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Mapping Approaches to Recharge and Discharge Estimation and associated input datasets

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Cover Photograph:

Description: Limestone tufa on the Douglas River in Northern Territory.

Photographer: Anthony O'Grady

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1. EXECUTIVE SUMMARY

Considerable work has been carried out both in Australia and overseas on the spatial variations in groundwater recharge and discharge. In some instances this work has considered point measurements at the land surface. In many other areas assessments have been completed through detailed hydrogeological investigations and groundwater modelling. The latter is always the preferred method as recharge/discharge relationships can be explored in context of the hydraulic properties of the aquifers and groundwater flow systems.

In less well-studied areas there are opportunities to transfer concepts and knowledge from well-studied groundwater systems with the same or similar geological and geomorphic character. Conceptual models of groundwater behaviour that provide a landscape context for recharge/discharge make this possible.

There is a considerable literature on the use of remote sensing and Geographic Information Systems (GIS) in mapping hydrological features including recharge and discharge zones.

This report brings together much of this work. It describes the various data that can be used at a national or finer scale as inputs to GIS-based models for the spatial distribution of recharge and discharge. These include:

- Remotely sensed satellite imagery and common interpretive products;
- Geophysical data (airborne electromagnetics, gamma-ray radiometrics);
- Digital elevation models and products of topographic analysis;
- Water table surface elevation mapping;
- Climate;
- Soil, regolith, geology and hydrogeology; and
- Vegetation and land cover/use.

The report warns that unsupervised mapping of soil and regolith properties is likely to produce questionable results. It is not sufficient to map recharge and discharge areas according to the hydraulic properties of soil and regolith alone. Simple concepts that consider recharge and discharge in terms soil fluxes are an inadequate basis for establishing the water balance of most groundwater systems. This is particularly true where aquifers are confined for most of the flow system, or in instances where multiple aquifers are superimposed one upon the other.

The report describes various mapping frameworks that could be adapted to provide a spatial context for mapping the distribution of recharge-discharge characteristics including Atlas of Australian Soil (ASRIS), Hydrogeomorphic Units (HGUs), Hydrogeological-Landscapes (HGLs) and Groundwater Flow Systems (GFSs).

It is recommended that remote sensing and GIS methods be further developed for mapping recharge and discharge zones using a variety of data from a variety of sources. It is essential, however, that these be guided by sound hydrogeological principles.

2. INTRODUCTION

2.1. Background

It is believed that the primary requirement of water managers responsible for the allocation of water resources for any region is an understanding of the water balance. Whilst this is readily achievable for surface water, it is much more challenging for groundwater. Understanding the water balance of a groundwater system requires the estimation of recharge and discharge fluxes and these typically vary in time and space in sympathy with landscape morphology, climate, land use and land management.

The relationships that prevail between surface water systems and groundwater systems are most often quite complex and they vary from one type of groundwater system to another. There will always be fundamental differences in hydrogeological processes consistent with geological and geomorphic settings, aquifer properties and regolith character. It is also understood that recharge and discharge vary over time in a land with ‘droughts and flooding rains’. Recharge and discharge fluxes are not fixed in time, instead they move up and down with the climate.

Water managers deal with this complexity in a variety of different ways. Some commission detailed water balance assessments and go on to assemble fully distributed groundwater models. Others make assumptions in simplistic spread-sheet models. In the latter instance recharge (for example) is most often assumed to be a percentage of annual rainfall. The value chosen can vary from less than 2% to 10% or more.

In moving to a more rigorous national approach there is a need to: (a) recognise that the potential for groundwater recharge and groundwater discharge varies with the geological and geomorphic character of the component groundwater systems that make up the area of concern, and (b) to appreciate that actual groundwater recharge will vary temporally, consistent with climate and vegetation. The former deals with the attributes of the landscape that modulate recharge/discharge fluxes, while the latter deals with the biological and climatic circumstances that drive the same.

The essential task is to identify the suite of techniques most appropriate to identifying potential recharge/discharge areas within each flow system and, then, armed with this information to consider the soil water and vegetation relationships that give effect to recharge and discharge in each of the defined areas.

2.2. This report

This report is a product of the "A Consistent Approach to Groundwater Recharge Determination in Data-Poor Areas" project which is funded by the National Water Commission. It aims to develop consistent approaches that can be applied by groundwater managers to determine recharge and discharge fluxes in areas that have not been subject to detailed investigation.

The project is divided into two phases (Figure 1).

Phase 1 – This assembles an understanding of (a) previous studies that have established point source estimates of groundwater recharge and discharge in Australia and, (b) the most applicable techniques that could be deployed to map the distribution of recharge and discharge fluxes across Australian groundwater systems.

Phase 2 – The intention in the second phase is to construct a decision support system (DSS) that will afford groundwater managers first order estimates of recharge and discharge fluxes. The DSS will reference the point source data and landscape context established in phase 1.

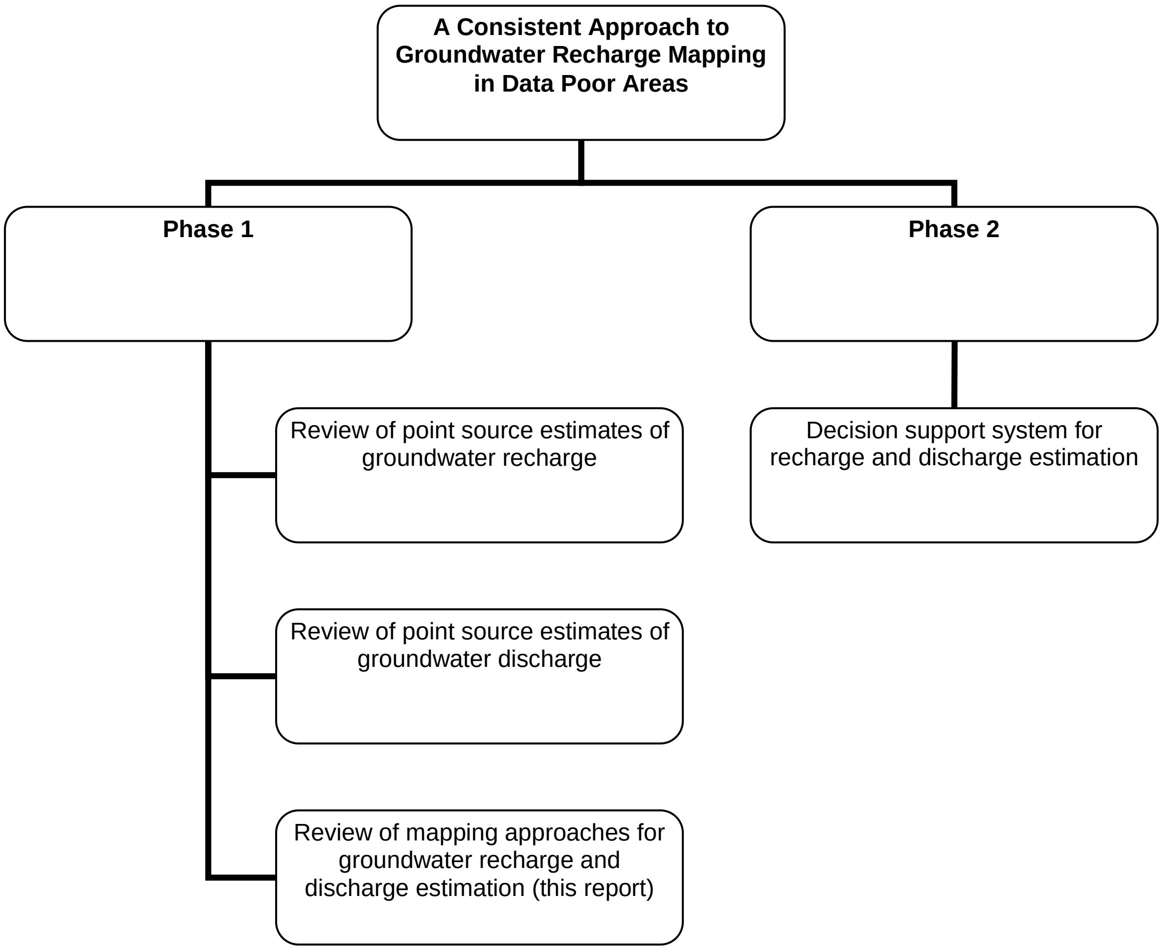

Figure 1 Flow diagram identifying sub-project order.

Phase one activities

Three reports were commissioned under phase 1.

(a) A literature review of previous studies that have established point sources estimates of groundwater recharge in Australia.

(b) A literature review of previous studies that have established point sources estimates of groundwater discharge in Australia.

(c) A review of approaches for mapping the spatial extent of recharge and discharge zones across Australian groundwater systems.

This report is concerned with activity (c) above. It firstly presents a number of mapping approaches for disaggregating the landscape into zones with common properties that could be used as a basis for developing a landscape classification of recharge and discharge zones. It then describes the range of datasets that are relevant to mapping recharge characteristics, taking into consideration scale, national coverage, availability and ease of use. It by no means provides a comprehensive review of all previous mapping approaches or all possible input datasets. In some cases recent reviews have already been undertaken (e.g. Guerschman et al, 2009).

Phase two scope

- Applies empirical relationships and methodologies touched on during phase 1 of the project.
- Relationships developed from recharge and discharge modelling studies will only be considered providing they utilise parameters/data easily obtained in data poor areas.
- The methodologies are not intended for irrigation areas.
- Baseflow, river leakage, (sub) marine discharge and inter aquifer leakage will not be considered.

3. GENERAL PRINCIPLES

3.1. Recharge and discharge definitions

The principles of recharge and discharge are covered in detail in the two accompanying reports (Crosbie *et al*., 2010; O'Grady *et al*., 2010) however a brief definition of the two terms is provided below.

In the context of this report, groundwater recharge is considered to be the hydraulic process of downward water movement from surface water to groundwater. It usually occurs in the vadose zone below plant roots and is often expressed as a flux to the water table surface. Groundwater is typically recharged naturally by rainfall and to a lesser extent by rivers and lakes.

Petheram *et al*. (2002) identify three primary factors controlling recharge through soils in semi-arid Australia: land-use, soil type and climate. Land use determines evapotranspiration from different vegetation types and controls the amount of water available for percolation below the root zone. Soil depth establishes the amount of surface water that can be stored in the soil prior to deep percolation, and soil permeability dictates the rate at which percolation will occur. Climate drives the water balance and determines the volume of water available for recharge subject to evapotranspiration and soil storage.

Groundwater discharge is the loss of water from an aquifer. It can occur by leakage to the ocean, rivers or another aquifer (Cook *et al*. 2003). It may also occur from depths through narrow breaks in a low permeability layer (e.g. mound springs). In this report, however, our primary consideration is discharge through the land surface either through evaporation from a shallow watertable over a large area (Jolly *et al*. 1993) or through transpiration from vegetation.

3.2. Landscape variations in recharge and discharge

Groundwater recharge and discharge are influenced by two distinct processes: The first is the natural propensity of the land to recharge or discharge in accordance with its inherent geological and geomorphic character. The second is concerned with the water balance of the land given dynamic interactions between climate and vegetation.

The geological and geomorphic character of land dictates the nature of a groundwater flow system and this in turn provides insight into areas of potential recharge and potential discharge. The 'geo-character' of the land dictates the connectivity of soils and landscapes with aquifers and groundwater systems down a groundwater flow path. The hydrological properties of soil-landscape-aquifer vary spatially but are generally fixed in time.

Unlike geological and geomorphic attributes the water balance of the land varies in time and space. Climate and land-use and land management may vary seasonally, from year to year or over several decades. Accordingly, the interactions between rainfall, evaporation and transpiration determine the volume of surface water available to drive groundwater recharge and groundwater discharge processes in any given season and in any given year.

Recharge/discharge fluxes to and from a groundwater system reflect the imposition of variable surface hydrology (climate land use and land management) on landscapes that have a defined potential for recharge and discharge attributable to their geological and geomorphic character. Recharge and discharge may occur in accordance with fixed hydrological properties of soils and landscapes when hydrological conditions at the land surface are sufficient to drive the processes.

