2 level, during very dry years greenness of stressed vegetation appear to below 0.2 level.

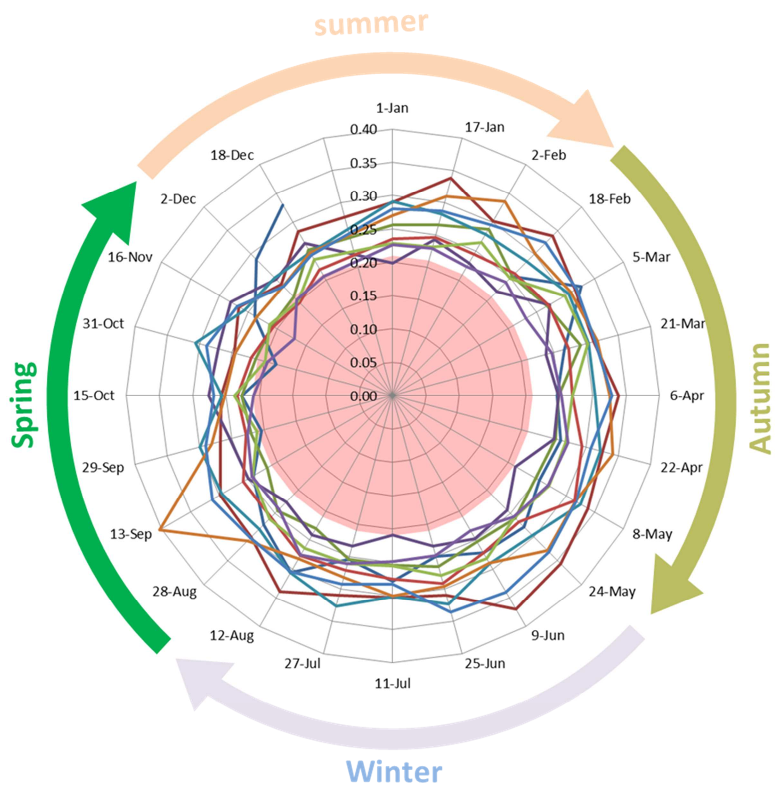

Figure 9: Radial plot showing the seasonal EVI dynamics of a known GDE location during 10 year period.

Note: Each line graph, which takes a near-circular pattern and propagates in clockwise direction with the progress of season. Colours of the outer circle represents seasons winter, spring, summer, and autumn.

The extracted NVI data sets were then used to derive statistical parameters such as mean, minimum, maximum, and standard deviation for major land cover types on a seasonal, annual and long-term basis by major eco-hydrological zones (SKM 2011). The derived statistical parameters provided the basis for identifying land areas that satisfied the main selection criteria of consistent greenness and wetness and low stress during seasonal and annual cycles to form annual map layers. The annual maps were added together (see examples in Figures 10 and 11). These figures show the frequency of a vegetation community potentially accessing groundwater during 2000 to 2009. The frequencies developed from this process are those that are then used in the decision rules (Section 3.6) and in Tables 5 to 7.

In the development of the spatial model for the identification of probable GDEs, five sets of decision rule matrices were tested for applicability of the decision rules and assumptions. The main assumption that was tested was that a high probability GDE could be defined using a "potential frequency of groundwater use" of 5 to10 years out of a 10 year period. A rapid field validation looking at vegetation species and location, and local knowledge of groundwater levels was conducted prior to adoption of the final decision rules in a coastal catchment. A coastal catchment was chosen due to the higher rainfall occurring on the coast than inland. The Hunter Central Rivers catchment area was chosen due to the number of vegetation species present, variation in topography and rainfall. The rapid field verification revealed this assumption to be false, due to the likely influence of soil moisture in coastal areas, hence the move to defining a high probability GDE as a 9 to10. This has resulted in a more conservative classification approach in the decision rules used for the identification of potential GDEs.

In Figures 10 and 11 the frequency of 1 refers to the potential use of groundwater by vegetation once in a ten year period and 10 refers to the potential use of groundwater almost every year during the same period. Frequency of 11 is for the areas where the pixel resolution has not allowed vegetation to be detected or there is no vegetation present.

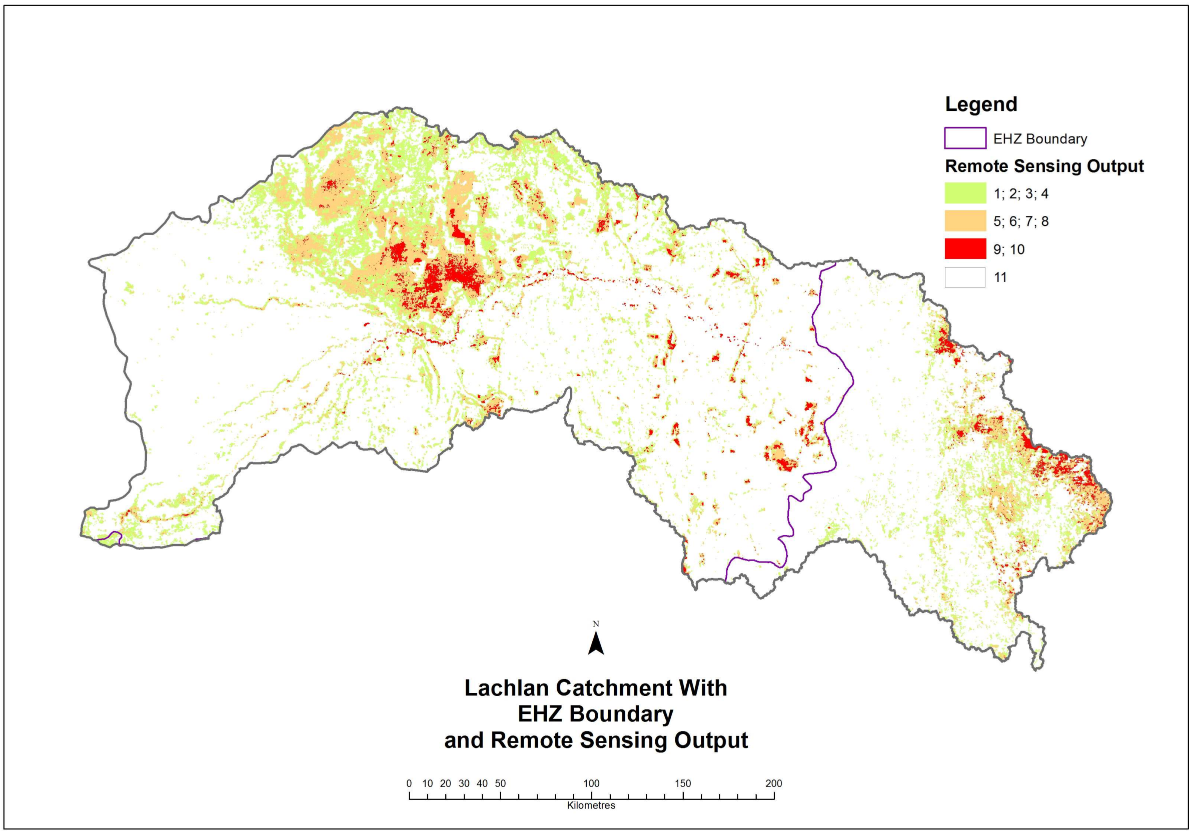

Figure 10: Probability of groundwater use in the Lachlan Catchment based on MODIS data

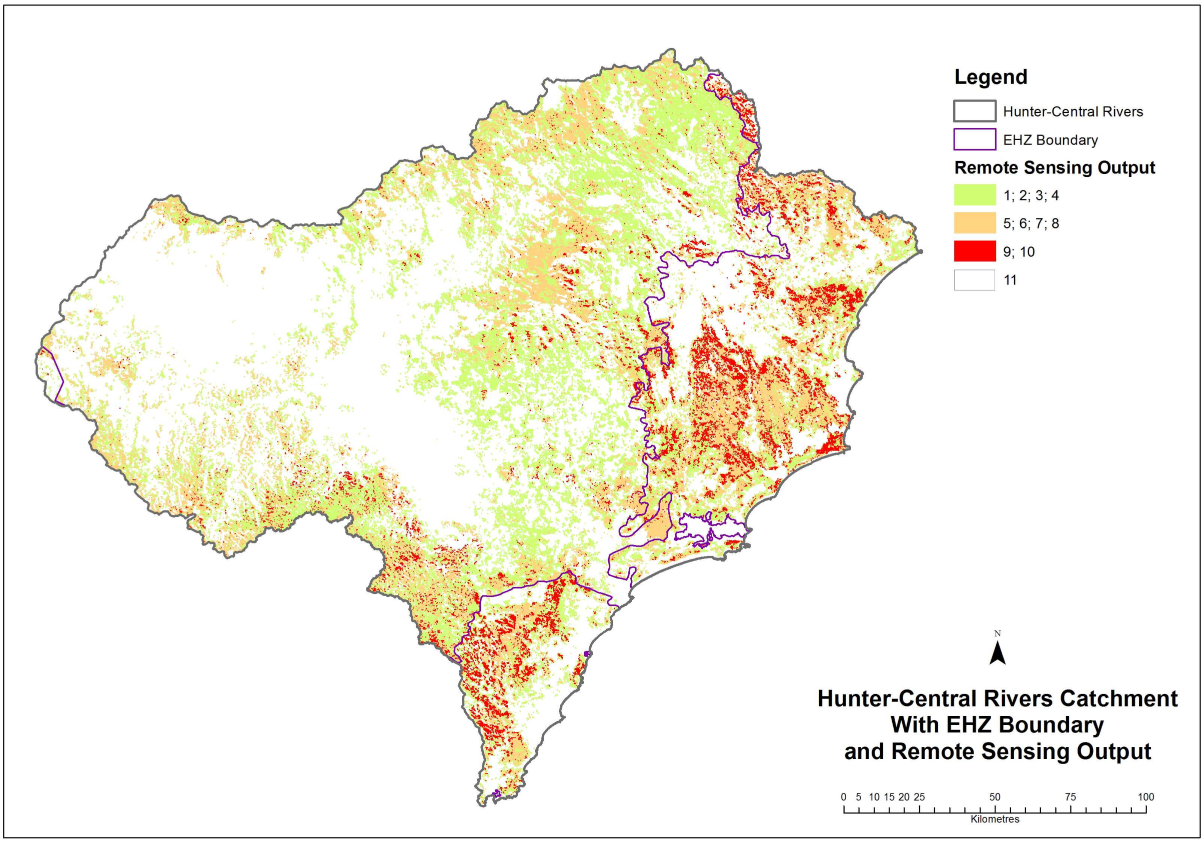

Figure 11: Probability of groundwater use in the Hunter Central Rivers Catchment based on MODIS data

3.2 Vegetation communities

Vegetation community data were sourced from the Office of Environment and Heritage (OEH). This data were developed as part of the OEH state-wide vegetation classification and mapping program that aims to provide a consistent, regional scale reference map of the NSW Plant Community Types for all NSW (Office of Environment and Heritage 2015). This data set was used as the GIS base layer for the structure classification in Level 1 and the basis for the Level 2 assessment (Figure 4). Associated community descriptions were used to identify structure and classify vegetation into woody and non woody classification. This separation was essential as woody and non woody vegetation was assessed separately using different decision rules.

