3 Description of GDE Classes

The following sections contain a brief overview of each of the major classes of groundwater dependent ecosystems, following the classification scheme of Sinclair Knight Merz (2001). This classification forms the basis for the regional terrestrial GDE mapping in this project. Although the state-wide mapping process is focused on the terrestrial GDEs, the process also identifies areas in the riverine aquatic and wetland classes of the original Hatton and Evans (1998) system. Supplemental geographic information on water bodies and wetland areas are overlain with the GDE mapping results to aid analysis and interpretation because the boundaries between the classes may be gradational (e.g. in riparian flood-plains).

3.1 Terrestrial vegetation

A definition for terrestrial vegetation GDE's was provided by Sinclair Knight Merz (2001, p. 9) as:

'*This class of groundwater dependent ecosystem includes vegetation communities that do not rely on expressions of surface water for survival, but which have seasonal or episodic dependence on groundwater*'

Groundwater use by terrestrial vegetation has long been established (e.g. Thorburn et al. 1993a; Thorburn et al. 1993b), however defining a degree of dependency has proven more difficult, considering for example that a species may use groundwater once every decade to survive or once each year. Terrestrial vegetation GDEs may be found in areas with no proximal surface water expression. However, they grade into riparian zones of ephemeral streams, streams, or other water bodies.

A large number of studies have been undertaken over the past two decades to identify different terrestrial ecosystems in Australia and overseas. A mixed Eucalypt forest within the Brindabella Range, ACT was recorded to use groundwater only during a severely dry period during the early 1980s (Talsma and Gardner 1986). *Eucalyptus camaldulensis* (river red gum) along the Chowilla flood plain use groundwater during summer months and use surface and groundwater during winter months or when fresher sources are available (Mensforth et al. 1994), indicating this species has established an annual pattern of groundwater use. An experimental study in the Murray-Darling basin showed *Eucalyptus camaldulensis* moisture stress was lower between flood events in plots underlain by shallow aquifers, implying groundwater dependency (Bacon et al. 1993). *Banksia* species on the Gnangara Mound, Western Australia were also shown to be groundwater dependent (Canham et al. 2009).

Lamontagne et al. (2005a) used δ^2H (deuterium) isotopic and soil water matric potential measurements to delineate groundwater dependency of tree species in a tropical savanna riparian zone in the Northern Territory. *Melaleuca argentea* and *Barringtonia acutangula* appeared to be obligate phreatophytes while *Cathorium umbellatum* and *Acacia auriculiformis* appeared to be facultative phreatophytes. Zencich et al. (2002) used δ^2H to determine seasonal variations in groundwater use by *Banksia ilicifolia* and *Banksia attenuate* on the Swan coastal plain, Western Australia.

O'Grady et al. (2006) evaluated groundwater dependence of subtropical woodland species in northern Queensland. They found evidence of some degree of groundwater use in all communities studied. Combined measurement of evapotranspiration rate, leaf and soil water potential, and δ^{18}O of soil water/groundwater/xylem water were used to model the depth of water extraction for different species in one stand (Cook and O'Grady 2006). The model was used to infer groundwater usage by species of *Eucalyptus platyphylla, Melaleuca viridiflora, Lophostemon suaveolens,* and *Corymbia clarksoniana*. The estimated dry season groundwater contribution ranged from < 15% for *E. platyphylla and L. sauveolen*s, to 100% for *C. clarksoniana.*

Costelloe et al. (2008) extended the investigation of GDEs to saline groundwater use by arid zone riparian *Eucalyptus coolabah* in the Lake Eyre Basin, South Australia. They used a combination of δ^{18}O, δ^2H, soil chloride, and soil matric potential profiles. *E. coolabah* adapted to the dry saline conditions by depending to a greater extent on soil water including bank storage, by maintaining a low evapotranspiration rate compared to other riparian species, and by a higher salinity tolerance than other riparian eucalypts.