From the discussion above the mapping of recharge and discharge fluxes across groundwater catchments for the purpose of establishing a water balance can be divided into two fundamental activities. The first is concerned with mapping potential recharge areas and potential discharge areas according to their geological and geomorphic character. The second is concerned with assigning fluxes to each landscape unit in order to estimate recharge and discharge volumes for the entire groundwater catchment.

4. MAPPING HYDROLOGICAL CHARACTERISTICS OF THE LANDSCAPE AND GROUNDWATER SYSTEMS

Recharge and discharge areas vary in accordance with the geological and geomorphic character of groundwater systems. In the high relief fractured rock aquifers of the uplands of eastern Australia, for example, recharge is greatest where the rock either outcrops or is covered by thin soils of high permeability. These areas most often correspond with the upper slopes and hill crests of catchment headwaters. Groundwater discharge in the same terrain usually occurs as seeps or springs in adjacent valleys.

In contrast to fractured rock aquifers, groundwater recharge in the large alluvial aquifers of sedimentary basins is often highest in the large alluvial fans that form at the juncture with upland river valleys. In these systems the potential for elevated recharge reflects the presence of high permeability soils associated with coarser grained sandy sediments of alluvial fans.

The geomorphic and geological character of groundwater recharge areas and groundwater discharge areas are fundamental considerations in exploring hydrogeological relationships that define groundwater systems. It is common practice to express understanding of the dynamics of each groundwater system through conceptual models.

Conceptual models that have been formulated from well studies areas are useful because established principles from one system can be extrapolated to similar systems elsewhere. The conceptual model establishes an expectation of where and how recharge and discharge might occur. This understanding affords a more strategic, targeted, knowledge-based approach to mapping fluxes consistent with well-established hydrogeological principles.

The starting point in building a water balance for areas that have not been well studied in a hydrogeological sense should be the disaggregation of the area of concern into component groundwater systems. Attempts should then be made to build conceptual models for each system that are based on local geological and geomorphic information and knowledge drawn from similar well-studied systems elsewhere. Mapping of recharge areas and discharge areas should then target the specific soil-regolith-landform conditions that define these fluxes in each groundwater system (Figure 2).

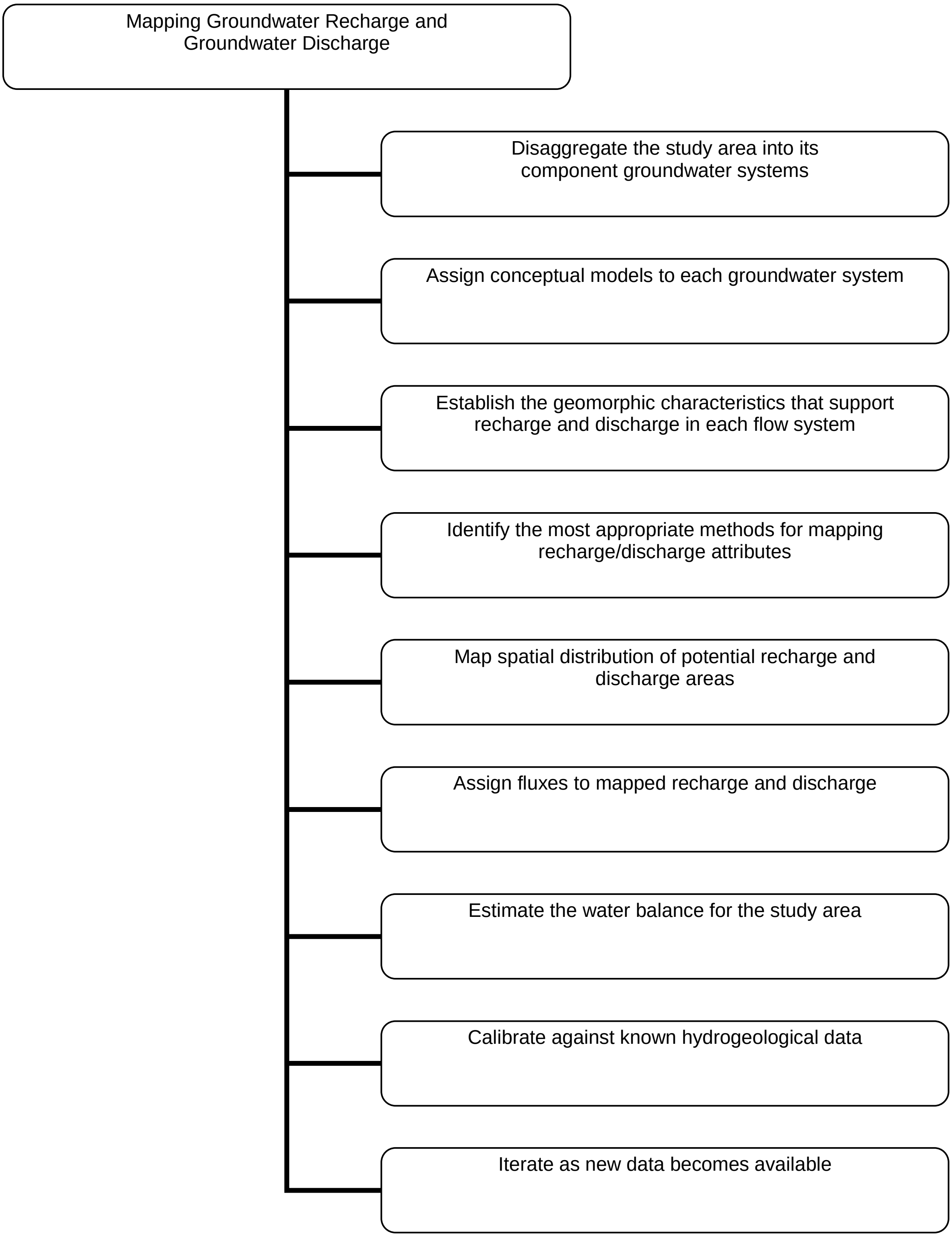

Figure 2 Elements of water balance estimation where data is limited

4.1. Disaggregation of study areas into component groundwater systems

In generating distributed hydrological models the choice of an appropriate spatial discretization is a crucial issue and is linked to data availability and spatial resolution (Dehotin and Braud, 2008). A process of disaggregating large catchments or regions into their component groundwater systems is described in Coram *et al*. (2000). Landscape/aquifer function and performance can be assigned from knowledge of geology and geomorphology and extrapolation from well-studied hydrogeological investigations. For example the extent of fractured rock groundwater systems, large alluvial or marine groundwater systems, can be easily mapped.

Dehotin and Braud (2008) propose a general methodology for catchment discretization using a nested approach. The first level of discretization was composed of sub-catchments organized by river network topography. Sub-catchment variability was described by a second level of discretization - hydro-landscape units. These units took into account topography, land-use, and soil.

Wolock *et al*. (2004) were able to divide the United States into hydrologic landscape regions (HLRs) based on the hydrological-landscapes concept of Winter (2001). HLRs were generated using readily available spatial data layers, GIS tools, and statistical analysis. A three step process was involved in generating HLRs: 1) delineate catchments using a synthetic stream network (derived from DEM; 2)define hydrologic landscapes using land-surface form described by terrain characteristics of the DEM, soil permeability estimated as a percentage of sand in soil, bedrock permeability quantified by assigning permeability classes to general lithologic groups, and climate characteristics described by mean annual precipitation minus potential evapotranspiration; and 3) use principal components and cluster analysis to group similar catchments.

Dahl *et al*. (2007) detailed a number of groundwater classification systems (e.g. Toth's groundwater flow systems (1963); Heath's two-levelled classification of groundwater systems (1982) and Miljostyrlsen's groundwater body typology (2004)). After reviewing the literature they proposed the development of a multi-scale classification system based on eco-hydrological concepts. The typology was based on geomorphologic, geologic and hydrological concepts reflecting functional linkages and controlling flow processes on gradually smaller spatial scales.

4.2. Scale of mapping and assessment

The nature of groundwater flow systems for different terrain types is generally well known even for those areas that have not been well studied. It is, however, scale dependent. Groundwater systems are usually defined down to scales of 1:250,000. At finer scales, however, more detailed assessments of regolith variability are most often required.

Mapping at 1:100,000 scale or finer may be attractive in terms of establishing a more detailed definition of the water balance, but it also presents a range of challenges. At these more detailed scales the range of local geological and geomorphic conditions that influence groundwater systems is much greater. Equally assessments at the more detailed scales must account for increasing complexity in local land use, land management and climate.

The scale of mapping should reflect the purpose of the water balance assessment. Investment in very fine scaled landscape definition will only realise a more accurate water balance where the density of point-scale estimates of recharge and discharge is sufficient to account for landscape variability.

Whilst it is beyond the scope of this project contemporary recharge/discharge estimation invariably calls for a multi-discipline approach, and in particular the use of point source estimates in the calibration of soil-water-vegetation models that account for land use, land management and climate.

4.3. Specific mapping approaches

The development of geographical information systems (GIS), remote sensing techniques and computational methods have stimulated the construction of spatially distributed models since the 1970s (e.g. Abbs and Littleboy, 1998; Mendoza *et al*. 2002; Crosbie *et al*., 2008). Computational spatial modelling can be used to provide a predictive estimate of water balance parameters including recharge and discharge however such models often require extensive data, calibration and testing. Consequently these methods (e.g. WAVES, Zhang and Dawes, 1998) are not suitable for data poor areas and will not be included in this review.

In the absence of detailed hydrogeological mapping, different approaches have previously been undertaken to combine surrogate datasets to generate maps of groundwater flow systems, connectivity and other hydrogeological parameters such as recharge and discharge. These have been either through the development of conceptual frameworks based on understanding processes (e.g. the groundwater flow systems model – Coram *et al*. 2000); or through the use of GIS and remote sensing mapping of surrogates for critical controls (e.g. Tweed *et al*., 2007). It is clear that remote sensing, often combined with GIS, has been increasing in importance for mapping both landforms and hydrological processes (Mendoza *et al*., 2002; Smith and Pain, 2009).

By overlaying groundwater depths with the drainage network, Braaten and Gates (2003) interpreted relationships between hydraulic connection and geomorphology in the Murray-Darling Basin (Figure 3). Ransley *et al*. (2007) mapped stream-aquifer connectivity in the Border River by developing a GIS-based weighted index approach that combined soil and geological mapping data, watertable depth and DEM-derived slope parameters (MrVBF). Lubczynski and Gurwin (2005) used a similar weighted GIS approach, integrating various datasets including Landsat TM-derived lineament and ET analysis, with the numerical groundwater MODFLOW model to assess spatio-temporal variability of recharge. Xu *et al*. (2002) developed stream-aquifer connectivity models for South Africa based on a geomorphology. This geomorphological classification could be related to both aquifer type and boundary conditions, important for conceptualisation of the aquifer system.

Vegter and Pitman (2003) compiled a National Recharge Map of South Africa based on a national base flow map, estimates of recharge from rainfall, point measurements of recharge, and estimates from other methods. Yeh *et al*. (2009) produced a fairly simplistic groundwater recharge potential map of a study site in Taiwan. It employed a weighted GIS approach, combining lithology, land use/cover, lineaments, drainage and slope, derived from aerial photography, geology maps, land use data and field verification. Salama *et al*. (1994) combined detailed aerial photography interpretation (basic geomorphology) and Landsat TM imagery (lineaments and hydrogeomorpholgy) with hydrogeological interpretation to classify and map the recharge and discharge zones of the Salt River System, Western Australia.