Structure refers to the physical arrangement (e.g. height, horizontal cover and vertical layering) of plants that grow together (Keith 2004). The attribute field "structure" within the derived potential GDE dataset was based on Keith (2004). Categories within this attribute field are described below:

- Woodland/forest/rainforest (vegetation dominated by trees and include grassy woodlands, dry and wet sclerophyll forests and rainforests);
- Heathlands (vegetation that lacks trees other than short mallee forms or occasional emergents; contains a dense to open layer of shrubs with small, hard leaves and sedges, sometimes with isolated trees);
- Shrublands (vegetation dominated by shrubs and include the chenopod shrublands and acacia shrublands);

- Grasslands (vegetation that is dominated by large perennial tussock grasses with herbs; and lack trees and woody shrubs);
- Freshwater wetlands (inland/coastal -wetlands dominated by shrubs, sedges or herbs; excludes wetlands that are dominated by trees. They occur in areas that are waterlogged or flooded from time to time, on coastal lowlands, elevated tablelands and floodplains of inland river systems). Freshwater wetlands also include upland wetlands (e.g. bogs and swamps, fens);
- Forested wetlands (wetlands dominated by trees including eucalypts, paperbarks and casuarinas, with an understorey of water-loving herbs, sedges and rushes. They are restricted to floodplains and riverine corridors on coastal lowlands and along inland watercourses); and
- Saline wetlands (include a variety of communities composed of plant species that tolerate high levels of salt. Most saline wetlands, including mangrove forests, salt marshes and seagrass meadows, occur within coastal estuaries, although some are associated with salt lakes in arid inland regions).

The broad vegetation types defined as woody, non woody and non woody wetlands are identified in Table 4.

Table 4: Classification of vegetation into woody and non-woody

Woody vegetation	Non woody vegetation	Non woody wetlands
Woodland/forest/rainforest	Heathlands	Freshwater wetlands
Estuarine forests	Shrublands	Saline wetlands (includes seagrass/salt marsh)
Forested Wetlands (includes swamp forests)	Grasslands	Upland wetlands (includes bogs and fens)

3.2.1 Identification of definite GDE vegetation species or communities

Scientific literature and the community descriptions provided by OEH also provide information to help inform if a species or community is a probable or definite GDE to create a data set for Level 2 of the model which is a key step in Level 2 (see Section 3.5). Although there is much uncertainty as to which species within a given ecosystem depends on groundwater (fully or partially), certain plants/communities can indicate the presence or absence of shallow groundwater. The scientific literature and OEH vegetation descriptions were used to make an informed decision for the rating of each vegetation community a 1 (high), 2 (medium) or 3 (low) for probable groundwater dependence. A subset of 1 (high) was classified as definite GDEs, to override outputs from Level 1 in those cases where the Level 1 output may be questionable (i.e. where Level 1 does not support a “definite” Level 2) (see examples in Figures 12 and 13)).

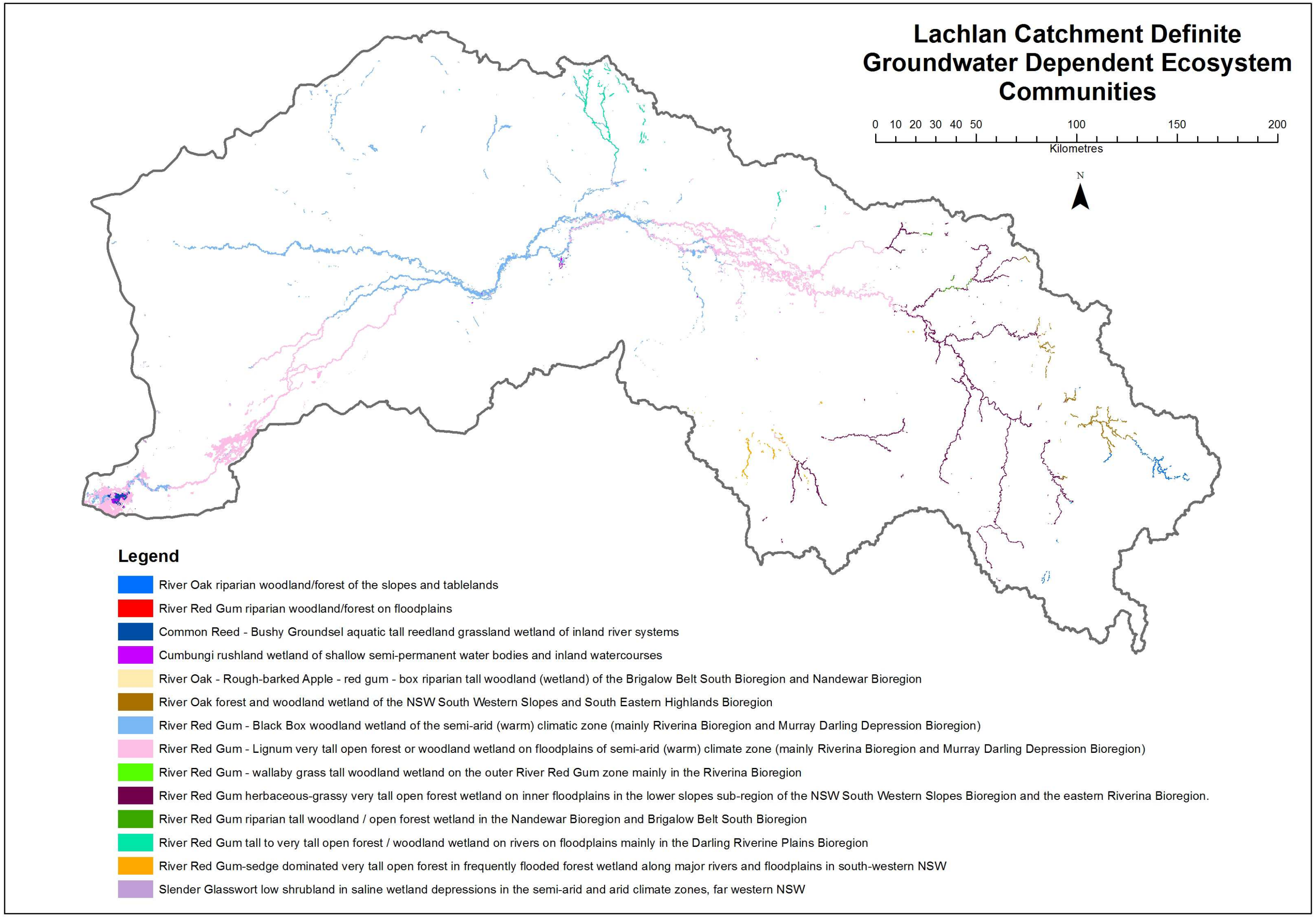

Figure 12: Definite groundwater water dependent vegetation communities identified in the Lachlan catchment, based on Level 2 assessment.