Gries et al. (2003) demonstrated that the growth rate of woody vegetation in the Taklamakan Desert, China, depended on the depth to groundwater for *Populus* species but to a lesser degree for *Tamarix.* The ability to use groundwater from depths up to 24 m depth resulted from upward growth of above ground shoots as the sand dunes shifted. Thus the vegetation is susceptible to rapid water table decline due to anthropogenic activities. Additional evidence for groundwater dependency of forests at the periphery of the Taklamakan Desert was presented by Bruelheide et al. (2010). Although groundwater depths ranged from 2.3 to 17.5 m, periodic flooding and vadose zone soil moisture use was discounted as water sources for the vegetation. Forestry or water usage may permanently impact the ability of these phreatophyte species to respond to shifting dunes and other environmental disturbances for which they are adapted. Hao et al. (2010) determined that, along the Tarim River on the margin of the Taklamakan Desert, the optimum groundwater level for major plant growth is 2-4 m with a threshold for groundwater dependency of approximately 6 m.

A number of different terrestrial ecosystems dependent on groundwater have been described in South Africa (Colvin et al. 2007). Of note are the abundant *Acacia erioloba* stands on Kalahari sands that have root systems up to 30-60 m deep. The authors consider the areas with groundwater dependent species to be keystone ecosystems, supporting a rich variety of fauna, and the deep-rooted trees acting as nutrient pumps and providing water to shallower-rooted plants by hydraulic lift.

Terrestrial GDEs have also been identified in North America. Woody and herbaceous groundwater dependent species were identified in a study of the impacts of groundwater withdrawal on vegetation in the Great Basin and Mojave deserts (Patten et al. 2008). The authors identified phreatophitic species of *Atriplex*, *Prosopis*, *Isocoma*, *Chrsothamnus*, Distichlis, *Sporobolus*, *Artemesia*, *Salix*, and others in the upland zone adjacent to springs and in the wetland/upland transition zone. The expected response to declining water tables would be replacement of transitional communities by upland communities and increasing encroachment of salt tolerant plants (halophytes). Conversely in upland communities, a decline in soil salinity could occur with declining water tables, with loss of halophytes. Phreatophytic upland communities would be altered to favour deep-rooted species or replaced by non-phreatophytes.

Effects of groundwater decline on Dutch forests include loss of moist forest types, in particular those dependent on Ca-rich groundwater (Van Tol et al. 1998). Groundwater level decline was associated with decline in base-exchangeable cations, decrease in pH, and increased nitrogen availability. Wagner and Bretschko (2003) found diurnal flow variation in an Austrian stream due to groundwater use by trees in the riparian zone. The interconnection between the stream and groundwater was through a network of preferential flow paths.

3.2 Wetlands - fresh and saline groundwater dependency

Wetlands can be defined as ‘land permanently or temporarily under water or waterlogged, with temporary wetlands having surface water or waterlogging of sufficient frequency and/or duration to affect the biota’ (Paijmans et al. 1985, cited in Hatton and Evans 1998). Most, but not all of the wetlands in Australia depend on groundwater to some degree. Groundwater dependent wetlands are generally considered to be vulnerable to changes in groundwater level, because small changes in the depth to groundwater can significantly reduce the water available to vegetation.

Wetland GDE vegetation type is often strongly related to groundwater chemistry (Bedford and Godwin 2003). Examples include fens in the North America and Europe fed by calcareous, high pH groundwater, (Siegel and Glaser 1987; Almendinger and Leete 1998; Podniesinski and Leopold 1998; Kemmers et al. 2003). Conversely, organic acids produced in the wetlands neutralize the groundwater so that, depending on the groundwater composition and flux, a continuum is formed from neutral to alkaline – ‘extremely rich fens’, through ‘rich fens’, ‘poor fens’, to pH 3.6-4.2 ‘bogs’ (Siegel et al. 2006). In addition, the interaction of groundwater with organic matter in wetlands can result in redox gradients that influence soil composition and phosphorous availability, and thus the plant species (Boomer and Bedford 2008).

It may be difficult to draw a clear distinction between terrestrial vegetation GDEs and wetland GDEs. The former rarely have surface water expression while the latter have frequent or episodic inundation by surface water or groundwater discharge. Thus, strictly speaking a terrestrial GDE should only occur in a zone not classified as wetland. However, management changes, such as stream regulation and control of flooding in the Murray-Darling basin, may increase groundwater dependency and former wetlands may then be considered terrestrial systems. There can be considerable overlap in vegetation species wetlands and terrestrial GDEs. For example, *Eucalyptus coolabah*, is a salt-tolerant tree that grows in the riparian zone floodplains of the Lake Eyre Basin and Murray-Darling Basin. It may be mostly or completely reliant on saline groundwater use or may use a mixture of groundwater and infiltrating floodwater (Costelloe et al. 2008).