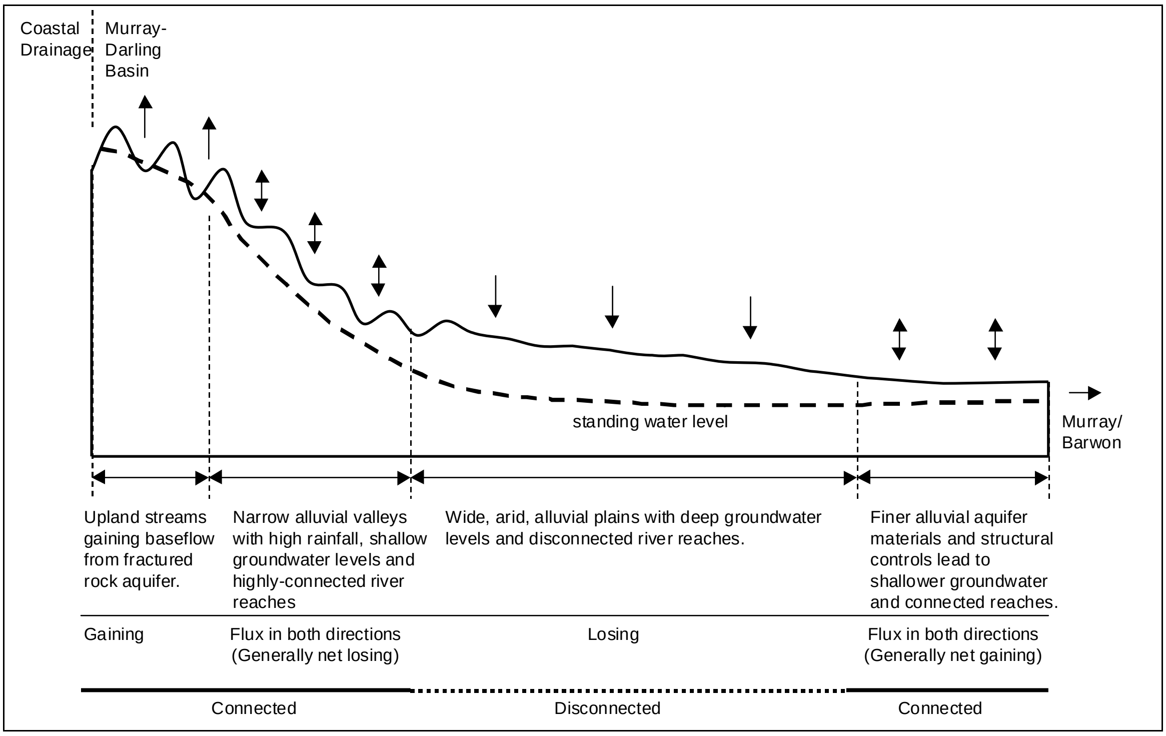

Figure 3 A schematic catchment cross-section showing difference in connectivity for different river reaches in the Murray-Darling Basin (Braaten and Gates, 2003).

Leblanc *et al*. (2007) combined a number of remote sensing datasets (thermal – Meteosat, AVHRR; elevation – SRTM; optical – MODIS, Landsat TM and AVHRR; and vegetation index – MODIS). Depending on the resolution of the imagery, various objects/processes were targeted (e.g. flood extents – Meteosat, AVHRR; ponds – Landsat). Hydrogeological data was combined with satellite imagery to identify and map key surface indicators of recharge and discharge. Preliminary mapping was imported into a steady-state groundwater model.

Bierwirth and Welsh (2000) assessed the usefulness of remotely sensed datasets (from the Great Artesian Basin) for mapping recharge beds and defining recharge properties. Airborne radiometrics identified quartzose sandstones (or their derived materials) which relate well to broadly mapped recharge beds. Satellite multi-spectral reflective (Landsat) and multispectral thermal infrared (AVHRR) data provided useful and complimentary information about surface mineralogical properties.

Tweed *et al*. (2007) used knowledge of the local hydrogeology to identify a series of surface and sub-surface indicators that best show recharge and discharge processes. These indicators are shown in Table 1and combine remote sensing and GIS techniques. Various other authors applied remotely sensed data to the estimation of recharge and/or discharge (e.g. Sultan *et al*., 2008; Milewski *et al*., 2009), employing these surface and sub-surface indicators. Meijerink (1996) made the important point that hydrogeological applications of remote sensing relies on the user to make the link between image or data interpretation and groundwater processes.

For example, Landsat imagery has been used to indentify soil salinisation and growth of salt-tolerant vegetation, both indicators of groundwater discharge (Metternicht and Zinck, 2003). Similarly, changes in lake temperatures observed from Landsat thermal imagery have been used to identify groundwater discharge (Bodda *et al*., 1992; Tcherepanov *et al*., 2005). Lineament mapping can also provide insight into distribution of groundwater springs (Sener *et al*., 2005) while topological information can be used to estimate submarine groundwater discharge at the global scale (Crossland *et al*., 2005). Soil moisture can be used to determine soil hydraulic properties.

Table 1.An example of the input of a variety of data layers into a model for mapping recharge and discharge for an area in Victoria (adapted fromTweed *et al.,* 2007).

	Indictor	**Input data**	**Spatial resolution (m)**	**Data processing**
Discharge	SDVI	Landsat TM and ETM+	30	Standard deviation of NDVI
	Topographic depression	DEM	20	Wetness index
	Break of slope	DEM	20	Profile curvature
	Depth to water table	DEM	20; 2,661 bores	DEM-hydraulic head
	Groundwater flowlines	DEM and Groundwater monitoring data	2,661 bores	Interpolation (inverse distance weight and 7 neighbour) and contouring of hydraulic head data
Recharge	Stoney rises	Wetland inventory mapping	30, 1.25	Visual interpretation and ground truthing
	Eruption points	Landsat ETM+ and true colour composition images and aerial photography	20; 1.25	Visual interpretation and ground truthing
	Less-weathering basalt	DEM and aerial photography	50	Threshold technique on K and Th bands
	Soil infiltration	Soil drainage property mapping		
Additional data	Land-use map	Land use mapping	50	
	Aridity index	Gridded rainfall and potential ET	2,500; 10,000	Rainfall/potential ET
	Monthly rainfall	Average monthly rainfall station data	15 stations	
	Groundwater EC	Groundwater monitoring data	2,870 bores	Interpolation (inverse distance weight and 7 neighbour) of groundwater EC data

5. GENERAL INPUT DATASETS

5.1. Introduction

Recharge and discharge can be influenced by the interplay of climate, soils, regolith, near-surface geology, landforms and vegetation. There are a number of national and regional scale datasets that either directly or indirectly provide information about these sub-surface and surface indicators. Table 2 lists some of the more applicable datasets currently available. Spatial resolution of these input datasets varies. As the larger project looks to develop a nationally consistent approach to estimating recharge and/or discharge, baseline national scale datasets are required for the various parameters. These datasets by their very nature provide broad scale classification; more detailed assessment of the numerous variables can only be provided with greater spatial resolutions of digital data.

This section will discuss the various parameters or themes and associated datasets (highlighted in Table 2) important for estimating recharge and discharge.

Table 2 Summary table of key mapping recharge/discharge themes for and associated datasets.

Key Themes	Dataset	Specific attributes	National scale	Limitations
Climate	Climate surfaces *(based on met-station data)*	Rainfall Temperature	yes	Variable density of met station recordings
Soil, regolith and geology	Surface geology map 1:500k scale	Lithology type Bedrock structure and fabric Consolidated and unconsolidated sediments	yes	
	National regolith map	Regolith and landforms	Yes	Very generalised
	ASRIS	Soil texture and composition (0-2m) Measured and inferred (pedotransfer functions) porosity and permeability Delineation of shallow soil bedrock and deeper soils Soil profile/structure	Yes	Highly variable quality at a national scale
	Gamma-ray Imagery and Weathering Intensity Index (WII)	Soil texture and composition 0-.5m (inferred porosity and permeability) Delineation of bedrock and regolith materials	Yes	Soil texture/composition and WII relationships not always unique – require integration with other datasets
	Landsat TM, SPOT	Soil texture and composition, soil moisture	Yes	Difficult to compare scenes of national mosaic due to different acquisition dates
	ASTER, NOAA	Soil texture and composition (inferred porosity and permeability)	No	Patchy coverage; Identification of soil responses difficult to resolve in highly vegetated areas.
	Radar	Soil moisture	No	Patchy coverage
Vegetation and land cover	MODIS	Land use mapping Leaf area index Greenness index Vegetation dynamics (rate of drying) Vegetation health	Yes	
	Landsat TM	Vegetation mapping Greenness index (NDVI) Vegetation health Bare soil vs. vegetated	Yes	National scale mosaics available but difficult to compare between scene to scene due to different acquisition dates
	ASTER, SPOT	Vegetation/land use mapping Bare soil vs. vegetated	No	Patchy coverage
Topography	DEM Slope, aspect, elevation, relief	Delineation of landforms/landscapes - surrogates for predicting soil types and hydrological processes	Yes	
	FLAG, MRVBF	Water-logging, Seepage areas, landscape position		
Hydrology	Water table surface	Depth to water table	No	Data currently being compiled nationally by Bureau of Meteorology
	ET	Evapotranspiration	Yes	Various input datasets available
	GFS, HGU, HGL, IBRA	Flow systems framework, aquifer architecture and hydrological characteristics	Yes	Regolith component not well described – based largely of reclassified geology

5.2. Climate

Rainfall and temperature

The effects of climate and rainfall on recharge can be simplified into two different types:

- in wetter areas, normal rainfall can exceed potential evaporation for a period of the year, leading to deep drainage when the excess water cannot be stored in the soil; and
- in drier areas, deep drainage is likely to occur mainly as a result of exceptional circumstances, such as intense rainfall and flooding that may only occur once every 3-20 years (Walker *et al*., 2007).

In determining deep drainage, rainfall distribution is as important as the total amount of rain. As a simple rule, increased rainfall means greater recharge, as summarised in the recharge review (Crosbie *et. al.,* 2010). The sequence of rainfall events is also critical, particularly for the episodic nature of deep drainage and recharge. Seasonality is another major climatic factor that affects leakage amounts. While recharge is often lower in summer dominated rainfall areas, it tends to be more episodic and depends on the rainfall sequence. Summer rainfall can be as effective in causing deep drainage as winter rainfall if it is concentrated over short periods (Walker *et al*., 2007).

In the winter rainfall dominated southern parts of Australia, most of the rainfall occurs during the cooler part of the year, when evaporation and hence the amount of water exploited by vegetation is low. Under these circumstances, the rainfall infiltrating the land must be stored in the soil (if leakage is to be prevented) however if the soil already contains water, deep drainage occurs more readily (Walker *et al*., 2007). In summer rainfall-dominated northern parts of Australia, most of the rain coincides with the period of highest evaporation, thus increasing chances for vegetation to use the rainfall.

Leaney and Herczeg (1999) showed that in the Mallee region of South Australia and Victoria, climate had a temporal as well as spatial importance; they reported that fresh groundwater in that area was a consequence of higher rainfall 20,000 years ago.

Rainfall and other climatic observations are regularly recorded from hundreds of weather stations across the country. This time series data is freely available from the Bureau of Meteorology (http://www.bom.gov.au/climate/).

Remote sensing

CMORPH (CPC MORPHing technique) produces global precipitation analyses at very high spatial and temporal resolution. This technique uses precipitation estimates that have been derived from low orbital satellite microwave observations exclusively, and whose features are transported via spatial propagation information that is obtained entirely from geostationary satellite IR data. With regard to spatial resolution, although the precipitation estimates are available on a grid with a spacing of 8 km (at the equator), the resolution of the individual satellite-derived estimates is coarser than that - more on the order of 12 x 15 km or so. The finer "resolution" is obtained via interpolation (Joyce *et al*., 2004).

Quantitative precipitation is also measured (in the tropical regions) from the TRMM (Tropical Rainfall Measuring Mission) Microwave Imager (TMI). TMI was based on the design of the Special Sensor Microwave/Imager (SSM/I) but with improved spatial resolution. It has a swath width of ~880 km (http://trmm.gsfc.nasa.gov/overview_dir/tmi.html). Other studies have employed METEOSAT 5 to generate a precipitation surface (Brunner *et al*., 2004). This surface was subtracted from an NOAA-AVHRR derived ET surface to identify zones of recharge.