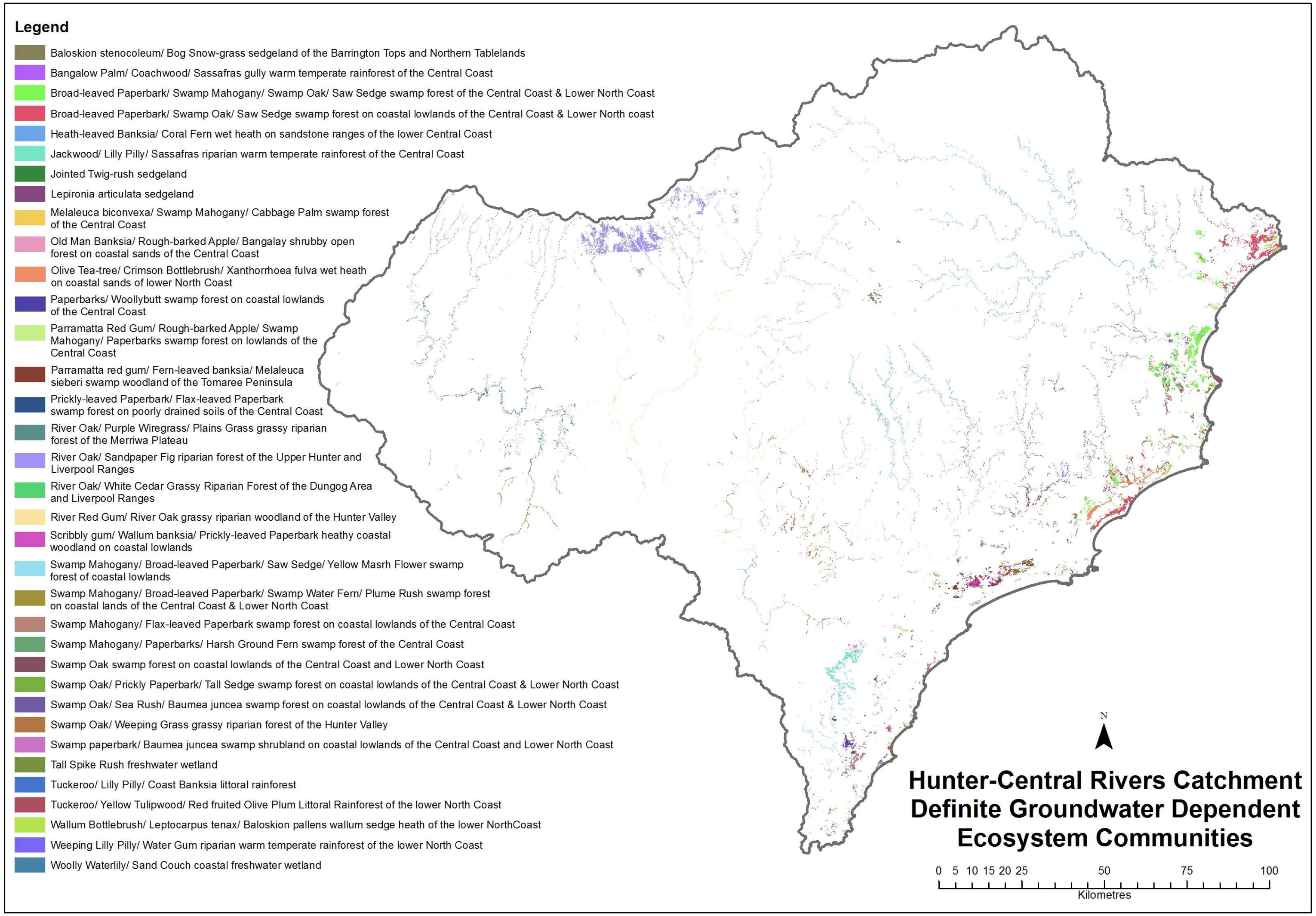

Figure 13: Definite groundwater water dependent vegetation communities identified in the Hunter Central rivers catchment, based on Level 2 assessment.

3.3 Groundwater levels

DPI Water has an extensive monitoring bore network across NSW. Observed groundwater level data were extracted for all bores in each of the catchments in NSW. These bores provide both continuous and manual measured groundwater levels in a time scale ranging from daily to monthly. From these observed data, an average groundwater level for the time period from 2000-2009 was used to obtain groundwater level contours for the shallowest groundwater levels. The groundwater data were accessed from DPI Water groundwater database and the contours were developed using the SURFER version 12 contouring software package. The aim of using this data were to ensure that the groundwater levels used were representative of the time period that was used in the remote sensing data analysis. Using the observed data increased the certainty in the data and thus the model outputs.

The groundwater data component of the spatial model provided two options for data type to be used, observed data from monitoring bores or modelled groundwater levels. Initially modelled groundwater data were assessed if appropriate for the level of confidence required for GDE identification. The model chosen was the state wide depth to water table data set used was a modelled raster layer developed by Summerell and Mitchell (2011) and based on a 50m grid resolution. The issues around this model are that it was based upon the Fuzzy Landscape Analysis Geographic information system (FLAG) upness model (Summerell et al. 2004). This model was developed to predict spatial extents of water logged to seasonally water logged, saline and sodic soils. Summerell and Mitchell (2011) improved this model by incorporating groundwater levels, however the model was only applicable for the coast areas of NSW east of the Great Dividing Range. Other researchers have explored the use of various regional models including climate and groundwater to monitor for impacts and potentially aid in the identification of potential GDEs (Dresel et al. 2010; Hocking and Beverly 2011; Klove et al. 2014). The degree of uncertainty in model outputs is dependent on the hydrogeological system being modelled and the type of model being used to take into account the interactions between ecological, hydrological and hydrogeological systems (Klove et al. 2014).

Based upon the Summerell and Mitchell (2011) model having a decreasing reliability further west of the Great Dividing Range and no outputs for far western NSW, and the information gained by other researchers, the decision was made to have a more consistent approach to the type of groundwater level data used. This consistent approach across the state was aimed at giving a higher confidence in groundwater data and spatial model results.

DPI Water has an extensive monitoring bore network across NSW that are either monitored on a monthly basis via manual water level readings or via telemetered continuous monitoring network. Based upon the level of data available, the decision was made to use observed groundwater level data, as this would provide a more representative data set of the shallowest groundwater levels within each catchment. These data will also be used in further field validation and condition monitoring of the identified probable GDEs throughout the life of the WSPs and WRPs. A consistent approach with use of groundwater data will also increase the certainty of the spatial model results. Figures 14 and 15 show the groundwater contours for the Lachlan and Hunter. The extent of groundwater monitoring bores in the coastal catchments is far less than the inland catchments, thus groundwater information from other sources will be used to supplement the DPI Water dataset.

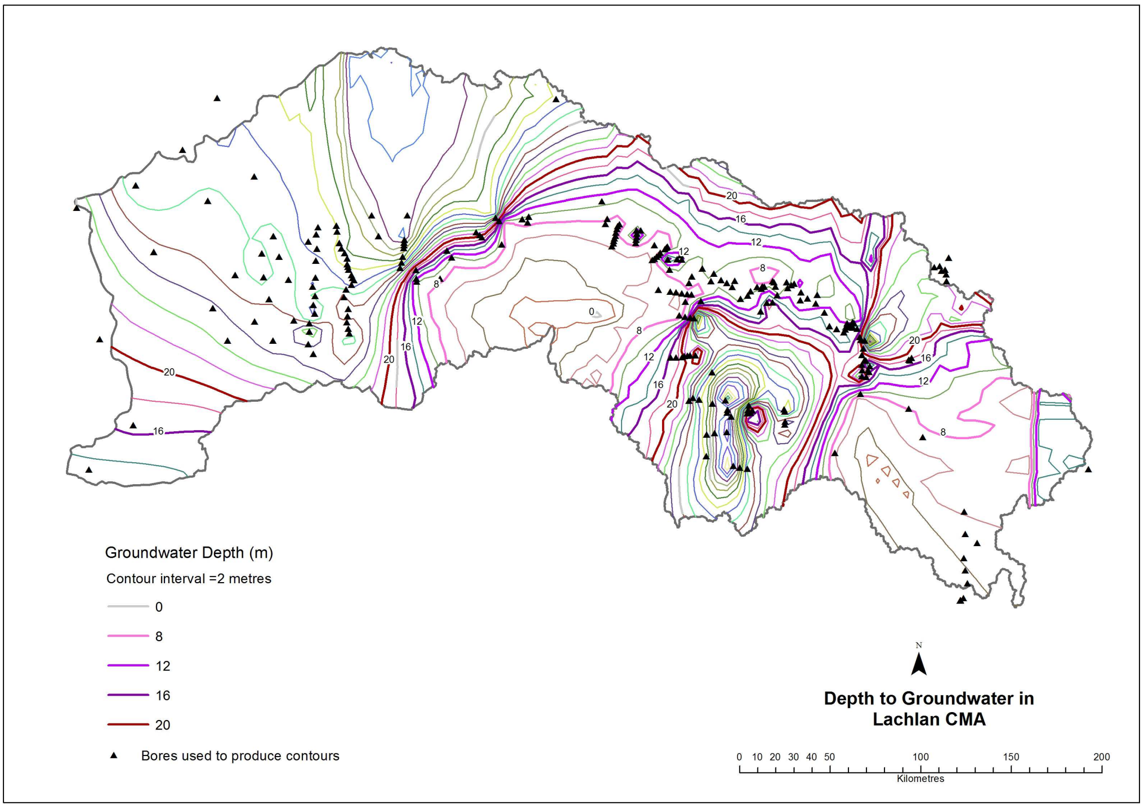

Figure 14: DPI Water groundwater monitoring bore locations and groundwater level contours for the Lachlan.

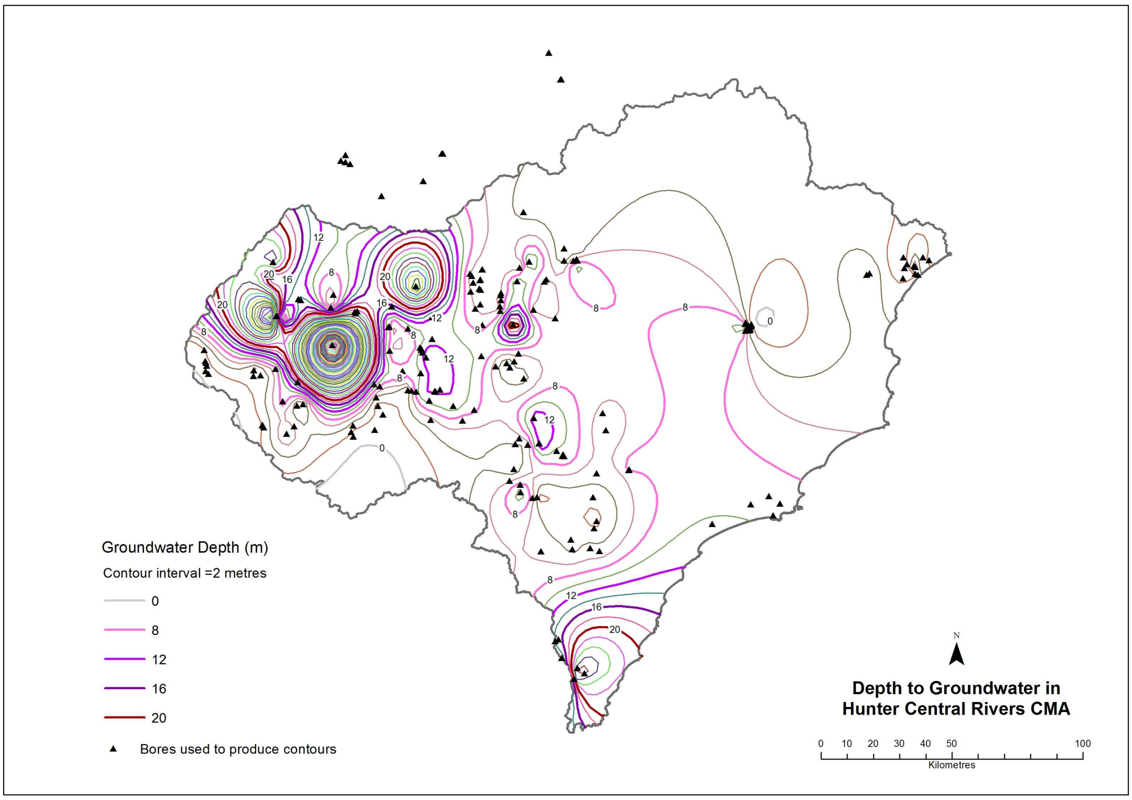

Figure 15: DPI Water groundwater monitoring bore locations and groundwater level contours for the Hunter.