Hatton and Evans (1998) felt that groundwater dependent wetlands form the most extensive and diverse set of the ecosystems within Australia that interact with groundwater. They described a number of these groundwater dependent wetland ecosystems including:

Swamp sclerophyll forests and woodlands – These ecosystems occupy the riparian corridors of ephemeral or base flow dependent streams and exhibit at least seasonal dependency on groundwater. They include a wide range of mostly eucalypt species such as *E.ovata*, *E.viminalis* and *E.leucoxylon* communities in South Australia, *E.camaldulensis* and *E.largiflorens* woodlands of the Murray and Darling River floodplain and of the inland river systems of central Australia.

Swamp scrubs and heaths – This group of ecosystems normally occupy sandy or peaty soils in landscapes ranging from coastal dunes to swampy areas fed by snow melt in the southern Australian highlands. Farrington et al. (1990) found substantial use of groundwater by swamp scrub on the sumplands and damplands of the Swan Coastal Plain in Western Australia.

Swamp shrublands –Lignum shrublands *(Muehlenbeckia cunninghamii)* often grow in association with *E. largiflorens* woodlands in the Murray-Darling basin on heavy-textured grey and brown soils that are periodically inundated. Halophytic shrublands (*Chenopodium auricomum, C. nitrariaceum, Atriplex nummularia, Maireana* spp.*, Bassia* spp. *and Rhagodia* spp.*)* occur around the margins of inland salt lakes in central Australia and also colonise groundwater discharge areas and the edges and beds of salt lakes that are only inundated periodically across Australia (*Arthrocnemum* spp.). The links between these swamp shrublands and groundwater is not known at this stage.

Sedgelands – Sedgeland communities are found in the coastal, floodplain and valley floor environments of eastern Australia. Most require at least seasonal waterlogging. Those that require permanent surface wetness are almost certainly groundwater dependent e.g. *Eleocharis sphacelata* sedgelands in lagoons of the Murray River and tributaries. *Baumea* sedgelands occur in permanent and semi-permanent wetlands from the coastal areas of south-east Queensland down to Tasmania and around to south-west Western Australia. Their need for continual surface wetness suggests that they are likely to be interacting with groundwater. Button Grass (*Gymnoschoenus spaerocephalus*) sedgelands occupy waterlogged, peaty, infertile soils that are periodically flooded on valley floors in Tasmania's south-west and on the tablelands of New South Wales. Where the sites are continually wet, button-grass may be replaced by *Leptocarpus tenx, Xyris operculate, Lepidosperma longtitudinale, L. filiforme and Restio tatraphyllus*. Groundwater is almost certain to be influencing the vegetation community at these sites. *Carex* sedgelands occupy permanently waterlogged sites that are periodically flooded on the tablelands of New South Wales, Victoria and Tasmania. Groundwater clearly has a role in maintaining the permanently wet state at some sites, but at others the degree of interaction is not clear.

Swamp grasslands – *Phragmites* and *Typha swamp* grasslands are common in seasonally and permanently waterlogged locations across coastal and inland parts of south-eastern Australia. Their groundwater dependency was considered by Hatton and Evans (1998) to vary widely, but communities associated with more permanent water features are considered the most likely to exhibit some degree of dependency. Sod tussock grasslands characterised by *Poa caespitosa, Themeda australis, Danthonia nudiflora and Calorophus lateriflorus* occur in the subalpine and alpine areas of Victoria. Any ground water interaction is likely to be limited. Canegrass (*Eragrostis australasica*) grasslands grow in low-lying, flood-prone locations in North-western Victoria. The regular flooding regime at these sites suggests at most a limited dependency on groundwater.

Swamp herblands – Floating and floating leaved herblands are common in coastal rivers and dune swales and lakes throughout Australia. The characteristic wetness of the locations implies some role for groundwater and associated ecosystem dependency.

Hypersaline lakes – A number of the RAMSAR wetlands in the Kerang-Swan Hill region and Lake Tyrrell wetland complex in northern Victoria and numerous lakes across the Basalt Plains in southern Victoria are examples of unique and viable ecosystems that have successfully developed around these hostile environments. These areas are dependent on groundwater and the aquifers may have had their groundwater function altered/threatened by irrigation practices and water supply management. Natural spatial and temporal variability in salinity is an important characteristic of saline wetlands (Jolly et al. 2008). The salinity and chemistry of saline lakes in the Wimmera is dependent on the chemistry of the source groundwater and the hydrologic setting, leading to high diversity between individual lakes (Radke and Howard 2007). The effects of changing salinity on vegetation in the salt marsh fringe of Lake Austin, Western Australia was studied by van Etten and Vellekoop (2009).