5.3. Soil, regolith and geology

There are limitations with establishing recharge and discharge fluxes through mapping the spatial distribution of soil and regolith properties alone. Some care needs to be taken to not assume deep percolation below the root zone of vegetation equates with groundwater recharge. In many instances small groundwater systems comprising local flow cells may function above regional aquifers. Equally, regional aquifers are often superimposed one over the other. Under these circumstances it is not possible to map fluxes without first knowing how and where they occur. Accordingly, it is necessary to reiterate that accurate water balance assessments cannot be completed in the absence of realistic conceptual hydrogeological models. Soil and regolith mapping of recharge/discharge flux is only appropriate when all of the water that passes below the below the root zone reaches the aquifer of concern. There is considerable literature on digital soil mapping and pedotransfer functions, both of which include aspects of soil hydrology that relate to recharge and discharge (e.g. Lagacherie *et al*., 2007; Pachepsky and Rawls 2004). Bui *et al*. (1999) stress the importance of extracting soil property data from prior soil surveys (see also Wielemaker *et al*. 2001) to use in the generation or validation of geology and terrain map products. Bui and Moran (2003) describe the extrapolation of data from small areas using surrogate data to produce a new soil map of the Murray Darling Basin (Figure 4).

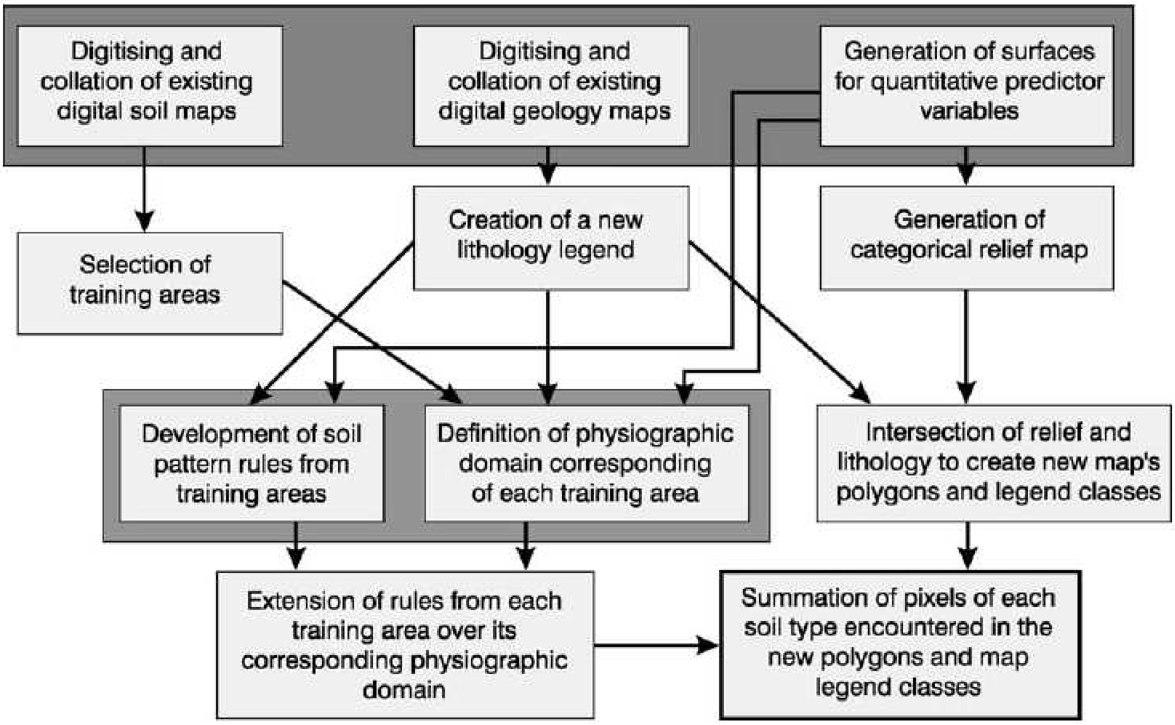

Figure 4 Flow diagram of the implementation of the strategy for re-mapping the MDB (from Bui and Moran 2003).

Soils can affect the amount of leakage by controlling the balance between water holding capacity and soil drainage. Sandy or rocky soils store little water, thus associated deep drainage is typically greater than in heavier clay or loam soils. The type of landform and position in the landscape is closely linked to surface materials. For example, scroll plain meander tracts of rivers are typically sandy in nature and are good sites of recharge. England and Stephenson (1970) used soil depth, texture, and rockiness to develop an index of soil water-holding capacity. This was combined with geology and landscape position to generate four broad hydrologic response units that ranged from low to high water holding capacities.

Additionally, the amount of deep drainage depends on the drainage characteristics of the soils and sub-soils, for example some sub-surface clay may be less permeable and prevent water draining into the groundwater system. Under these circumstances, water may move laterally instead of draining vertically into groundwater systems (Walker *et al*., 2007). An empirical relationship has been identified between % clay surface soil and the rate of deep drainage (Kennett-Smith *et. al*., 1994*)*. SKM (2002) looked at this relationship for surface to 0.5 m, surface to 1.0 m and surface to 2.0 m depth intervals and found the correlation was best for the surface to 2.0 metre interval. The Australian Soil Resource Information System (ASRIS) has been used for mapping % clay in the top few cm of soil, and may be used as a surrogate for recharge in some environments. Consequently soil landscape maps may be used to estimate deep drainage regionally via the % clay surrogate measurement. Measured or estimated recharge for particular soil types has been used as a basis for assigning values in broader regions (e.g. O'Connell *et al*., 1995; Leaney and Herczeg, 1999; SKM, 2002).

Anuraga *et al*. (2006) used simplified soil and land use maps to generate Hydrological Response Units, with respect to cropping systems, irrigation and soil for estimating recharge. Their procedure is shown in Figure 5. Generated simulation units may be subdivided into transported materials such as alluvium and basin sediments, sepiolite and other *in situ* weathered materials.

Asseng *et al*. (2001) mapped simulated deep drainage under wheat in the WA wheat belt using rainfall and soil types to estimate recharge. Particle size distribution, water holding capacity and root density were found to be important soil characteristics. Another example of the mapping of soil attributes is provided by Cialella *et al*. (1997), who used vegetation indices from AVIRIS combined with a DEM to delineate zones with different soil drainage classes. Smerdon *et al*. (2009) estimated relationships for capillary pressure, water saturation, and relative permeability from soil types present from the ground surface to the water table (i.e., depth profile). Profiles were compiled from digital soil maps and surficial geology maps. Hydraulic properties for soil columns for the top 1.3 m were estimated from soil data, and below 1.3 m from data on surficial geology. In the Australian context, soils data from ASRIS and regolith information can be used in a similar way.

Pedotransfer functions are also an important potential approach to mapping soil characteristics that relate to recharge and discharge (e.g. Børgesen *et al*. 2008). The term pedotransfer is a predictive function where certain soil properties or characteristics are used to infer other properties. For example information on soil texture could be used to infer soil porosity and permeability characteristics.

Soil landscape units are areas of land that have recognisable and specifiable topography and soils. The description of soil landscapes requires soil characteristics, geological or geomorphological materials, and specific landform patterns, as well as an understanding of vegetation, climatic and drainage regimes (Kovac and Lawrie, 1990). The strength of soil landscape units is that they allow the integration of both soil- and landform-related constraints into a single mapping unit (Atkinson, 1993).

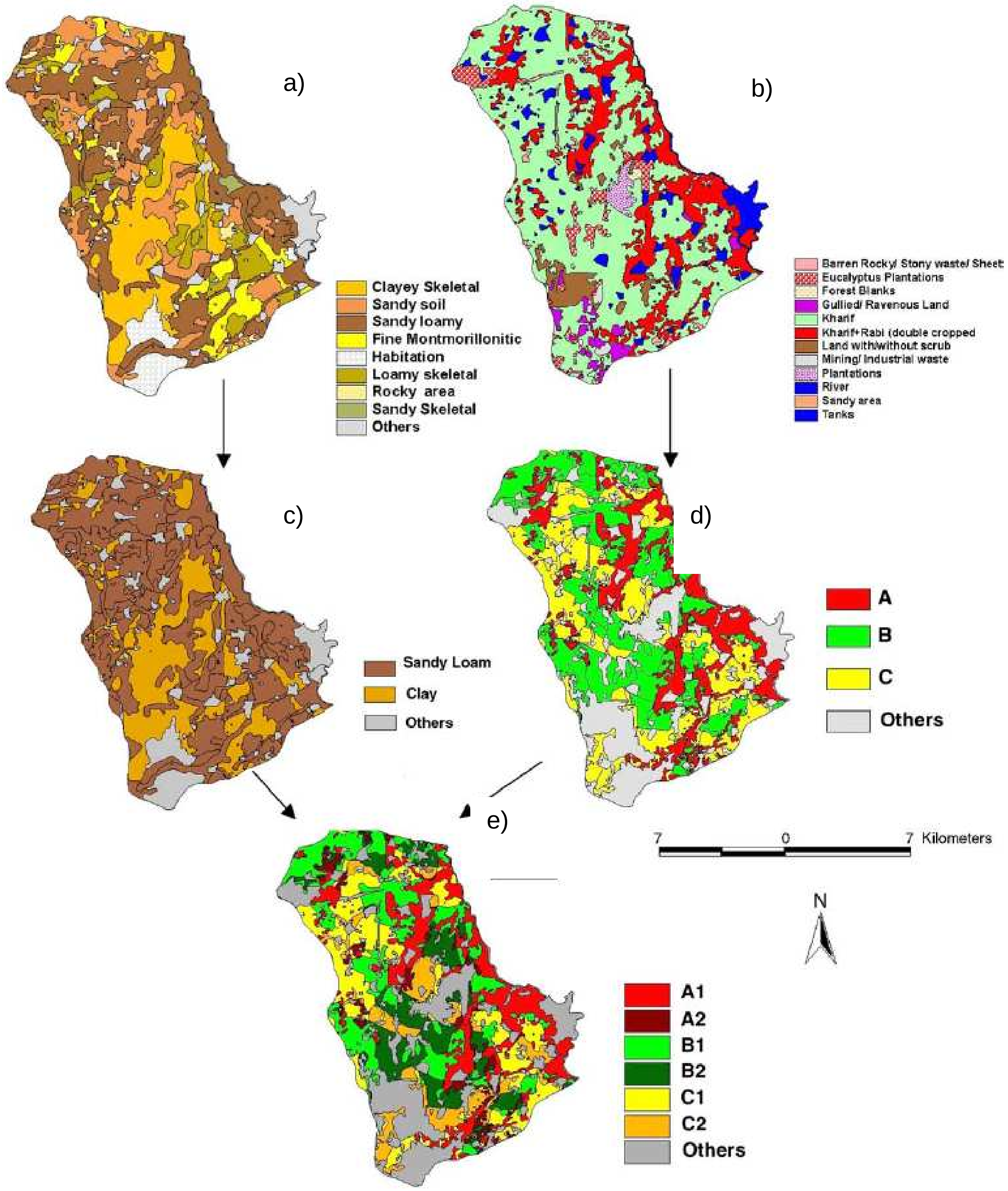

Figure 5 Soil and land use maps (a and b) are simplified (c and d) and combined to generate a 'simulation units' map (e) (from Anuraga *et al*. 2006).

Geological datasets are regularly used in conjunction with soil and landscape datasets. The key attributes that can be extracted from geological maps include whether the surface materials are consolidated or unconsolidated, the grain size or texture and fabric. In the case of fractured bedrock, structural information (e.g. faults, fractures, jointing) may also be locally important. These attributes all influence to varying degrees, the porosity and permeability characteristics of the bedrock or sediments. In most areas recharge takes place through the vadose zone. Figure 6 shows that most groundwater flow in fractured rock systems, especially in upland areas, occurs near the surface in the upper part of the regolith where regional connections are more continuous. It follows that the potential for recharge in these settings are likely to be greater where regolith is thicker and has higher hydraulic conductivity.