3.4 Spatial model assumptions

Dependency on groundwater was inferred using decision rules. These rules were based on scientific literature that describes how these ecosystems function, as well as a generic understanding of groundwater/ecological interactions. A brief literature review of this understanding was presented in Section 2.

The decision rules used to determine the probability of groundwater use by an ecosystem are based on a number of assumptions (e.g. Cresswell and Bridgewater 1985; Dodd and Heddle 1989; Froend & Zencich 2001; Froend et al. 2004; Naumburg et al. 2005; Eamus et al. 2006a; Griffith and Wilson 2007), including:

1. The greater the groundwater depth the less likely the dependence of an ecosystem on that groundwater.
2. If groundwater is within the potential reach of the rooting zone, the more likely the dependence on that groundwater.
3. Plants, particularly those with deeper root systems (e.g. woody vegetation), are more likely to access shallow water tables (i.e. 0 to 12 m) but can access water levels down to 20 m.
4. Ecosystems that rely on the sub-surface expression of groundwater are more likely to occur where water tables are shallow. Therefore, landscape position of vegetation communities can be used to infer a potential dependence on groundwater.
5. Topography can be used to indicate areas of shallow groundwater (e.g. topographic depressions) or where groundwater is likely to discharge (e.g. bottoms of steeply incised valleys).
6. Vegetation surrounding springs are likely to be groundwater dependent.
7. Vegetation occurring along streams are likely to access groundwater.
8. Certain types of communities/species are more likely to use groundwater (see Appendix 1 for examples).
9. Permanent water bodies can be indicative of groundwater discharge (i.e. especially if flow/water is maintained during drier periods).
10. If vegetation exhibits a relatively constant level of activity within an identified spectral threshold it is assumed to be accessing groundwater.

There are a number of limitations associated with the decision rules used to determine the probability of groundwater use, including:

1. The rules only infer groundwater use/dependency.
2. The rules are based on a limited knowledge of plant rooting depth.
3. The rules that relate to ecosystem type and landscape position are not as robust as the rules associated with water depth.
4. The rules do not take into account that vegetation will access and use the most readily available water source (i.e. vegetation will use soil water in preference to groundwater, even if readily available).
5. Application of rules is limited by the spatial extent of datasets (layers) and gaps in the data due to spatial variations and/or anomalies. This can result in an over or under representation of potential GDEs.

6. Spatial limitations also occurred due to the spatial resolution of MODIS being quite large (250 x 250 m). This may cause small or linear GDE communities to go undetected.

3.4.1 Defining potential Groundwater use

A number of specific rules were developed to define 'bands' for potential groundwater use. These rules, as described below, are incorporated into several decision matrices that were applied to woody and non-woody communities to identify vegetation that might be dependent on groundwater. These rules are constrained to allow for increased certainty of potential of groundwater use.

3.4.1.1 Defining a very high and high potential for groundwater use

The following rules have been applied to vegetation communities that have a high potential for groundwater use:

- Occur at a location that has groundwater levels less than 12 metres;
- Occur at locations where the topography is low lying (e.g. gentle slopes, topographic depressions) and groundwater is likely to be close to the surface;
- Occur at the bottom of steeply incised valleys where groundwater is likely to discharge;
- Occur on the banks of rivers and creeks;
- Have species with a documented association with groundwater (not necessarily at that particular location);
- Have species that are considered to be deep rooted (refer to Section 2 for a discussion on rooting depth); and
- Be located on well drained geological substrates for example gravels and sandy soils (e.g. alluvial sediments and coastal sands).

3.4.1.2 Defining a moderate potential for groundwater use

The following rules have been applied to vegetation communities that have a moderate potential for groundwater use should:

- Occur at a location that has groundwater levels between 12 and 16 metres;
- Occur mostly in landscapes that are generally low lying where groundwater is more likely to be closer to the surface;
- Have species with a potential association with groundwater use; and
- Have species that might be deep rooted.

3.4.1.3 Defining a low and very low potential for groundwater use

The following rules have been applied to vegetation communities that have a low potential for groundwater use should:

- Occur at a location that has groundwater levels greater than 16 metres;
- Occur in locations that are steep, or hilltops, ridges and rocky hills;
- Have species that are considered to be shallow rooted (e.g. chenopods, grasslands); and
- Be located on heavy, clay soils, skeletal or shallow soils.

3.5 Decision rules used to determine potential access to groundwater

The process by which potential Level 1, Level 2 and Level 3 vegetation community GDEs were identified is shown in Figure 16. This figure also lists the codes and decision rules (matrices) that are assigned at various points in the process.

Where the decision matrices could not be applied and a probability of groundwater use could not be assigned, arbitrary codes were assigned to track these combinations within the data set. The identification code 90, for example, was assigned to polygons where water table level information was available but vegetation mapping and remote sensing information was not. The identification code 99 was assigned to polygons classified as urban, rock, water etc. (i.e. polygons to which a vegetation "structure" could not be assigned) and no remote sensing data. The final level 3 results will be derived from the Level 2 result.

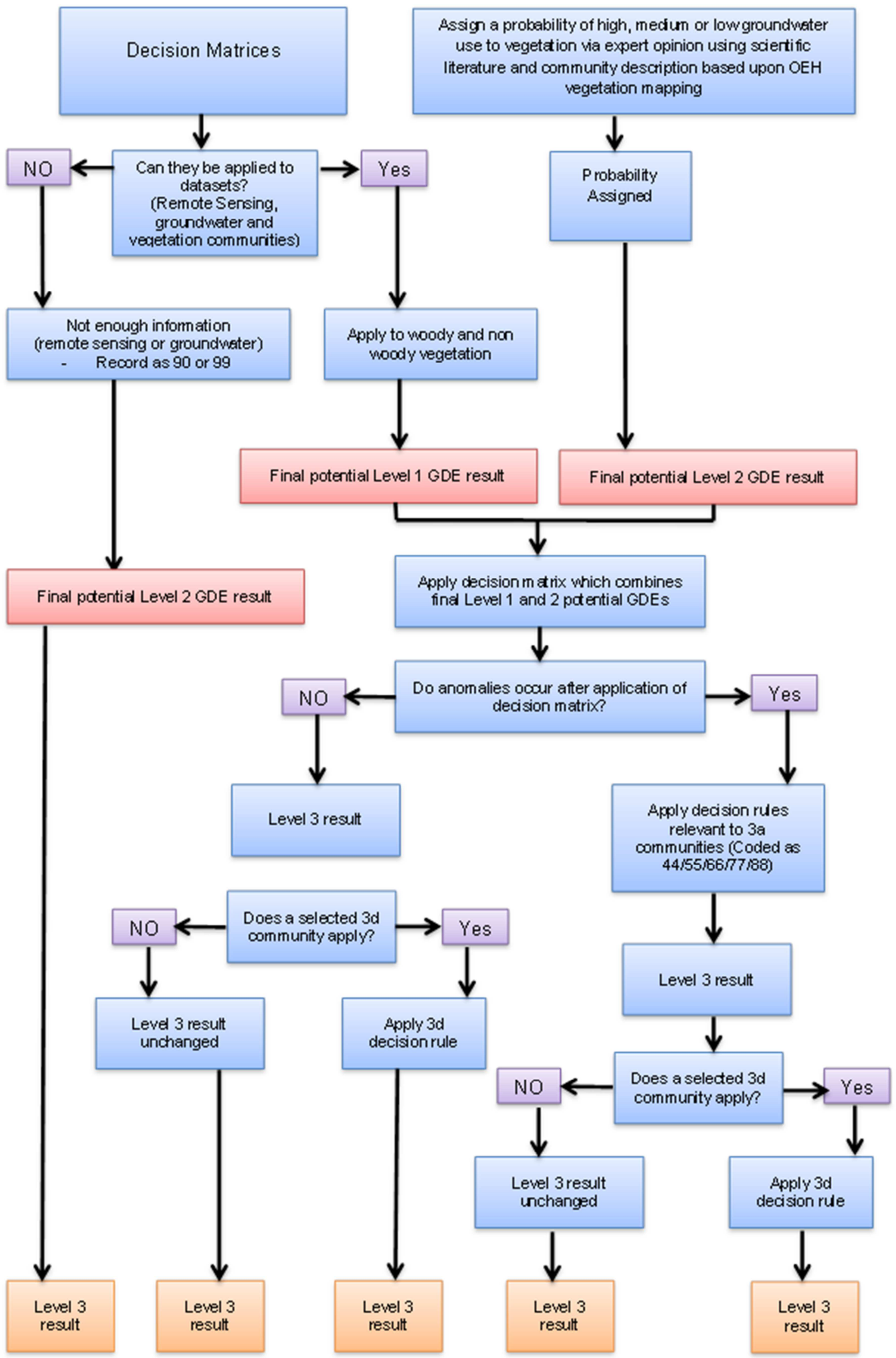

Figure 16: Process logic for identifying potential GDEs

Note: 3a rules coded are 44/55/66/77/88 are codes relating to anomalies that result out of the combination of Level 1 and 2 results (see Appendix 1). 3d decision rule are the definite GDEs.