3.3 Coastal estuarine and near shore marine systems

Coastal estuaries including brackish lakes and salt marshes can be zones of groundwater discharge. The groundwater sources can have important impacts on salinity and nutrient levels in the ecosystem and groundwater contamination may harm the ecological receptors. Recent research into submarine groundwater discharge (SGD) is increasing understanding of the role of the direct discharge to coastal waters in the regional water budgets and to marine vegetation and aquatic communities. However, the extent of groundwater dependency is generally poorly understood.

Gallardo and Marui (2006) review research on submarine groundwater discharge, focusing on the physical processes rather than ecological effects. Burnett et al. (2003) review the physical and geochemical effects of SGDs. Bokuniewicz et al. (2003) discuss the importance of SGDs to coastal management and present a global assessment of coastal SGD areas. Evaluation of these GDEs is complicated by tidal effects leading to variability in discharge quantity, quality, and location of the groundwater interface with marine water and coastal streams (Acworth et al. 2007).

Loaiciga and Zektser (2003) reviewed methods for estimating SGD. Smith and Nield 2003) used a numerical groundwater flow model to estimate SGD to Cockburn Sound, Western Australia, while in the same area, Tanaguchi et al. (2003) compared estimated SGD from groundwater and porewater temperatures to seepage meter measurements. Danielescu et al. (2009) used thermal infrared imaging to evaluate groundwater discharge to a coastal estuary in Prince Edward Island, Canada. Several studies have used radon and radium as tracers to investigate SGD areas and estimate flux (e.g. Moore 2003; Lambert and Burnett 2003).

Nutrient phosphate and ammonia flux to estuaries and SGDs is a particular issue of coastal groundwater discharge. Crotwell and Moore (2003) used natural radium as a tracer to determine nutrient flux to Port William Sound, South Carolina, USA and suggest that the nutrient load may be reduced by regional groundwater use.

Several examples of groundwater dependent coastal and marine ecosystems described by Sinclair Knight Merz (2001) are presented below, with additional references.

Coastal mangroves and salt marshes – mangroves are widely distributed around the Australian coast. While most common in northern Australia, they may be found as far south as Corner Inlet in Victoria. While seawater is considered to be the primary water source for most of these vegetation communities, sites have been noted where mangroves occupy relatively fresh groundwater discharge areas (Adam 1994). Semeniuk (1983) related the distribution of mangroves in Northwestern Australia to areas of groundwater discharge where conditions were more arid. Drexler and Ewel (2001) investigated a coastal area in Micronesia and showed that groundwater flowed from a freshwater swamp to a mangrove stand during normal conditions but was reversed during an El Niño-Southern Oscillation (ENSO) drought and suggested possible mechanisms of groundwater dependency for the mangroves.

Salt marshes tend to replace mangroves in coastal locations in southern Australia. The nature of any groundwater dependency is unknown. Protection of coastal mangroves and salt marshes from clearing and drainage may play an important role in maintaining groundwater discharge and preventing the activation of acid sulphate soils.

Coastal lakes – coastal lakes along the south-west coastline of Western Australia support the development of stromatolites (Palinska et al. 1999) and have quite varying aquatic communities. Groundwater is the principal source for many of the lakes. Some Victorian coastal lakes and wetlands maintain fresh to brackish species compositions due to the discharge of relatively fresh groundwater.

Sea grass beds – the distribution of sea grass beds in some coastal areas is influenced by groundwater discharge. Anthropogenic impacts to groundwater nitrogen may increase nutrient loading in shallow coastal waters, increase macroalgae growth, and decrease eelgrass distribution. Eutrophication and other effects associated with shift from sea grass to magroalgae then lead to decreased benthic animal abundance and fish kills (Valiela et al. 1990).

Marine animals – some marine and estuarine animals depend on groundwater discharge to provide a suitable habitat or an appropriate environment in which the species of plant and/or animal they eat will prosper. Groundwater discharge may be in the form of direct off-shore discharge or base flow into streams that discharge to the ocean. Examples of groundwater dependent fauna include crocodiles, turtles, fish and macro-invertebrates.