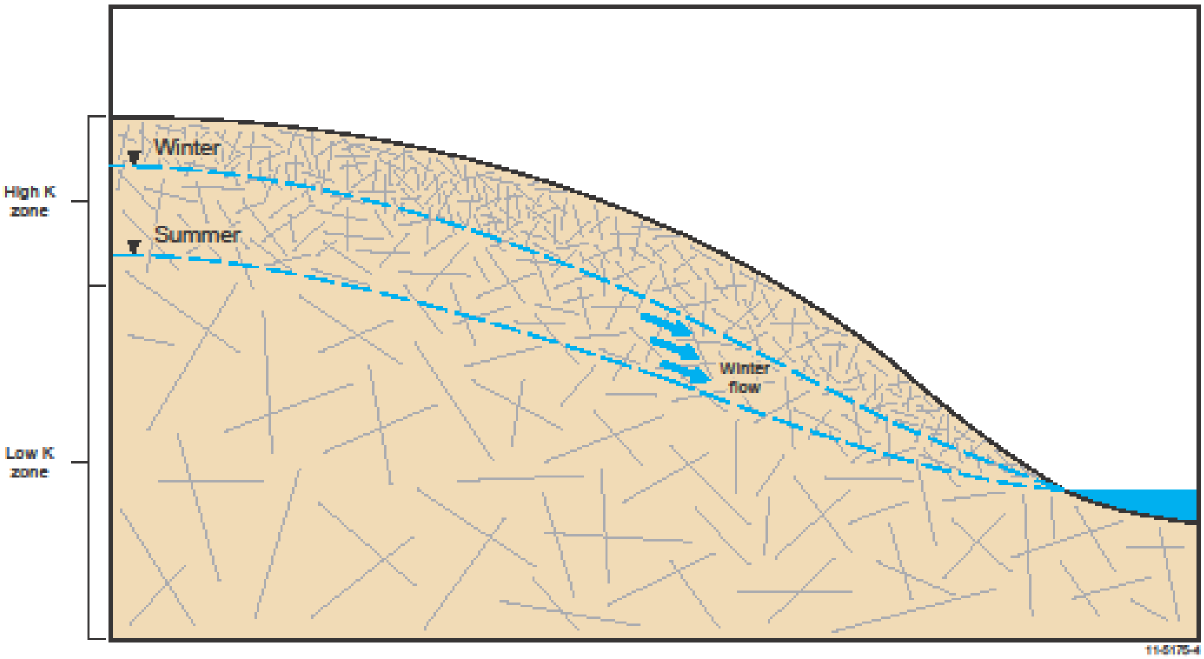

Figure 6 Schematic representation of regional groundwater flow through fractured rocks (adapted from Cook, 2003). Note that fractures are more continuous nearer the surface.

Melloul *et al*. (2006) developed a GIS map of the unsaturated zone of an area in Israel that enabled 3-dimensional depiction of the varying permeability characteristics of underlying stratigraphic layers. The resultant map conveyed information about areas having low to high permeability and areas in which perched aquifers might be found. This contributed to a better understanding of the recharge process, and of the reasons for deterioration of groundwater quality in the aquifer.

Australian Soil Resources Information System (ASRIS)

ASRIS is a national database, providing maps of soil profiles, soil and land resources and other relevant datasets (Johnston *et al*., 2010). It was initially designed to build a nationally consistent database from the extensive soil point and soil survey map data previously collected by the State and Territory agencies. Type and quality of the data however varies enormously and there are inconsistencies in the way soil horizons are described and named (Johnston *et al*., 2010), despite the existence of an agreed standard for horizon description (McDonald *et al.*, 1990). Similarly, methods used for laboratory determinations of specific soil properties also vary widely and in many cases cannot be compared directly. The Atlas of Australian Soils, considered to be a consistent source of spatial data on soils (McKenzie *et al*., 2000), has been incorporated into ASRIS (McKenzie *et al*. 2005).

An important objective of ASRIS was to produce nationally consistent spatial estimates of key soil properties, suitable for use in regional to national scale assessments. The collated ASRIS datasets were used as inputs to estimate soil properties based on point-based, polygon-based or combined point and polygon-based models (Johnston *et al*., 2010). Carlile *et al*. (2001) outline a procedure for estimating soil texture from ASRIS data while Henderson *et al*. (2001) address the point-modelling of soil properties from the database. Continental soil property models were constructed from ASRIS using decision trees that relate the soil property to the environment through a suite of environmental predictor variables at the locations where measurements are observed. These decision tree models were then used to extend predictions from known points to the whole of Australia using techniques similar to pedotransfer functions. The models developed have good to fair predictive ability. Their overall reliability varies spatially and depends on the property being predicted. As might be expected, topsoil models are stronger than subsoil models. There is however a large amount of unexplained variation in all models. This is to a large degree expected given the heterogeneous nature of the database.

For some soil properties, insufficient soil profile data were available to produce reliable models based on the point data in ASRIS. In these cases, maps of soil type linked to look-up tables of soil properties were used, following the method described by McKenzie *et al*. (2000). Uncertainties associated with the polygon-based models relate to scale and accuracy of the base maps; how well the maps represent soil variability; variation in the accuracy of tabulated estimates of the different soil properties; and whether estimates of soil properties existed for specific soil types (Johnston *et al*., 2010). Finally in some cases point- and polygon-based models were combined which has the advantage of retaining some spatial structure from the soil map, while allowing estimates of % clay to vary as a function of other environmental predictors.

Table 3 The hierarchy of ASRIS spatial mapping units modified from McKenzie *et al*. (2005).

Level	Order of land-unit tract	Characteristic dimension	Mapping Criteria	Descriptive attributes	Appropriate map scale
0	Division	100 km	Very broad physiography and geology	Physiography, geology	1:30 million
1	Province	30 km	Broad physiography (grouped from level 2)	Physiography (slope, relief) and geology	1:10 million
2	Region	10 km	Landforms (SRTM DEM)	Physiography, geology, water balance, regolith, dominant soil order	1: 2.5 million
ASRIS mapping hiatus Levels above are based on subdivisions of the continent Levels below are aggregated from more detailed surveys					
3	Zone	3 km	Broad landforms and regolith materials	Water balance, dominant soil suborder	1:1 million
4	District	1 km	Landform patterns	Groupings of geomorphically related systems, dominant soils	1:250 000
5	System	300 m	Related soil profile classes (soil-landscape)	Local climate, relief, modal slope, lithology, drainage net, landform patterns	1:100 000
5.1		100 m	As for Level 5		1:25 000
6	Facet	30 m 10 m 3 m	Soil profile class	Landform elements, slope, aspect	1:10 000 1:2500 1:1000
7	Site	10 m	Soil profile attributes	Regolith properties, surface condition, microrelief	NA

ASRIS provides access to spatial data on soil mapping and soil landscape units at various scales as shown in Table 3. Levels 0–2 are complete for the whole continent, whereas coverage of levels 3 onwards is patchy. Information on coverage is available from the ASRIS web site (http://www.asris.csiro.au/). As the current project is aimed at regional to national scale, level 2 may be the most appropriate. However, for some parts of the continent more detailed soil mapping is available which may be advantageous for groundwater managers to use on site specific cases as more detailed soil information is critical for estimating recharge and discharge at operational scales.

Surface Geology of Australia Map

The Surface Geology of Australia (2010 edition) is a seamless national coverage of outcrop and surficial geology, compiled for use at or around 1:1 million scale (Figure 7). The data maps outcropping bedrock geology and unconsolidated or poorly consolidated regolith material covering bedrock. Geological units are represented as polygon and line geometries, and are attributed with information regarding stratigraphic nomenclature and parentage, age, lithology, and primary data source. The dataset also contains geological contacts, structural features such as faults and shears, and miscellaneous supporting lines like the boundaries of water and ice bodies.

The dataset has been compiled from merging the seven State and Territory 1:1 million scale surface geology datasets released by Geoscience Australia between 2006 and 2008, correcting errors and omissions identified in those datasets, addition of some offshore island territories, and updating stratigraphic attribute information to the best available in 2010 from the Australian Stratigraphic Units Database (http://www.ga.gov.au/oracle/stratnames/index.jsp). The map data were compiled largely from simplifying and edge-matching existing 1:250 000 scale geological maps. Where these maps were not current, more recent source maps, ranging in scale from 1:50 000 to 1:1 million were used. In some areas where the only available geological maps were quite old and poorly located, some repositioning of mapping using recent satellite imagery or geophysics was employed.

The National Surface Geology Map is available from https://www.ga.gov.au/mapconnect/

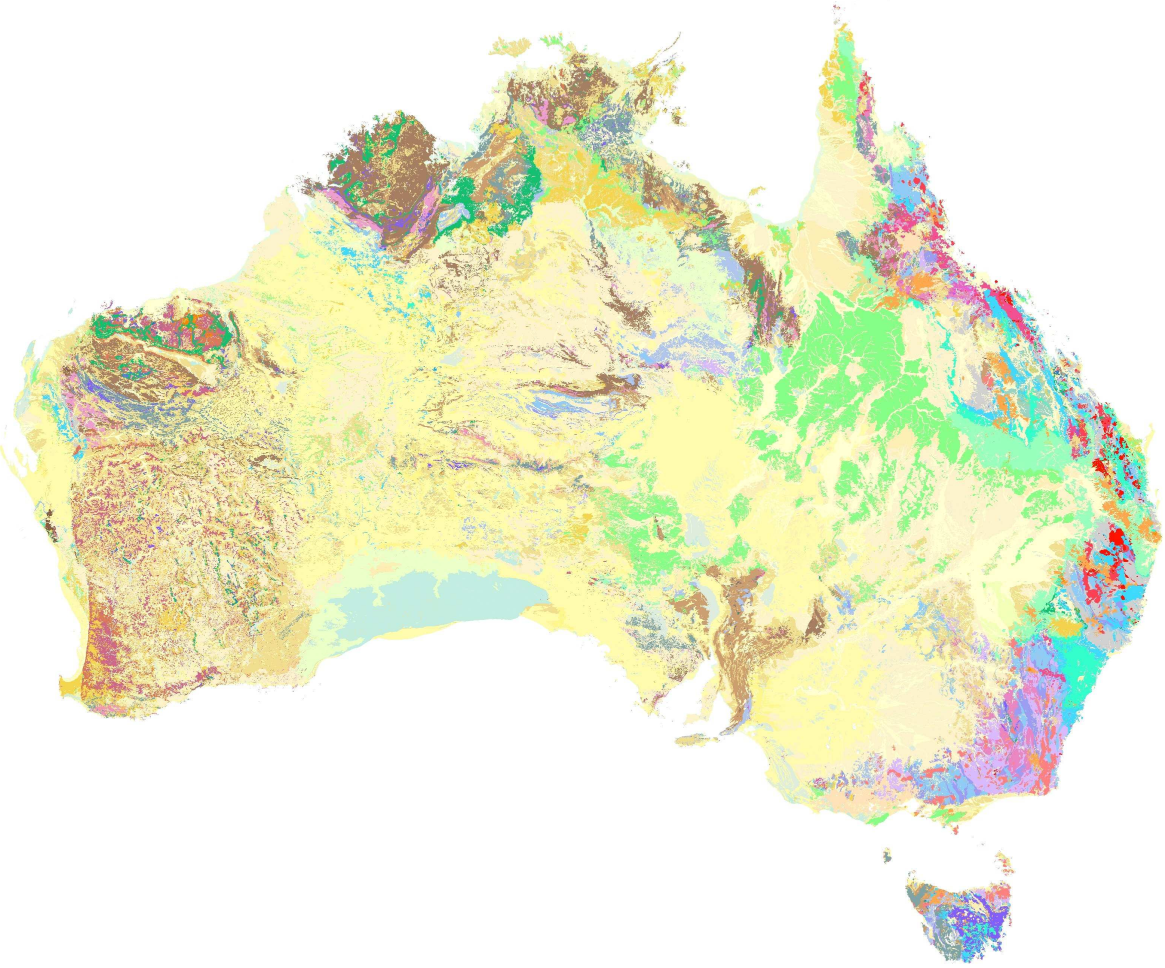

Figure 7 National-scale 1:1 million surface geology map.

