5 Identification of GDEs

The focus of this project is on the identification of areas of potential GDEs using large scale techniques but these can be supported by smaller scale field techniques.

Investigations to identify GDEs typically employ combinations of several indicators, each of which only provide partial information related to the groundwater use. First, the types of information will be described and then a number of examples from the literature will be discussed to illustrate the overall approaches.

A fundamental tenet of ecology is that ecosystems generally will use resources in proportion to their availability - whether the resource is light, water, nitrogen or anything else - and the availability of different resources will be a significant determinant to their structure, composition and dynamics (Colvin et al. 2003). Thus where groundwater is accessible, ecosystems will probably develop some degree of dependence on it and that dependence is likely to increase with increasing aridity of the associated environment (Hatton and Evans 1998).

An analysis of vegetation assemblages can show the presence of species likely having the ability to use groundwater. Hydrogeologic studies can identify where the groundwater is discharging to surface springs, streams, lakes, or coastal zones. Specifically studies of groundwater-surface water interaction can show areas, not only of aquatic groundwater dependency but where riparian vegetation is using groundwater. Other geologic and hydrogeologic features of importance include bedrock type, regolith depth, and depth to the water table.

Eamus (2009) discusses field methods to evaluate the groundwater dependency of ecosystems. He recommends determinations based on the use of vegetation and hydrologic measurements including pre-dawn leaf water potential, stable isotopes of oxygen and hydrogen in tree xylem and soils, soil sampling to establish root depth, leaf aria index measurement, depth to groundwater, diurnal changes in groundwater depth, and water balance calculations.

Colvin et al. (2003) and Clifton et al. (2007) produced tool boxes of the various techniques available to indicate groundwater use. They consider each method in terms of its technical basis, costs, constraints, suitability, time requirements, resolution of results, format of outputs, and previous use of the technique.

Clifton et al. (2007) provided a description of applications and limitations of a range of scientific approaches in GDE assessments (Table 2). With the exception of the geological mapping that already exists, the methods detailed in Table 2 are generally not sufficiently cost or time effective to be applied to broad scale identification or characterisation of GDEs.

5.1 Vegetation analysis

Where fresh groundwater discharges to the surface, the constant availability of water sustains plant photosynthetic activity longer in summer in that area (Tweed et al. 2007). Areas where shallow saline groundwater is close to, or discharges to the surface, are also evident from the limited vegetation activity. Soil subject to saline groundwater accumulates salts, thus limiting photosynthetic activity of salt sensitive vegetation throughout the entire year whilst supporting photosynthetic activity of salt-tolerant vegetation (Tweed et al. 2007).

Areas of vegetation that use groundwater typically exhibit low seasonal variability of photosynthetic activity when compared with productive agricultural areas. The inter-annual variability of the vegetation activity can also contain useful information to assist mapping of groundwater discharge areas (Tweed et al. 2007).

Vegetation that is relatively lush in comparison to surrounding areas is often associated with discharge areas. (Colvin et al. 2007). Leaf area index (LAI) is often used as an indicator to identify this type of vegetation. LAI is defined as the one sided green leaf area per unit ground area in broadleaf canopies, or as the projected needle leaf area per unit ground area in needle canopies. LAI is a strong indicator of water availability in semi-arid to arid environments (Hatton and Evans 1998; Colvin et al. 2007).

Table 2. Tools to identify GDE's (after Clifton et al. 2007)