3.6 Matrices for Level 1 results

Level 1 results for potential groundwater dependence of vegetation communities were identified by applying matrices (e.g. Tables 6 to 8). Embedded within these decision matrices are assumptions around the interaction of ecosystems and groundwater (section 3.4). Level 1 results were given a probability of groundwater use ranking of 1 to 4 (with 1= high, 2 = medium, 3 = low and 4 = other source).

Matrix 1 (Table 5) was applied to determine potential groundwater dependent level 1 woody ecosystems (Woodland/forests/rainforests, Estuarine Forests (includes mangrove forests) and Forested wetlands (includes swamp forests).

Matrix 2 (Table 6) was applied to determine potential groundwater dependent level 1 non-woody ecosystems (shrublands, heathlands and grasslands) excluding wetlands.

Matrix 3 (Table 7) was applied to determine potential level 1 non-woody groundwater dependent wetlands (saline wetlands and freshwater wetlands).

Table 5: Matrix 1 - decision rules used to identify potential groundwater dependent woody ecosystems, including woody wetlands

		Potential frequency of groundwater use from remote sensing (number of years in a 10 yr period)		
		1-4	**5-8**	**9-10**
Groundwater level (m)	**0-8**	3	2	1
	8-12	3	2	2
	12-16	3	3	2
	16-20	4	3	3
	>20	4	4	3

Table 6: Matrix 2 – decision rules used to identify potential groundwater dependent non-woody ecosystems, excluding wetlands.

		Potential frequency of groundwater use from remote sensing (number of years in a 10 yr period)		
		1-4	**5-8**	**9-10**
Groundwater level (m)	**0-8**	4	3	2
	8-12	4	4	3
	12-16	4	4	4
	16-20	4	4	4
	>20	4	4	4

Table 7: Matrix 3 - decision rules used to identify potential non-woody groundwater dependent wetlands.

		Potential frequency of groundwater use from remote sensing (number of years in 10 yr period)		
		1-4	**5-8**	**9-10**
Groundwater level (m)	**0-8**	4	2	1
	8-12	4	4	**2**
	12-16	4	4	**3**
	16-20	4	4	4
	>20	4	4	4

3.7 Decision rules for level 2 results

Potential level 2 groundwater dependent vegetation communities were identified via scientific literature and a desktop analysis of the vegetation community description (Section 3.2) together with the landscape in which that vegetation occurred (see Section 2 for literature review). A rating of 1 (high), 2 (medium) and 3 (low) was assigned to each vegetation community for probable groundwater dependence along with a subset of 1 (high) for definite GDEs used for 3d decision rules (Section 3.2). A rapid field assessment was undertaken in the Hunter Central Rivers WSP area to verify a subset of vegetation communities that are known to be groundwater dependent but can occur in various topographic locations (in valleys and on ridges). The results of the field verification were used to apply a more conservative approach to the assignment of a probability of groundwater use to particular vegetation communities. These communities were generally then assigned a moderate probability of being groundwater dependent.

4 Final model results

Final model results are derived from the combination of level 1 and 2 results from which the assumptions and decisions rules discussed above will allow the model to either accept level 1 results or level 2 results. The decision matrix in Appendix 1 shows when a level 1 or 2 result is accepted for all model combinations.

The main examples of the decision rules are:

- Level 1 results (shallow groundwater or potential frequency of groundwater use, from remote sensing data is 9 or 10) were to override level 2 result when the level 2 results is a low.
- Level 2 results (arising from the data set created from assigning potential groundwater using scientific literature as a definite GDE) override level 1 result. This occurred when there was a lower confidence in the data OR it may be an anomaly (i.e. the regional groundwater is deep, but the vegetation community is within a riparian zone and accessing local shallow groundwater).

The final model results for high probability are shown in Figures 17 and 18. The majority of the high probability GDEs identified tend to be along riparian zones within the inland catchments (e.g. Figure 17 showing the Lachlan catchment). Within the coastal zone, the high probability GDEs, occur at a high density in areas such as the coastal sands (e.g. Figure 18 showing the

Hunter Central River catchment). The majority of these species are known to be definite GDEs as described in Section 3.2.1 and shown in Figures 12 and 13.

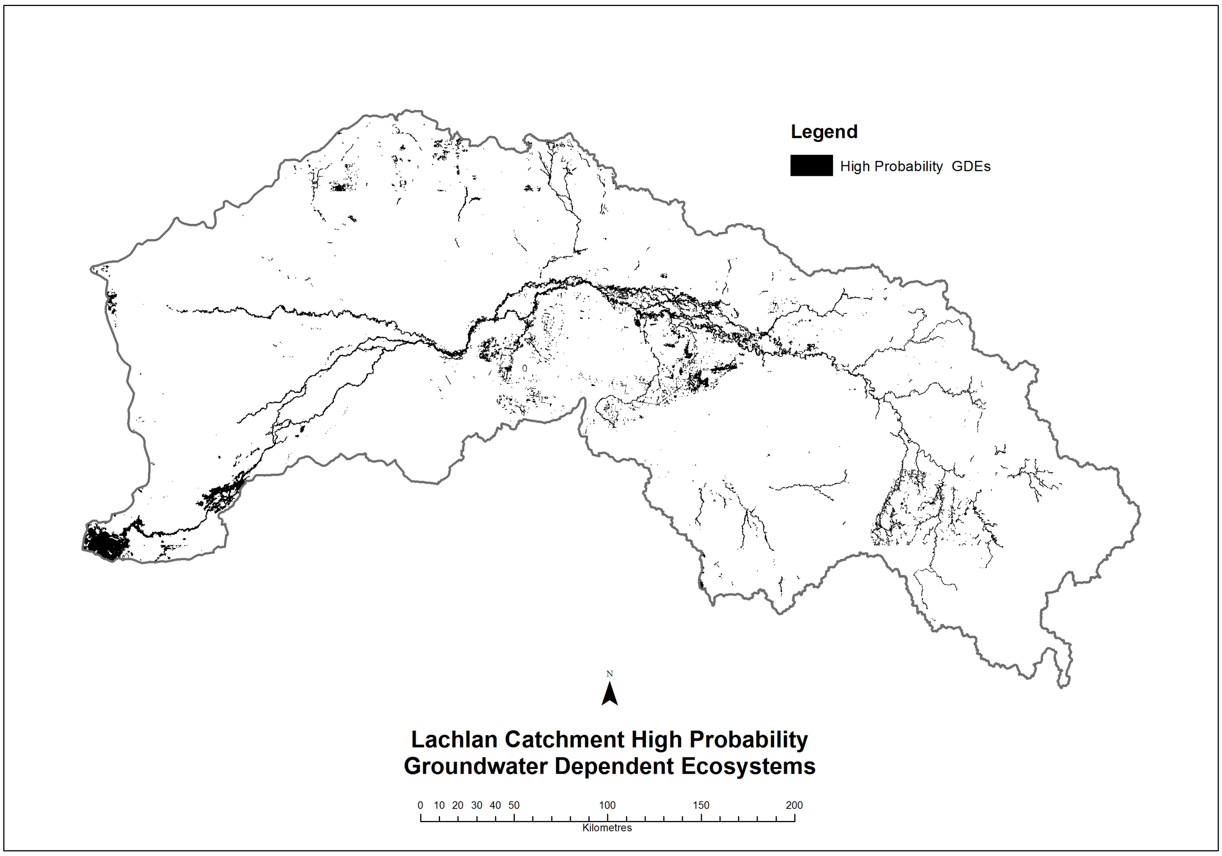

Figure 17: High probability GDEs located within the Lachlan catchment

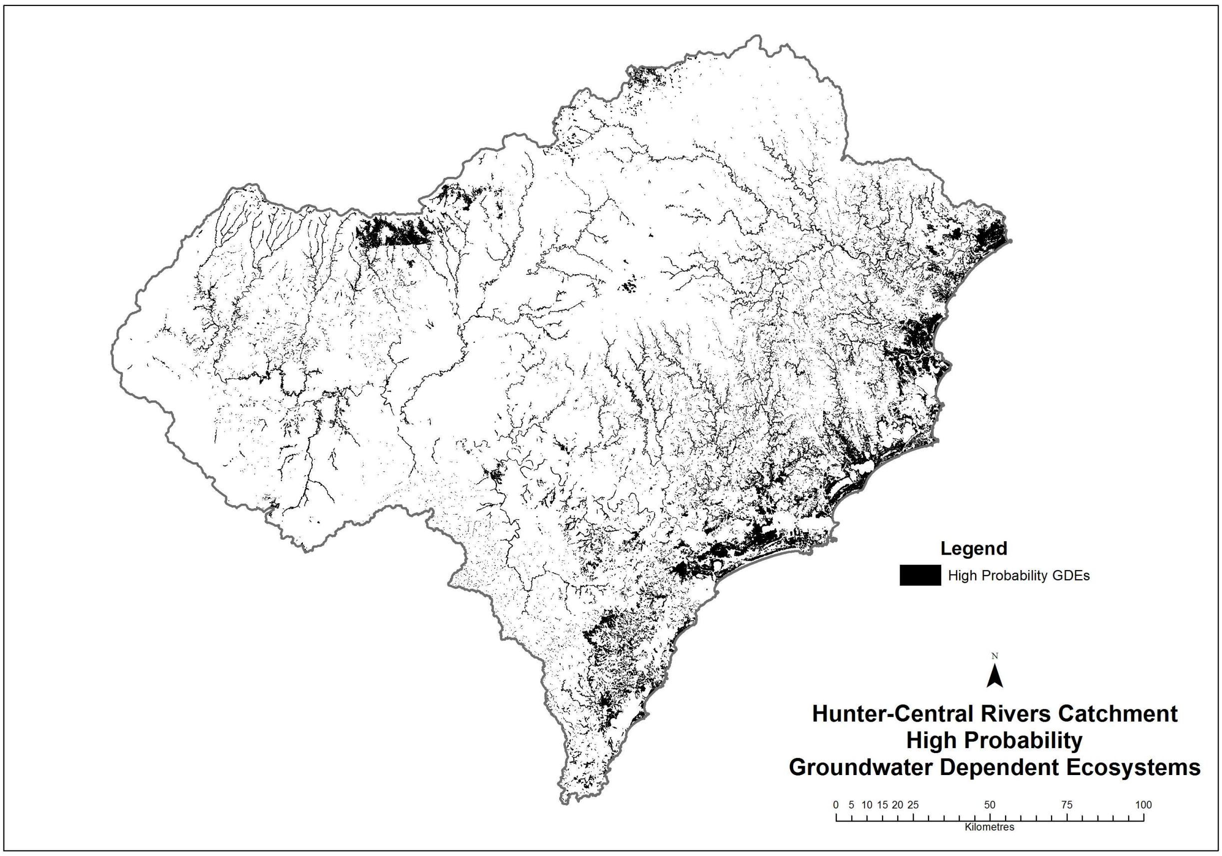

Figure 18: High probability GDEs located within the Hunter Central Rivers catchment