Regolith Terrains of Australia Map

Regolith-landform maps show the type and distribution of regolith landform units. These units are distinct patterns of recurring landform elements with characteristic regolith associations. The map (Figure 8) presents a systematic analysis and interpretation of 1:82000 aerial photography, Landsat TM imagery, field mapping and literature research. Regolith-landform mapping is similar to soil landscape mapping and divides the landscape into units that are characterised by similar landform and regolith attributes (Ollier and Pain, 1996).

The regolith map is available for download from https://www.ga.gov.au/products/servlet/controller?event=DEFINE_PRODUCTS.

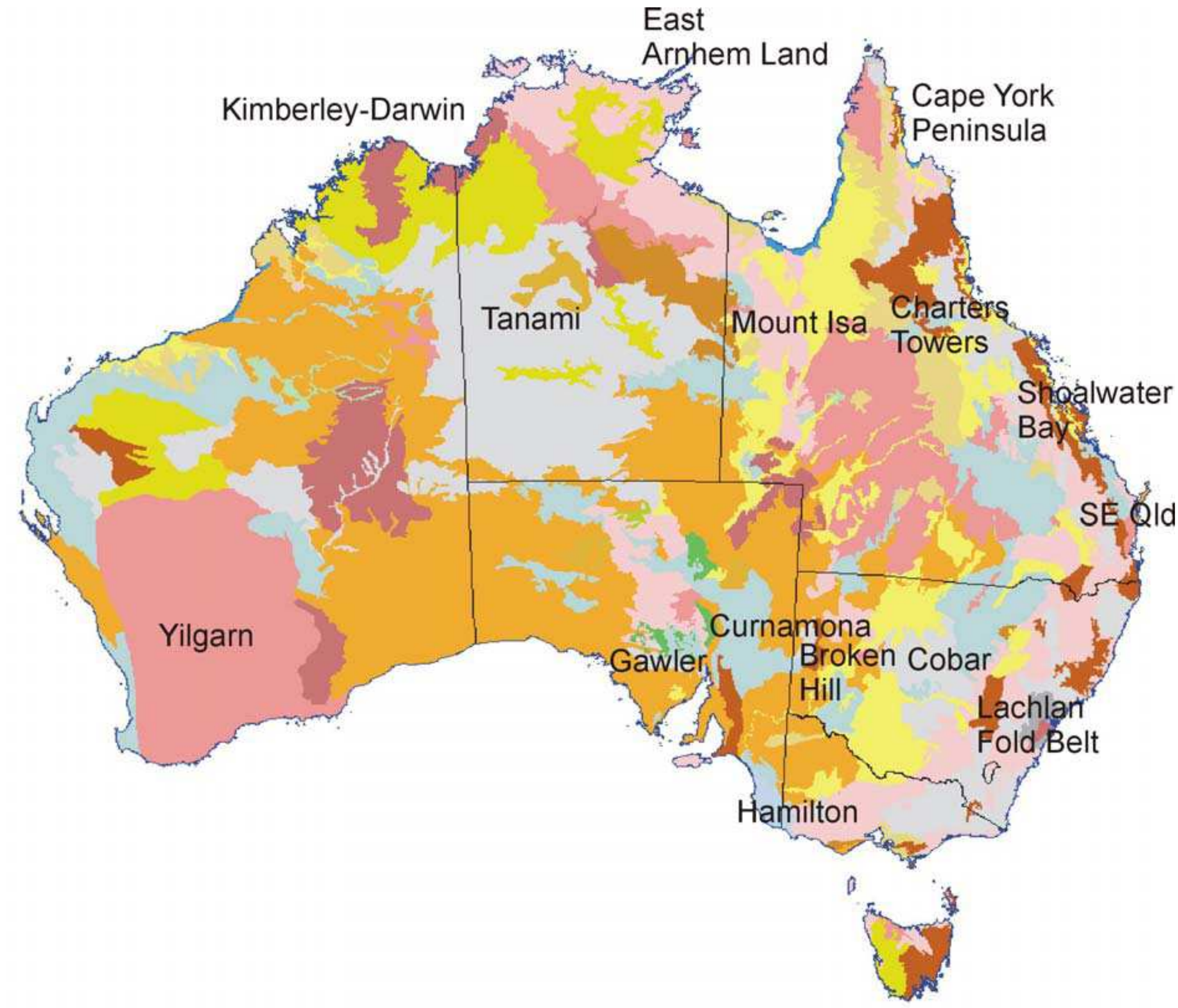

Figure 8 National Regolith Map.

Remote sensing

Various different remote sensing techniques can be used to provide information about soil and geological characteristics including radiometrics (and Weathering Intensity Index), Digital Elevation Models, Landsat TM, ASTER and NOAA-AVHRR.

Airborne and ground based Electromagnetic (EM) geophysical datasets are becoming increasingly important in addressing natural resource management issues, particularly in relation to groundwater and surface water salinity. EM methods can be used to generate 3D conductivity maps of regolith and bedrock materials (Lane, 2002). From a recharge and discharge perspective EM datasets have the potential to identify saline discharge sites, regolith porosity (e.g. clay vs. sandy substrates) hydrological structures (e.g. buried palaeo channels, aquifers and aquitards) and areas of enhanced recharge (e.g. river leakage).

Ground EM has been used for some time and with considerable success as a means of extrapolating measurements on recharge (e.g. Cook *et al*. 1989, Cook *et al*. 1992). The advent of airborne EM (AEM) has meant that much larger areas can now be covered (Cook and Kilty 1992). Currently EM datasets are still only available over relatively small areas of Australia due to the high cost of data acquisition. Consequently for the purposes of this research, EM is of limited application.

Airborne gamma-ray spectrometry (AGRS) measures the abundance of Potassium (K), Thorium (Th) and Uranium (U) in rocks and weathered materials by detecting gamma-rays emitted due to the natural radioelement decay of these elements. Airborne gamma-ray imagery therefore provides a near-surface (to a depth of approximately 35cm) perspective of soil and rock geochemistry. Once calibrated (ground 'truthed' with field observation/measurements) gamma-ray emissions have the potential to predict specific soil properties (e.g. soil mineralogy, texture and degree of weathering). This type of analysis can now be done at a national scale with the recent release of the (near-complete) radiometric map of Australia (Minty *et al*. 2008). The radiometric map of Australia is a levelled database and is consistent with the International Atomic Energy Agency's (IAEA, 2003) Global Radioelement Datum. This enables quantitative comparison of radiometric signatures reflecting bedrock and regolith materials across the Australian continent.

Geophysics

Radiometrics has been used effectively in soil and regolith mapping (e.g. Baxter *et al.* 1997; Bierwirth, 1996; Cook *et al*., 1996; and Wilford *et al*., 1997) and geological mapping (e.g. Taylor *et al*., 1995; Cayley and McDonald, 1995). Bierwirth and Welsh (2000) were able to discriminate quartzose sandstones and sandy surficial sediments, both of which are aquifers in the study site, using airborne radiometrics. Hocking (1997) reported that patterns of radiometric intensities can indicate a range of land type characteristics related to recharge potential. Potential recharge was mapped by selecting different land types and then characterising them according to their potential recharge rate based on calculated infiltration rates. The land types were then mapped using radiometrics. The final calculated correlation between the mapped potential recharge and manipulated potassium radiometric imagery was r^2= 0.61. The method requires a strong understanding of the hydrogeology and infiltration characteristics of the study area. In general strong contrasts in radiometric signatures were valuable in the delineation of soil/geology; where less significant variation in radiometric response occurred, changes in topographic relief became the more dominant mapping method (Muller and Hocking, 2002). The national scale radiometrics map (Figure 9) is available from http://www.geoscience.gov.au/bin/mapserv36?map=/public/http/www/geoportal/gadds/gadds.map&mode=browse.

Recently the radiometric map of Australia has been combined with terrain attributes to generate a Weathering Intensity Index (WII) for the whole continent (Wilford, in prep). Several hundred field site locations describing the degree of bedrock weathering were used to assess relationships between radioelement concentrations and terrain relief with changes in weathering intensity. Correlations between these environmental variables with the degree of bedrock weathering were then used to predict the weathering intensity across the landscape from largely fresh, unweathered material with minimal soil development at one end of the spectrum to very highly weathered soil/regolith at the other.

Changes in weathering intensity are reflected by changes in the chemical, physical and hydrological properties of the regolith/soils. The index can be used to separate fractured bedrock controlled hydrological landscapes from regolith dominated landscapes. Highly weathered clay rich substrates can often be separated from shallow soils over bedrock. For example in the central west region of NSW the WII identifies deeper and more highly weathered bedrock associated with a partially preserved palaeosurface (Figure 10). The weathered materials are clay rich and as a result the groundwater and interflow pathways are sluggish which in turn leads to waterlogging and salt scalding.

Figure 9 National radiometrics map.

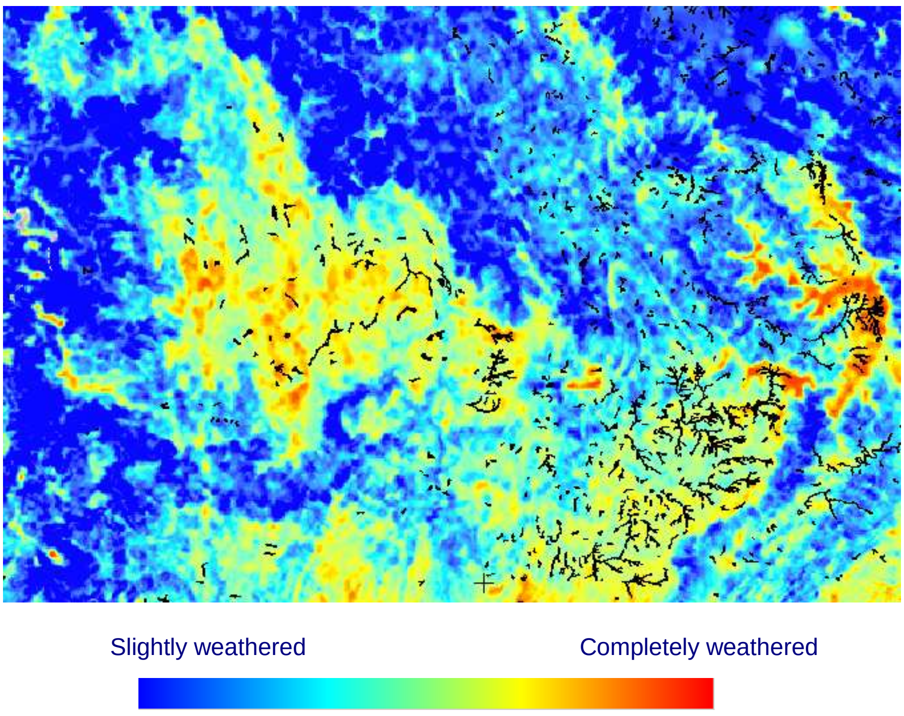

Figure 10 Weathering Intensity Index, showing highly weathered landscapes (yellows and red), corresponding to known salinity sights (e.g. salt scalds -black polygons).

GRACE (the Gravity Recovery and Climate Experiment) provides observations of the time-varying component of the earth's gravity field. Launched in 2002, GRACE measures precise change in the earth's gravity field arising from the redistribution of mass that occurs throughout a given region over approximately 1 month. Once the imagery has been corrected for tidal, atmospheric and oceanic effects, the observed changes over land can mainly be attributed to changes to variability in the total terrestrial water storage – integration of soil moisture, groundwater, surface water and snow/ice (Ellett *et al*., 2005). GRACE is well suited to providing data on a global scale however this results in limitations when dealing with catchment scale interpretation. Ellett *et al*. (2005) demonstrated the ability of GRACE to assess hydrological model simulations, principally water storage.