3.4 River base flow systems

This category of ecosystem was devised by Hatton and Evans (1998) to include the many ecosystems that are dependent on groundwater derived base flow in streams and rivers. Base flow is that part of stream flow derived from groundwater discharge and bank storage. Base flow may contribute year round to flows in coastal streams in south-eastern Australia and may contribute to flow in inland streams, although the extent of the contribution may be difficult to determine in some cases due to river regulation (Hatton and Evans 1998). The coastal rivers of south-eastern Australia maintain base flow throughout the year and support riparian forests, scrub, sedgelands and grasslands, as well as in-stream biota and floating and emergent herbfields.

Riparian and aquatic ecosystems in base flow dependent streams would be, to a greater or lesser extent, groundwater dependent themselves. Demarcation between groundwater dependent terrestrial vegetation, wetlands, and base flow systems may be difficult. The three types of community represent ranges on a spectrum of habitat and groundwater dependency.

O'Grady et al. (2006) point out that riparian woodland species tend to be opportunistic in the sources of water they are able to use. They provide the examples of Lamontagne et al. (2005a) and Zencich et al. (2002) of *Casuarina*, *Acacia*, and *Banksia* species using groundwater when it is shallow and accessible, but other sources as available.

Groundwater level in a riverine aquifer is also important in terms of maintaining a hydraulic gradient towards the stream that supports the necessary discharge flux. Hatton and Evans (1998) noted that across at least some of its range, the platypus was an example of groundwater dependent fauna. In some parts of this species' range, groundwater discharge is required to sustain the flow or pools in which it feeds.

Contamination of riverine aquifers by nutrients, pesticides and other toxicants may adversely affect dependent ecosystems in base flow streams. Aquatic communities would be expected to be the worst affected.

3.5 Aquifer and cave ecosystems

This category comprises the aquatic ecosystems that may be found in free water within cave systems and within aquifers themselves. Australia studies of these 'stygean' ecosystems have traditionally related to cave, rather than aquifer systems, however there is a growing body of information on the latter (e.g. Boulton et al. 2003; Eberhard et al. 2009; Hancock and Boulton 2009; Bradford et al. 2010). Karst and other cave systems also support diverse ecosystems (e.g. Piccaninnie Ponds in South Australia - Scholz 1990; palaeovalleys within central Australia - Humphreys 2006).

Aquifers themselves support a diverse array of ecosystems. Some ecosystems (e.g. in riverine plains) exist along a continuum between fully aquatic communities and completely aquifer dwelling communities (Danielopol 1989).

The environment in which aquifer ecosystems develop is characterised by darkness, consistency and persistence of habitat and low energy and oxygen availability. The organisms that inhabit these environments are often specialised morphologically and physiologically. They are also predominantly invertebrates. These stable and confined environments result in high levels of endemism and high proportions of relict species in comparison to surface environments (Danielopol 1989).

3.6 Terrestrial fauna

Descriptions of surface groundwater dependent ecosystems in the previous sections have mainly concentrated on plant communities. These communities provide habitat for a variety of terrestrial, aquatic and marine animals, which by extension must also be groundwater dependent.

However, there is an additional group of groundwater dependent fauna whose reliance on groundwater is not based on the provision of habitat, but as a source of drinking water. Groundwater, as river base flow or discharge into a spring or pool, is an important source of water across much of the country, particularly in northern and inland Australia and other areas with semi-arid climate. Its significance is greater for larger mammals and birds, as many smaller animals can obtain most of their water requirements from respiration.

Pastoralists in inland Australia have made extensive use of groundwater to supply drinking water to grazing stock. In addition to watering stock, groundwater is also used by native fauna (e.g. kangaroos) and pest and feral animals. Groundwater dependent terrestrial and riparian vegetation and wetlands may be used by terrestrial fauna as drought refuges. Access to groundwater allows the vegetation to maintain its condition and normal phenology (e.g. nectar production, new foliage initiation, seeding). Populations of some birds and mammals retreat to these areas during drought and then recolonise drier parts of the landscape following recovery. The long term survival of such animal populations relies on maintaining the vegetation communities and ensuring their water requirements are met. The key groundwater attributes will be flux and pressure. These are dependent on the hydrology of the groundwater flow system providing the water.