5 Limitations of the methods and derived data sets

A major limitation of the described method and associated spatial products is the lack of state wide and fit-for-purpose data, collected at the appropriate scale. The adopted method assumes that it was valid to extrapolate information over the broader landscape and that information provided was of suitable quality. Identification of GDEs was undertaken using existing datasets that varied both in scale and level of detail. No additional quality assurance to verify the accuracy or currency of the statewide spatial data sets was undertaken for data sets. Users of the derived data sets should therefore consult the metadata of both of these datasets and the component datasets used to create the new layers for information on reliability before making decisions on its use. It should be noted that field validation of the GDE maps produced using this method is proposed to be undertaken, and may result in further refinement of the methods.

Limitations include:

1. The location of GDEs depicts possible or potential GDEs and not actual extent.
2. Datasets used to determine probability were limited with respect to reliability, accuracy and age. Some limitations associated with the datasets used in the analysis included:
    - Base vegetation layers were inconsistent in terms of classification with regard to type.
    - Remote sensing observations relate to surface information. Application of remote sensing observations to groundwater dependency is indirect and based on temporal measurements of reflectance from land cover in the visible, near infra-red and thermal band.

- Remote sensed data may identify vegetation as groundwater dependent when in fact water maybe sourced from the soil profile. This particularly applies to high rainfall areas on the coast and ranges.
- Remote sensing data used to determine groundwater probability used MODIS data that was captured at a 250 m x 250 m scale. This introduces errors of scale in relation to the data leading to some vegetation being incorrectly identified as groundwater dependent. To improve the scale issues associated with MODIS, there will be an opportunity to refine the remote sensing data used with collaboration with Geoscience Australia and access to the Geoscience Data Cube once it becomes available.
- Sparse groundwater dependent vegetation may not be identified as such in areas where the soil background becomes a dominant over-riding factor at the pixel scale (see dot point on limitations of MODIS).

3. Assumptions regarding ecosystem functioning are built into the decision matrices used to determine probability of groundwater use were based upon published research that may or may not have been conducted in the same area. The extrapolation of those outcomes across all catchments within NSW may lead to uncertainty in the assumptions.
4. The use of multiple datasets generated at varying scales has implications for applying a single probability classification to a polygon, particularly in cases where polygons are relatively large and depth to water table can vary over a short distance (e.g. areas of complex topography).
5. The application of decision rules across large areas has implications for the classification of a community as a GDE. Groundwater use can vary not only from community to community but also from tree to tree and, as such, any groundwater dependent dataset produced on a community scale can only be used as a guide and not an absolute GDE rating (Gow 2010). Thus, the final outputs from the model must be regarded as potential or probable GDEs.
6. Groundwater quality, especially salt concentrations, and the impact that it has on groundwater use by vegetation was not considered. Although some species of vegetation are known to be adaptive to saline groundwater contributions (Jolly et al. 2002).

6 Discussion

The development of a broad scale catchment spatial model has been attempted by various state governments (Rutherford et al. 2005; Dresel et al. 2010, Harding and O'Connor 2012; QLD Department of Science, Information Technology and Innovation 2015) and nationally, in the GDE Atlas (SKM 2012). The methods applied in these studies used various spatial and remote sensing derived datasets and decision rules with various limitations. For example, some of these limitations included no field verification, differing spatial resolution (mapping units, spatial data and remote sensing imagery), incomplete data sets, single time period used for remote sensing analysis, limited Landsat data, inferred groundwater levels from modelled data and identification based upon only expert knowledge of the area.

Eamus et al. (2015) provided a detailed literature review of the application of remote sensing for the study of GDEs using various vegetation indices (VI) from LANDSAT and MODIS imagery. These studies used various combinations of VI and various models for estimating evaporation transpiration, leaf area index, surface energy balance (SEBAL) and groundwater level data. All of these applications are designed to expand on localised point information into broad scale measurements. Regardless of the application to which remote sensing is used, there are limitations which need to be considered. Remote sensing requires the use of other geospatial datasets including groundwater data, climate, soils, landscape morphology and ecological. Multiple sensors and image datasets are best suited for the study of GDEs as varying spectral, spatial and temporal sensors allow for the identification of GDE seasonal and annual functional dynamics (Eamus et al. 2015).

The methods used by SKM (2012) to develop the National GDE Atlas used MODIS data to assess changes in the rate of evapotranspiration (ET) over time, and Landsat data were used to map the vegetation greenness at finer spectral resolution. This method of using remote sensing is similar to the studies reported in Eamus et al. (2015) and was the basis of the work undertaken in Queensland and Victoria (Dresel et al. 2010, QLD Department of Science, Information Technology and Innovation 2015) and this project.

The National GDE Atlas (SKM 2012) provided a likelihood of access of water in addition to rainfall (water stored in the unsaturated zone, groundwater, or surface water). The ratings were between 1 and 10 where higher likelihood ratings (6 to 10) suggest that the landscape is more likely than not to be using an additional source of water, such as groundwater. Low likelihood ratings (1 to 5) suggest that the landscape is less likely to be accessing an additional water source–these landscapes are more likely to rely solely on rainfall (SKM 2012).

Dresel et al. (2010) selected the lowest EVI standard deviation range (<60%) for their remote sensing data set. This data set was generally observed that the range, encapsulated vegetation around wetlands, riparian stretches and deeper rooted vegetation (forested areas), but the selection was based on professional judgment for each aridity zone.

This project used similar likelihood ratings (Section 3.1 and Figures 10 and 11) for access to water as the National GDE Atlas (SKM 2012), however in the final decision matrices that were derived for the geospatial model (Section 3.6), only likelihood rates of 9 to 10 were considered to be more than likely accessing an additional source of water, such as groundwater. This approach was determined after a rapid field verification in a coastal catchment where soil moisture may have been over estimating likelihood of water source access. Applying the narrow likelihood range in the decision matrices appears to allow for a more conservative approach than the methods used by Dresel et al. (2010) and SKM (2012).

In conjunction with the use of remote sensing derived data for the identification of probable GDEs, groundwater and vegetation data were also used in this project and is consistent with other studies (Dresel et al. 2010; SKM 2012; QLD Department of Science, Information Technology and Innovation 2015).

The use of groundwater data appear to vary between the methods with depth to water table data, expressed spatially, being used by SKM (2012) in the National GDE Atlas and divided into the ranges of <2m, 2 to 20m and >20m for the GIS decision rules. No detail was provided on the spatial coverage of the dataset. However the data set was used to develop the Ecological Hydrological Zones (EHZs). Dresel et al. (2010) used an inferred groundwater map which used the integration of various spatial datasets, due to the lack of observed groundwater data available across Victoria. The resulting base layer provided an indication of the areas that suggested groundwater interaction, saturated and inundated environments.

This project has used observed groundwater data with the aim of providing representative groundwater levels for the time period of 2000 to 2009. This was the same period used for the remote sensing data analysis. Using observed data, rather than modelled or inferred groundwater information, in the spatial model provides increased certainty in the location of high probability groundwater dependent vegetation in areas where there are a large number of monitoring bores with observations. The project also used a more refined groundwater level ranges in the spatial model decision rules (0-8 m, 8-12 m, 12-16 m, 16- 20 m, >20 m (see Section 3.6).

Vegetation data used for each project was based upon the information and datasets available at the time. This information was limited in some areas and local expert knowledge and scientific literature was used to help fill in gaps in Queensland and Victoria. All the methods used the additional information to inform the decision rules within the spatial model. This project also used this vegetation information to assign probability ratings of high, medium or low to communities and provide a level 2 calculation to help inform the final model results when anomalies occurred (Section 4), whereas the National GDE Atlas (SKM 2012) used the information to exclude vegetation that was not considered to be groundwater dependent.

GIS spatial base layers used in all the reviewed methods, had limitations due to the scale at which those layers were applied (EHZs for the national atlas). The layers that had limited data coverage were generally unusable. Our method, and the approach used in Victoria (Dresel et al. 2010) attempted to address this by using smaller catchment areas and combining datasets to provide coverage over the whole catchment. The Queensland method used technical working groups to incorporate more data based on expert opinion (QLD Department of Science, Information Technology and Innovation 2015).

The overall GIS spatial model results for high probability vegetation GDEs for the National GDE Atlas and DPI Water is shown in Figure 19. There are clear differences between the national GDE Atlas and DPI Water model results in the Lachlan catchment. The DPI Water model results from this project have shown that the majority of the high probability groundwater dependent vegetation is restricted to the riparian zone of the Lachlan River and associated tributaries, which coincides with the shallower groundwater levels (Figure 20). The vegetation areas that are showing up as additional areas in the National GDE Atlas are coinciding with the remote sensing areas that are located in areas of deeper groundwater levels (Figures 19 and 21). This shows that the decision rules and data sets used in this project enable anomalies, which are not detected by the National GDE Atlas methods, to be filtered out. However due to the conservative nature of the decision rules, the project also does acknowledge that some GDEs may have been inadvertently filtered out. The methods in this project have also allowed the inclusion of vegetation communities that are definite GDEs in areas where the groundwater level data is deficient in identifying shallow alluvial groundwater levels due to spatial distribution of bores, or where the spatial resolution of MODIS is too coarse (Figure 20).