AMSR was launched on board the Advanced Earth Observing Satellite-II (ADEOS-II) in June, 2002. Various geophysical parameters, particularly those related to water (H2O), can be estimated from AMSR data. The new frequency channels launched with AMSR-E also provides information about soil moisture except in snow covered areas or dense vegetation.

Optical remote sensing

Landsat and SPOT sensor details and data sources are provided in Appendix A. Processed Landsat TM imagery is useful in identifying spectrally anomalous and homogenous units, which can be equated to terrain units when draped over DEM data in a GIS (Hou and Mauger, 2005). The use of Landsat TM data for geological mapping is well known (e.g. Drury and Hunt, 1989; Abrams *et al*., 1984; Podwysocki *et al*., 1985) but its use for mapping regolith materials is less common. Tapley and Gozzard (1992) found that most regolith units could be identified on enhancements of the Landsat TM data. Wilford (1997) was also able to use enhanced Landsat imagery to rapidly separate surface materials within erosional and depositional landform units. The effectiveness of the procedure can be attributed to the spectral resolution of the Landsat TM data, particularly the ability to detect reflectance features related to the absorption of iron oxides (bands 1-4) and the absorption of clay minerals in band 7. Landsat TM band 5 corresponds to the reflectance peak of most soils and rocks. Spectral characteristics of common surface features (vegetation, bedrock and regolith materials) can be resolved with Landsat TM bands (Figure 11; Wilford, 2000). Several band combinations and ratios can be useful for separating different weathered materials:

- 7+1 silica-rich materials (e.g. siliceous bedrock, quartz gravel lags);
- 5/4 ferrous iron (e.g. hematite, iron duricrust, ferruginous saprolite);
- 5/7 argillic materials – clay and carbonate;
- 3/4 differentiating saprolite versus vegetation;
- 4/2 differentiating ferruginous from non ferruginous saprolite; and
- 3/1 ferric (Fe3+) iron (e.g. geothitic saprolite and iron duricrust).

These band and ratio combinations can be displayed individually or as various three band false-colour combinations. How successful these band combinations are for regolith separation will depend on the vegetation cover and local complexity of the landscape and regolith material (Wilford, 2000). A clay–iron oxide–silica false colour composite (Figure 12) has been demonstrated to effectively separate a range of different materials. This colour composite utilises a technique called Directed Principle Component Analysis (DPCA) developed by Fraser and Green (1987).

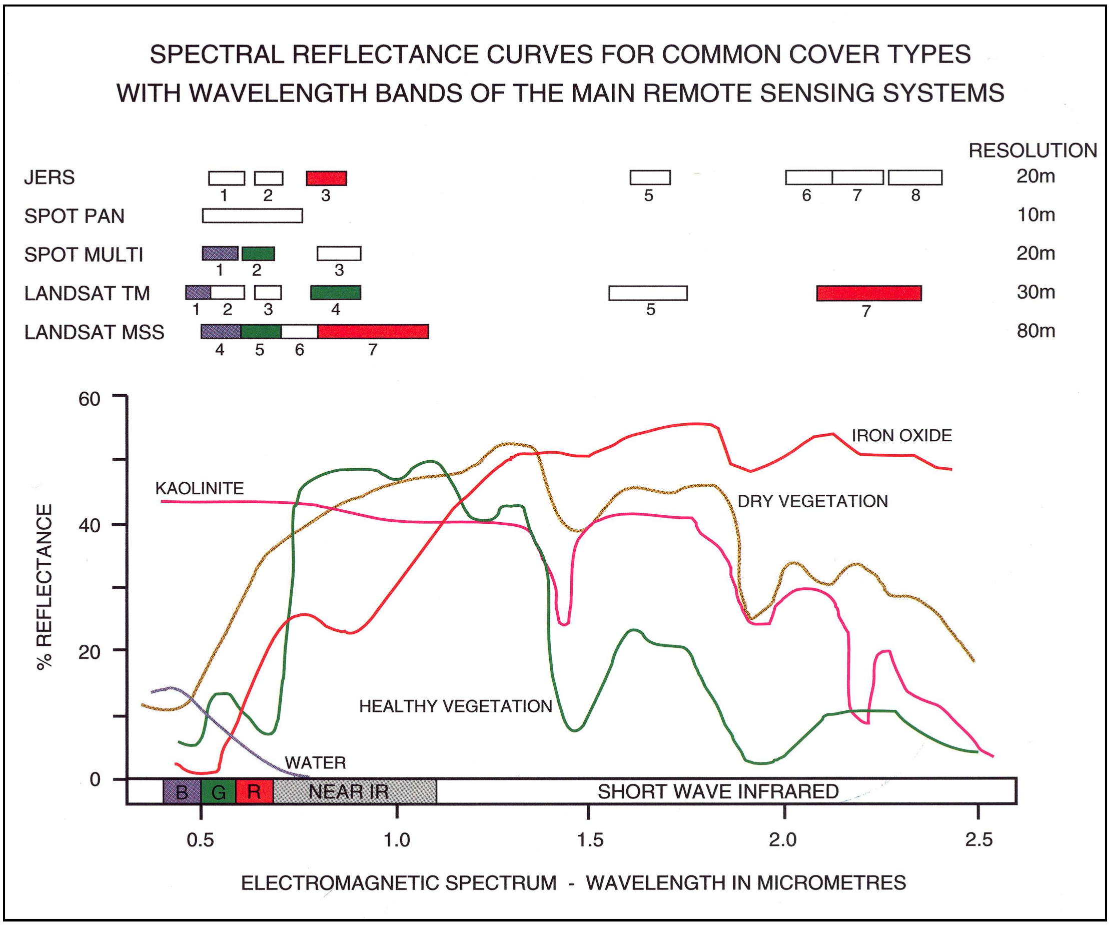

Figure 11 Channel positions for common satellite sensors (including Landsat TM 5) and spectral curves of common surface materials (from Geoimage PTY LTD, 1995).

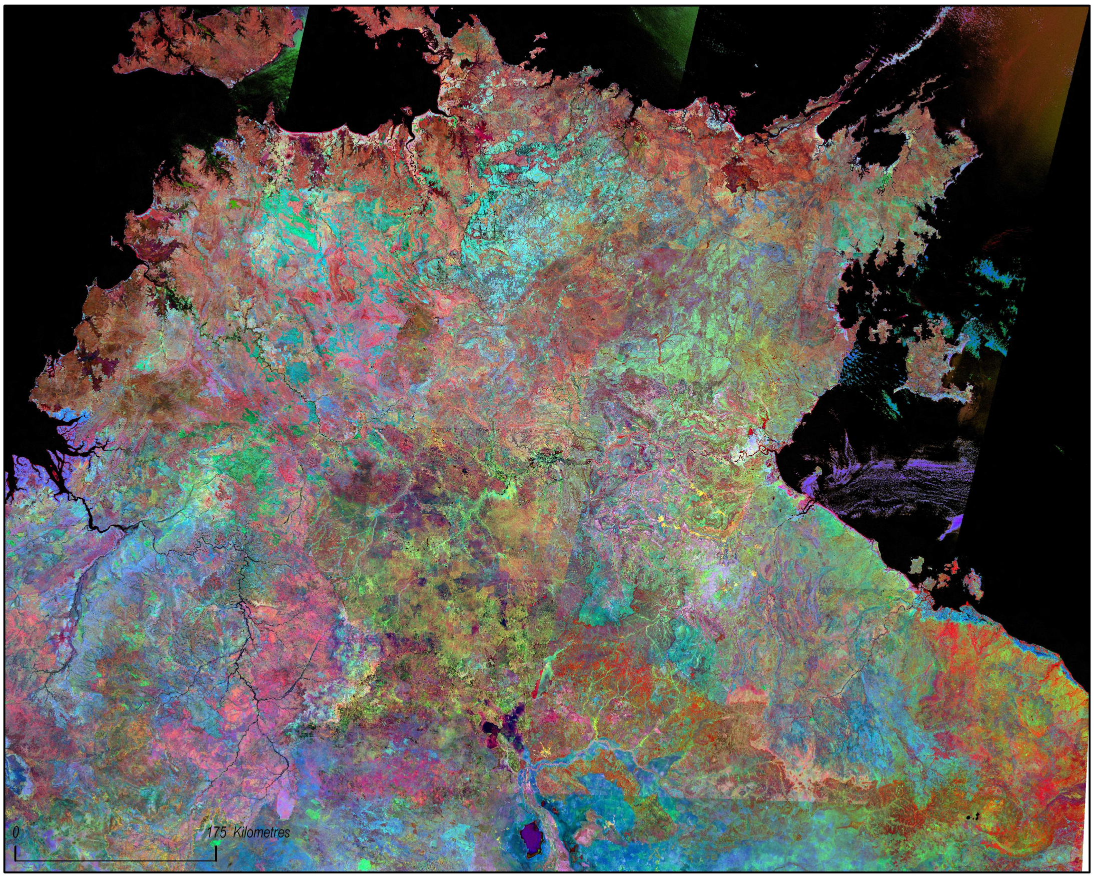

Figure 12 Clay-iron oxide-silica false colour composite.

National mosaics of Landsat TM and its predecessor MSS (Figure 13) are available for broad scale analysis of landforms, soils and vegetation. However temporal differences between individual scenes can cause issues when interpreting the data (e.g. seasonal differences between scenes). Imagery is available from http://www.ga.gov.au/remote-sensing/get-satellite-imagery-data/ordering/pricing/landsat-continental-mosaic/.

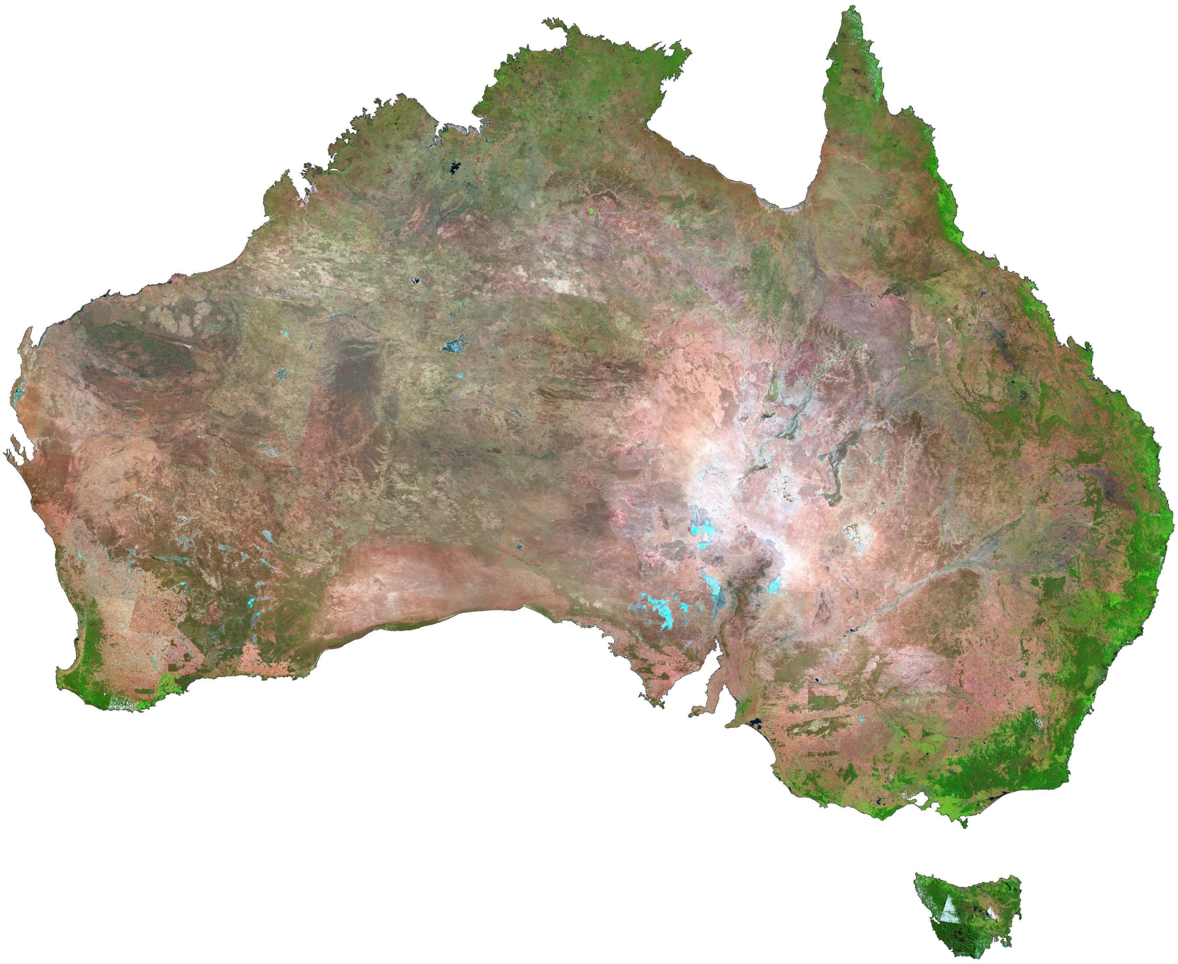

Figure 13 Landsat TM mosaic of Australia for 2005.