Tool	Description
1. Mapping tools	Mapping of geology and geological structures, water table depth or aquifer pressure and the distribution, composition and/or condition of vegetation as a means of identifying ecosystems that are likely to have access to and use groundwater.
2. Water balance techniques	Identify and quantify groundwater use by measurement or estimation of various components of an ecosystem's water cycle.
3. Pre-dawn leaf water potential	Pre-dawn leaf water potential measurements to identify groundwater use and depth of water uptake.
4. Stable isotope analysis - vegetation	Comparison of the fractionation of isotopes in plant xylem water with potential source waters to identify groundwater uptake.
5. System response to change	Long term monitoring of ecosystem composition and ecological function in response to management intervention, climate, and soil water, surface water and groundwater conditions.
6. Groundwater - surface water hydraulics	Application of hydraulic principles, statistical analyses of stream hydrographs and site measurements to derive the degree of interaction between groundwater and surface water features.
7. Physical properties of water	Measurement of water electrical conductivity and temperature change along the length of a river / wetland, or over time to identify a groundwater contribution.
8. Analysis of water chemistry	Chemical analysis of surface water and groundwater for isotopes, major anions and cations, and trace elements. Mixing relationships identify groundwater contribution.
9. Introduced tracers	Use of introduced chemical tracers to observe mixing and dilution relationships and assess the contribution of groundwater to a stream.
10. Plant water use modelling	Mathematical representations (or models) of plant water balance to estimate plant water requirements and/or groundwater uptake, and/or response to water table drawdown.
11. Groundwater modelling	Two or three-dimensional mathematical representations (or models) of water movement in the saturated and unsaturated zones to assess the potential level of interaction between groundwater and surface water bodies and between groundwater and terrestrial ecosystems.
12. Conceptual modelling	Use of expert knowledge of similar ecosystems, biophysical environments and relevant data to develop a conceptual model of the ecosystem and its interaction with groundwater.
13. Root depth and morphology	Assessment of the depth and morphology of plant root systems, and comparison with measured or estimated water table depth to assess potential for groundwater uptake.
14. Analysis of aquatic ecology	Use of ecological survey techniques to identify aquatic species with reproductive behaviour or habitat requirements that indicate groundwater dependency.

5.2 Groundwater – surface water interaction

Investigation of groundwater-surface water interactions is a broad and rapidly developing field that will only be briefly touched on here. Identification of groundwater discharge zones and quantity of discharge is not only important for determining the dependency of the surface water system, but the groundwater-surface water interface, termed the hyphoreic zone, often forms an important ecological niche.

Brodie et al. (2007a) provide an extensive discussion of groundwater-surface water interaction from the perspective of Australian water resource management. Field methods developed to investigate the spatial-temporal variability of recharge and discharge processes are typically site specific (Kishel and Gerla 2002). Field methods include:

- Water balance, seepage meters, piezometer, and stream gauging/hydrograph separation (Brodie et al. 2007a, 2007b)
- Temperature monitoring (Brodie et al. 2007b).
- Geophysical surveys, especially electrical conductivity in the subsurface or surface water (Brodie et al. 2007b)
- Chemical and oxygen/hydrogen isotopic relationships between groundwater and surface water (e.g. Chapman et al. 2003; Gibson et al. 2000; Zench et al. 2002)
- Tritium and ^{3}He measurements to characterize exchange between groundwater and wetlands, estimating transit times in catchments, and constrain flow models (e.g. Harvey et al. 2006; Stewart et al. 2010)
- Strontium isotopes in groundwater and surface water (e.g. Kirchner 1995; Kirchner 1997; De Villiers 2005),
- Radon and radium isotopic measurements have been used to characterize groundwater discharge to streams and the ocean (e.g. Ellins et al. 1990; Moore 2003; Wu et al. 2004; Dulaiova et al. 2005; Oliveira et al. 2006; Schmidt et al. 2009)

5.3 Remote sensing approaches

Smith et al. (2006) devised a method of determining use of groundwater by terrestrial ecosystems by modelling the groundwater levels and overlaying vegetation maps obtained from satellite imagery. This involved matching woody vegetation within the regions of influence of groundwater pumping to predict GDEs which may be as risk from groundwater extraction.

Tweed et al. (2007) applied a combination of remote sensing and geographic information system (GIS) techniques to map groundwater recharge and discharge areas in the Western District of Victoria. By reviewing hydrological processes, a series of surface and subsurface indicators of recharge and discharge were established. Various remote sensing and GIS techniques were then used to map these surface indicators including; terrain analysis, vegetation activity or normalised difference vegetation index (NDVI) obtained from satellite imagery and mapping of infiltration capacity.

Münch and Conrad (2007) used a combination of remote sensing and GIS modelling to produce a GDE probability map in South Africa. Starting with remote sensing data, satellite images were assessed to identify probable GDEs. A GIS model predicted landscape wetness based on terrain and geomorphologic character or land wetness potential. It was modified to highlight groundwater generated landscape wetness. Other techniques were then applied to the modelling and included a groundwater elevation model, interpolated and digital elevation data and biomass indicators generated from Landsat. The information was then classified and combined with GIS layers and followed up with field verification. The result was a map of areas of potential GDE’s based on groundwater level and soil moisture availability.