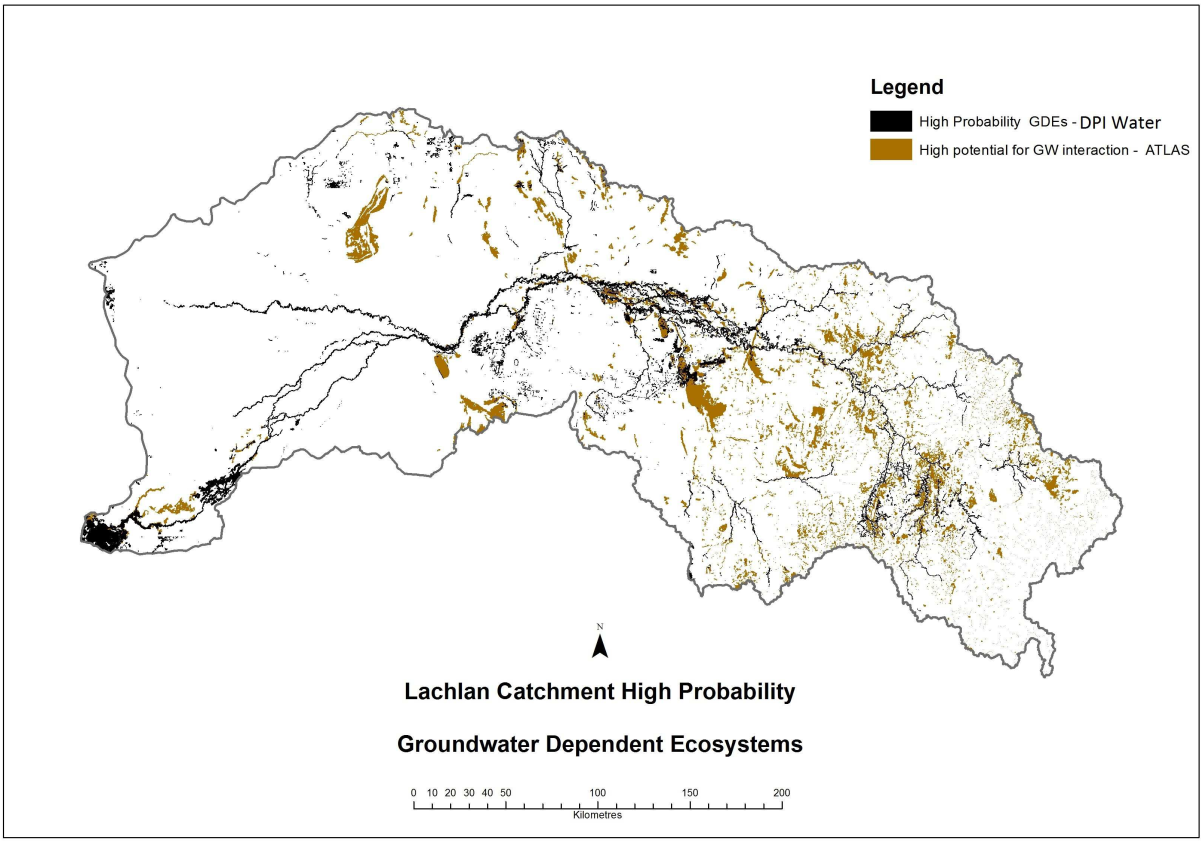

Figure 19: Comparison of National GDE Atlas and DPI Water high probability GDEs for the Lachlan Catchment

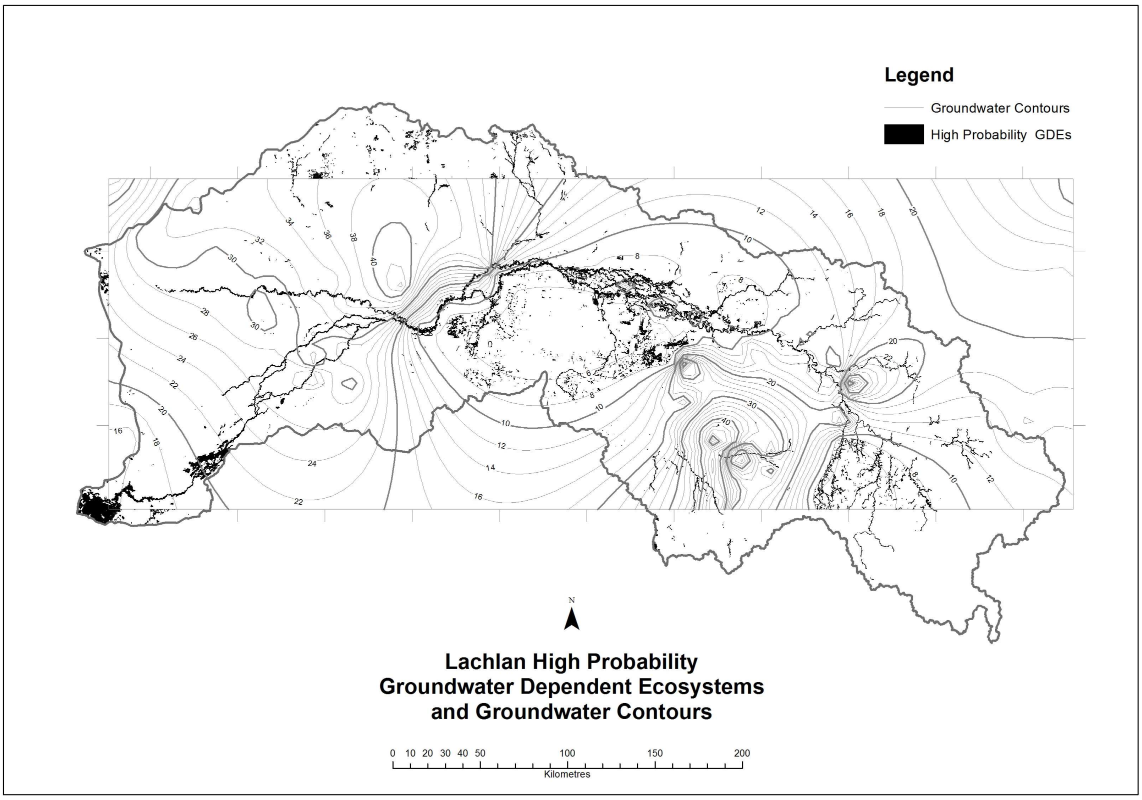

Figure 20: High probability GDEs and groundwater level contours in the Lachlan catchment

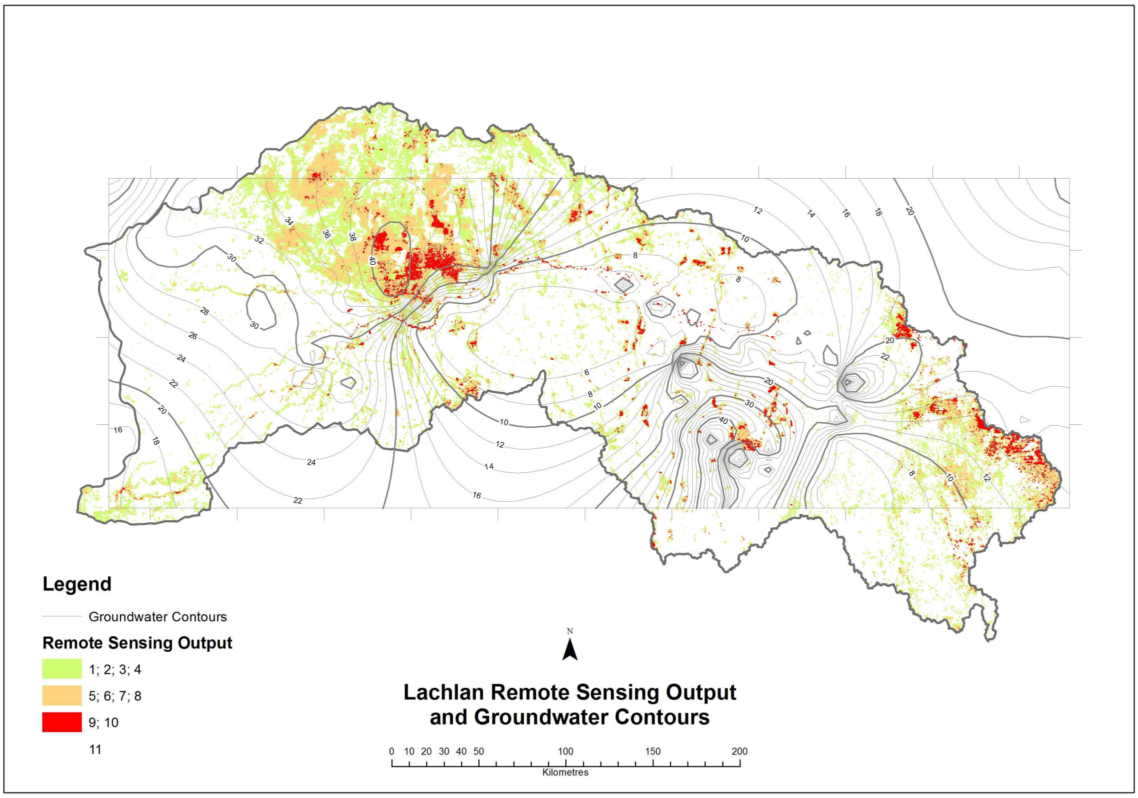

Figure 21: Groundwater level contours and potential groundwater use inferred by remote sensing

The identification of potential groundwater use by vegetation communities was based on a desktop assessment using several data sources. Although limited rapid fieldwork was undertaken to improve the robustness of the decision rules used to identify GDEs, further validation was required.

A rapid field validation was conducted by Eco Logical Australia (2016) to determine PCT vegetation mapping consistencies and accuracy, and for model accuracy in the Lachlan, Namoi and Hunter River Catchments. This work identified that whilst the PCT mapping accuracy was less than 50%, the GDE model outputs were highly accurate with an average of 76% across all catchments. The model accuracy was determined from a smaller sample size of approximately 550 sites compared to the 1000's of PCT site data. The field component of the study was designed to fill in data gaps for the entire PCT dataset which was not representative of the whole catchment and the 24% model errors were found be an artifact of landscape position and scale issues of the mapping (Eco Logical Australia 2016). These Limitations have been highlighted in section 5.

In conclusion, this project has aimed to build upon the previous methods used by other states and the National GDE Atlas to provide more rigor and confidence in the final modelled high probability GDEs. The process adopted here has used various data sets and scientific knowledge to build a complex model based around certain assumptions and conservative decision matrices. The project has acknowledged the model limitations (Section 5), however the confidence in the data sources and assumptions made in the decision rule process is relatively high.

6.1 Recommendations

6.1.1 Identification of other types of GDEs

The method described in this document identifies groundwater dependent terrestrial vegetation and wetlands embedded within vegetation mapping. Other types of GDEs, particularly wetlands and base flow systems require identification (and verification) under a similar spatial process. The prediction and identification of stygofauna is a potential project to be investigated with potential collaborative partners into the future and to look at hyporeic zone macroinvertebrates for base flows and stygofauna for aquifer ecosystems.

6.1.2 High Ecological Value GDEs

All vegetation communities that were identified as being highly groundwater dependent in the process above will be used as a data source in the determination of high ecological value (HEV) GDEs. The method for determining HEV GDEs will be based upon aspects of the High Ecological Value Aquatic Ecosystems (HEVAE) framework, which includes groundwater *(see Aquatic Ecosystems Task Group (2012))*. This method has been currently adopted for surface water instream value and the framework includes a groundwater component. The four criteria of Diversity, Distinctiveness, Naturalness, Vital Habitat from the surface water instream values will be modified and used to provide a value scale. The criteria that are related to the vegetation input of the HEVAE model will be used directly from the current HEVAE methods.

Defining value proceeds the development of a risk assessment process that allows management of GDEs to be commensurate with value and risk.

6.1.3 Risk Assessment

As per the requirements of the Basin Plan, a risk assessment for each catchment needs to be undertaken. A method will be developed based upon the data created from the HEVAE work above and the impacts due to groundwater extraction.

6.1.4 Degree of groundwater dependency for identified GDEs

The degree of groundwater dependency needs to be verified for GDEs identified. It will provide information on when groundwater is required and the extent of drawdown that could impact on groundwater availability. Collaborative projects with research organisations will be investigated to potentially include plant physiology work, isotope analysis, verification of remote sensing analysis using in field thermal imaging. All the above will be investigated in conjunction with targeted groundwater level monitoring.

6.1.6 Performance monitoring of GDEs

Most groundwater sharing plans in NSW have objectives, and associated performance indicators, to allow the assessment of the effectiveness (or otherwise) of the plan rules in maintaining or improving the health of GDEs. A project has commenced that will use the Namoi region as a pilot study for determining and monitoring condition of vegetation communities using remote sensing and spatial analysis techniques coupled with vegetation community and groundwater datasets. The aim is to develop a robust and cost effective methodology to enable the long term monitoring of GDEs to meet WSP plan objectives and performance indicators. Partnership opportunities are currently being explored with Geoscience Australia.

This project will generate knowledge and capacity to monitor tree condition, and develop standards and extension materials to guide management of riparian lands in the northern Murray-Darling Basin.

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Appendix 1

Matrix 6 - decision rules used to determine potential LEVEL 3 groundwater dependent vegetation and wetland ecosystems

LEVEL 1	LEVEL 2			LEVEL 3a	Rule applied to determine LEVEL 3
	1	**2**	**3**		
1	Yes			n/a	1 (i.e. accept LEVEL 1)
1		Yes		n/a	1 (i.e. accept LEVEL 1)
1			yes	**55**	Note that the rules for 3a 55 and 66 are the same Accept Level 1 when groundwater level are 0-8; 8-12 and GDE class is 9/10 for woody vegetation Accept Level 1 when groundwater level are 0-8; and GDE class is 9/10 for non woody vegetation Accept Level 2 when groundwater levels are 0-8; 8-12 and GDE class is 1/2/3/4/5/6/7/8 and 11 for woody vegetation Accept Level 2 when groundwater levels are 12-16; 16-20 and >20m and GDE class is 1/2/3/4/5/6/7/8/9/10 and 11 for woody vegetation Accept Level 2 when groundwater levels are 0-8 and GDE class is 1/2/3/4/5/6/7/8 and 11 for non woody vegetation Accept Level 2 when groundwater levels are 0-8; 12-16; 16-20 and >20m and GDE class is 1/2/3/4/5/6/7/8/9/10 and 11 for non woody vegetation Note, for most cases, expert opinion was accepted as the final LEVEL 3 result. It is unlikely that those communities selected as having a low probability of groundwater use would access groundwater except under conditions where the groundwater was very shallow and GDE class high. It is possible however that application of this rule as stated will miss those communities with an opportunistic use of groundwater.
2	yes			n/a	2 (i.e. accept LEVEL 1)

2		yes		n/a	2 (i.e. accept LEVEL 1)
2			yes	**66**	Note that the rules for 3a 55 and 66 are the same Accept Level 1 when groundwater level are 0-8; 8-12 and GDE class is 9/10 for woody vegetation Accept Level 1 when groundwater level are 0-8; and GDE class is 9/10 for non woody vegetation Accept Level 2 when groundwater levels are 0-8; 8-12 and GDE class is 1/2/3/4/5/6/7/8 and 11 for woody vegetation Accept Level 2 when groundwater levels are 12-16; 16-20 and >20m and GDE class is 1/2/3/4/5/6/7/8/9/10 and 11 for woody vegetation Accept Level 2 when groundwater levels are 0-8 and GDE class is 1/2/3/4/5/6/7/8 and 11 for non woody vegetation Accept Level 2 when groundwater levels are 0-8; 12-16; 16-20 and >20m and GDE class is 1/2/3/4/5/6/7/8/9/10 and 11 for non woody vegetation Note, for most cases, expert opinion was accepted as the final LEVEL 3 result. It is unlikely that those communities selected as having a low probability of groundwater use would access groundwater except under conditions where the groundwater was very shallow and GDE class high. It is possible however that application of this rule as stated will miss those communities with an opportunistic use of groundwater.
3	Yes			**77**	Note that the same decision rules apply to 3a code 77 and 88. Accept Level 1 when groundwater levels are 0-8; 8-12 and GDE class is 1/2/3/4/5/6/7/8/11 for woody vegetation Accept Level 1 when groundwater levels are 12-16; 16-20 and >20m and GDE class is 1/2/3/4/5/6/7/8/9/10 and 11 for woody vegetation Accept Level 1 when groundwater levels are 0-8 and GDE class is 1/2/3/4/5/6/7/8/11 for non woody vegetation Accept Level 1 when groundwater levels are 12-16; 16-20 and >20m and GDE class is 1/2/3/4/5/6/7/8/9/10 and 11 for non woody vegetation Accept Level 2 when groundwater level are 0-8 or 8-12m and GDE class is 9/10 for woody vegetation

					(note that it is possible that deep rooted woody vegetation could access deeper groundwater levels than non woody vegetation) Accept Level 2 when groundwater level are 0-8 and GDE class is 9/10 for non woody vegetation
3		Yes		n/a	3 (i.e. accept LEVEL 1)
3			Yes	n/a	3 (i.e. accept LEVEL 1)
4	Yes			**88**	Note that the same decision rules apply to 3a code 77 and 88. Accept Level 1 when groundwater levels are 0-8; 8-12 and GDE class is 1/2/3/4/5/6/7/8/11 for woody vegetation Accept Level 1 when groundwater levels are 12-16; 16-20 and >20m and GDE class is 1/2/3/4/5/6/7/8/9/10 and 11 for woody vegetation Accept Level 1 when groundwater levels are 0-8 and GDE class is 1/2/3/4/5/6/7/8/11 for non woody vegetation Accept Level 1 when groundwater levels are 12-16; 16-20 and >20m and GDE class is 1/2/3/4/5/6/7/8/9/10 and 11 for non woody vegetation Accept Level 2 when groundwater level are 0-8 or 8-12m and GDE class is 9/10 for woody vegetation (note that it is possible that deep rooted woody vegetation could access deeper groundwater levels than non woody vegetation) Accept Level 2 when groundwater level are 0-8 and GDE class is 9/10 for non woody vegetation
4		Yes		**44**	Accept Level 1 when groundwater levels are 0-8; 8-12; 12-16; 16-20 and >20m and GDE class is 1/2/3/4/5/6/7/8 and 11 for non woody vegetation Accept Level 1 when groundwater levels are 0-8; 8-12; 12-16; 16-20 and >20m and GDE class is 1/2/3/4 and 11 for woody vegetation Accept Level 1when groundwater levels are 8-12; 12-16; 16-20 and >20m and GDE class is 5/6/7/8/9/10 for woody vegetation Accept Level 1 when groundwater levels are 8-12; 12-16; 16-20 and >20m and GDE class is 9/10 for non woody vegetation

					Accept Level 2 when groundwater level are 0-8 and GDE class is 9/10 for non woody vegetation Accept Level 2 when groundwater level are 0-8 and GDE class is 5/6/7/8/9/10 for woody vegetation (note as per decision matrices it is possible that deep rooted vegetation located in shallow groundwater and having moderate GDE class could have a moderate probability of groundwater use)
4			Yes	n/a	4 (i.e. accept LEVEL 1)

Notes:

1=high probability of groundwater use 2=moderate probability of groundwater use

3=low probability of groundwater use 4=alternative source of water

GDE class refers to the potential frequency of groundwater use within a 10 year period with 1 meaning once in a ten year period and so forth.