Bierwirth and Welsh (2000) used a combination of airborne radiometric and satellite remote sensing measurements to investigate groundwater recharge in the Great Artesian Basin.

5.4 Geological mapping approaches

Regional information on geology, structural geology, regolith mapping and the geomorphology can be assessed to help search for areas where potential GDEs may exist. The surface and sub-surface characteristics generated by the geology and structures define groundwater flow pathways and thus the establishment and support of ecosystems within certain areas. Salama et al. (1993, 1994) used geological and geomorphological data to determine the likelihood of groundwater discharge sites. Salama et al. (1994) integrated the interpretation of geomorphic and geological features, from Landsat satellite imagery and aerial photographs, with on-ground hydrogeological studies to map recharge and discharge areas. It was found that recharge areas were linked to increases in permeability of the surface geology, whereas discharge areas were associated with major drainage lines, geological boundaries and topographic depressions.

- Groundwater discharge and shallow watertable levels correlate to areas of soil salinity, saline lake systems and fresh water springs. (Macumber 1991; Tweed et al. 2007) and areas of GDEs. (Colvin et al. 2003). Groundwater transpiration by vegetation and direct discharge to wetlands and rivers, means that shallow water tables are an essential component of sustaining ecologically significant areas. (Batelaan et al. 2003).
- Geology, geomorphology and structural geological features influence groundwater flow and groundwater discharge (and potentially the location of GDEs.) (Macumber 1991; Colvin et al. 2003) Ecosystems or species which occur in association with (potential) discharge areas, such as topographic low points or along dykes or fault lines can be used as groundwater indicators (Colvin et al. 2003)
- Potential indicators of groundwater discharge include terrain indicators such as topographic depressions and break of slope and groundwater flow direction towards surface water bodies (rivers, wetlands, and the ocean) (Tweed et al. 2007)
- The influence of stratigraphical layers and jointing patterns on spring locations within the bedrock of New Mexico was determined by Walsh (2008).

Macumber (1991) identified distinct geomorphology units where groundwater discharges to the surface in the north-west regions of Victoria. Colvin et al. (2003) used geological features as indicators of fractured aquifer potential or areas where groundwater availability was greatest. This was followed up with botanical field verification of these areas to see if the areas supported GDEs in South Africa. The reasoning behind the study was that geology and lithology control groundwater flow and impose aquifer boundaries. Fractures, faults, folds and intrusive dykes may form a preferred pathway or barriers to groundwater flow and thus availability of groundwater for terrestrial ecosystems.

Brodie et al. (2007b) developed a mapping method to predict surface and groundwater interaction using site and area specific characteristics and formulae developed for weighting these inputs. The method takes into account hydrological and hydrogeological factors. It focuses on the conductance of the geological material and watertable depths to derive an indicator for the potential for groundwater – surface water connectivity. It provides sufficient information to identify potential connected and disconnected systems to enable targeting of further investigations and management. The stream-aquifer connectivity potential is rated using an index. The input required includes:

- Depth to groundwater
- Streambed characteristics
- Geology
- Geomorphology.

The final single index value is categorised into low, medium or high connectivity potential classes based on the output classification classes in the model. These categories can be mapped to spatially represent the estimates of potential connectivity along river reaches. Potentially connected surface and groundwater systems support ecosystems that are potentially dependent on the groundwater to some degree. Indirectly studies have developed methods of mapping springs, and therefore developed maps of GDE's, for example Walsh (2008), utilised GIS data to map jointing patterns within bedrock across New Mexico that are associated with springs. .

Previous work on regional identification of potential accessibility of groundwater to vegetation generally uses a depth of 5 metres as the limit within which dependent plants are likely to access groundwater, although this could be seriously challenged in some Australian landscapes. Depth to groundwater maps can be used to help locate GDEs but these are very difficult to construct with reliable accuracy at regional scales due to landscape complexity and sporadic distribution of groundwater level data.