Using Landsat TM and SPOT imagery, Shaban *et al*. (2006) mapped lineament frequency, drainage density, lithology and land cover/land use in Occidental Lebanon. A weighted approach was then used to generate a map of potential recharge areas. Sener *et al*. (2005) also used Landsat TM in lineament mapping, providing insight into distribution of groundwater springs.

Thermal remote sensing

The thermal band from Landsat TM can be used to map soil moisture and areas of discharge. Studies undertaken by Bodda *et al*. (1992) and Tcherepanov *et al*. (2005) identified groundwater discharge by mapping changes in lake temperatures. This band has spatial resolution of 120 metres.

The multi-spectral thermal infrared band of ASTER allows for the retrieval of land surface temperature and emissivity spectra at high spatial resolution (Coll *et al*., 2007). ASTER imagery can be used for mineral mapping including bedrock, soil and regolith (Gozzard,

2006) and soil moisture (e.g. Vincente-Serrano *et al*., 2004; Stamoulis, 2006). ASTER thermal imagery has a spatial resolution of 90 metres.

Similarly NOAA-AVHRR sensor has also been used for accessing thermal data on a more regional scale than ASTER (Hou and Mauger, 2005; Hou *et al.*, 2000; Stamoulis, 2006). The thermal infrared satellite sensor measures the radiant earth temperature, effectively a measure of the earth's ability to absorb and re-radiate thermal energy. This measured parameter varies greatly depending on moisture content, mineral composition and texture of the land surface (Statham-Lee, 1995). Thus, NOAA–AVHRR imagery can be used to directly detect the relative temperature differences which occur between moist sediments and surrounding (dry) bedrock areas. This national dataset may provide some insight into the spatial distribution (on a regional scale) of zones of recharge/discharge. NOAA thermal bands have a spatial resolution of 1 kilometre.

NOAA-AVHRR imagery can be downloaded from http://www.ga.gov.au/remote-sensing/get-satellite-imagery-data/no-charge-online-data/noaa.jsp.

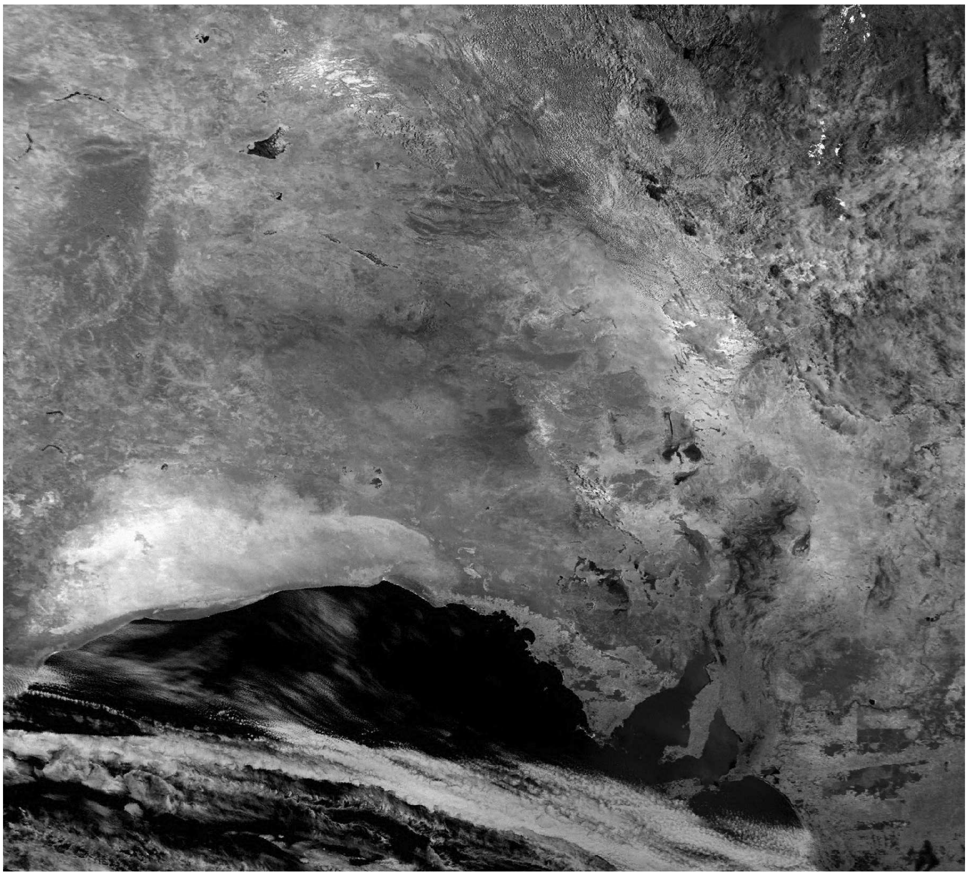

Figure 14 NOAA-AVHRR night-time thermal image.

Microwave remote sensing

Microwave remote sensing provides a direct measurement of the surface soil moisture for a range of vegetation cover conditions. Two approaches are used – passive and active. In passive methods, the natural thermal emission of the land surface (or brightness temperature) is measured at microwave wavelengths. In active methods (or radar), a microwave pulse is sent and received; the power of the received signal is compared to that which was sent to determine the backscattering coefficient (Jackson, 2002). Microwave sensors operating at very low microwave frequencies (<6 GHz) provide the best soil moisture information. Attenuation and scattering problems associated with atmosphere and vegetation are reduces. The instruments also respond to a deeper soil layer and a higher sensitivity to soil water content is present.

Jackson provided a summary of the available microwave remote sensing systems in 2002. Satellite systems included SSM/I (Special Satellite Microwave/Imager) - only applicable in arid or semi-arid areas with low amounts of vegetation; TMRR (Tropical Rainfall Measurement Mission) – only provides coverage of the tropics; MSMR (Multi-frequency Scanning Microwave Radiometer) – has a very large footprint (>100 km); AMSR (Advanced Microwave Scanning Radiometer) – shows promise. More recent advancements in microwave satellites include SMOS (Soil Moisture Ocean Salinity), ALOS Advanced Land Observing System) and Radarsat.

Radar (in preference over passive microwave) is capable of penetrating into deeper soils even in the presence of dense vegetation. Three observation frequencies that can be used are, with increasing penetration depth, L-band, UHF and VHF. Entekhabi and Moghaddam (2007) detail the use of microwave remote sensing (i.e. radar) to measure land surface states, specifically soil moisture. The soil moisture profile in the top few centimetres to meters plays a key role in determining the rate of evaporation (including transpiration by plants) and recharge. Moghaddam *et al*. (2000) demonstrated the ability of radar to accurately estimate soil moisture under 15 m tall forest canopy and to a soil depth of ~0.5-1m.

Once these soil-moisture profile observations have been obtained there are various approaches to infer diffuse recharge (e.g. Rushton and Ward, 1979; Sophocleous and Perry, 1984; Sophocleous, 1991; Finch, 1998; Rushton *et al*., 2006). Most of these techniques use mass balance, Darcy equation, or zero-flux plane techniques (Scanlon *et al*., 2002). The quality of the estimates does depend on the vertical resolution of the measurements and temporal sampling.

5.4. Vegetation and land cover

Vegetation and land cover play an important role in estimating both recharge and discharge. There is not a simple relationship between root depth and rainfall however vegetation affects the amount of recharge in two ways: the depth of plant roots, and whether the plants are perennial. Perennial vegetation grows all year round, thus require continual access to water for transpiration. It is the combination of longer growing seasons and deeper roots that tend to result in decreased recharge (Walker *et al*., 2007). Similarly, discharge of groundwater through vegetation depends principally on the rooting distribution and depth to water table. The accompanying discharge review (O'Grady *et al*., 2010) discusses these principles in more detail. It can however be quite difficult to ascertain rooting depth of vegetation as this can vary considerably between and within species, depending on a number of factors such as climate, depth to water table, substrate and landscape.

Petheram *et al*. (2002) found that across a broad range of locations, recharge was higher under shallow-rooted annual vegetation than deep-rooted vegetation, particularly native vegetation. Land clearing and the development of dryland agriculture have led to significant increases in recharge (Tolmie and Silburn, 2003; Tolmie *et al*., 2003). Percentage recharge has been observed to change from 18% of rainfall under native vegetation to 34% of rainfall after clearing (Crosbie *et al*., 2002). In irrigated areas, rates are higher still. Several studies have estimated the average annual increase in potential recharge since clearing of native vegetation (e.g. Kennett-Smith *et al.,* 1994; Cook *et al*., 2003). Consequently in relation to recharge, vegetation type and any land use change are key factors to consider.

Land cover/use maps can be used to provide information about the type of vegetation present, such as annuals (shallow-rooted annual crops or pastures), perennials (perennial crops, pastures and native herbaceous vegetation) or trees (very deep-rooted vegetation) (Petheram *et al.,* 2000; 2002), and whether any land use change has occurred.

Remote sensing

Vegetation indices (e.g. Normalised Difference Vegetation Index and Enhanced Vegetation Index) can be used as surrogates to indicate whether vegetation is exploiting groundwater; maintained vegetation health during dry periods can suggest groundwater discharge (via transpiration). The basis of the vegetation index is the high reflectance of leaves in the near infrared due to multiple scattering in the mesophyll, together with visible-wavelength absorption due to plant pigments (e.g. chlorophyll). Reflectance measurements in the optical and near infrared bands are thus strongly correlated with the fraction of photosynthetically active radiation absorbed by the plant material, and hence with the rate of primary production (Rees, 1999). Ringrose (2003) showed that riparian vegetation in the distal Okavango Delta remained healthy in areas of active discharge from freshwater shallow aquifers. There are a number of different VIs; two of the more common (NDVI and EVI) are discussed here.

Normalised Difference Vegetation Index (NDVI) uses the radiances or reflectance from a red channel (~0.66μm) and a near-infrared channel (NIR) (~0.86μm) to display vegetation in terms of greenness; the NDVI formula is given below (Equation 1). The red channel is located in the strong chlorophyll absorption region, while the NIR channel is located in the high reflectance plateau of vegetation canopies (Gao, 1996). Chlorophyll in plant leaves strongly absorbs visible light for use in photosynthesis while the cell structure of the leaves strongly reflects near-infrared light. NDVI ranges from -1 to 1; vegetated surfaces are depicted by high NDVI values while soils typically result in low but positive NDVI that can vary somewhat with soil type, wetness and brightness. For example NDVI has been found to produce larger index values for the same vegetation amount over dark backgrounds (Bausch, 1993). Open water bodies result in negative NDVI due to higher reflectance in the red relative to the strong absorption in the NIR (Glenn *et al*., 2007). Thus NDVI can be used to partition the landscape into water, soil and vegetation.

Equation 1 $$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{RED}) / (\mathrm{NIR} + \mathrm{RED})$$

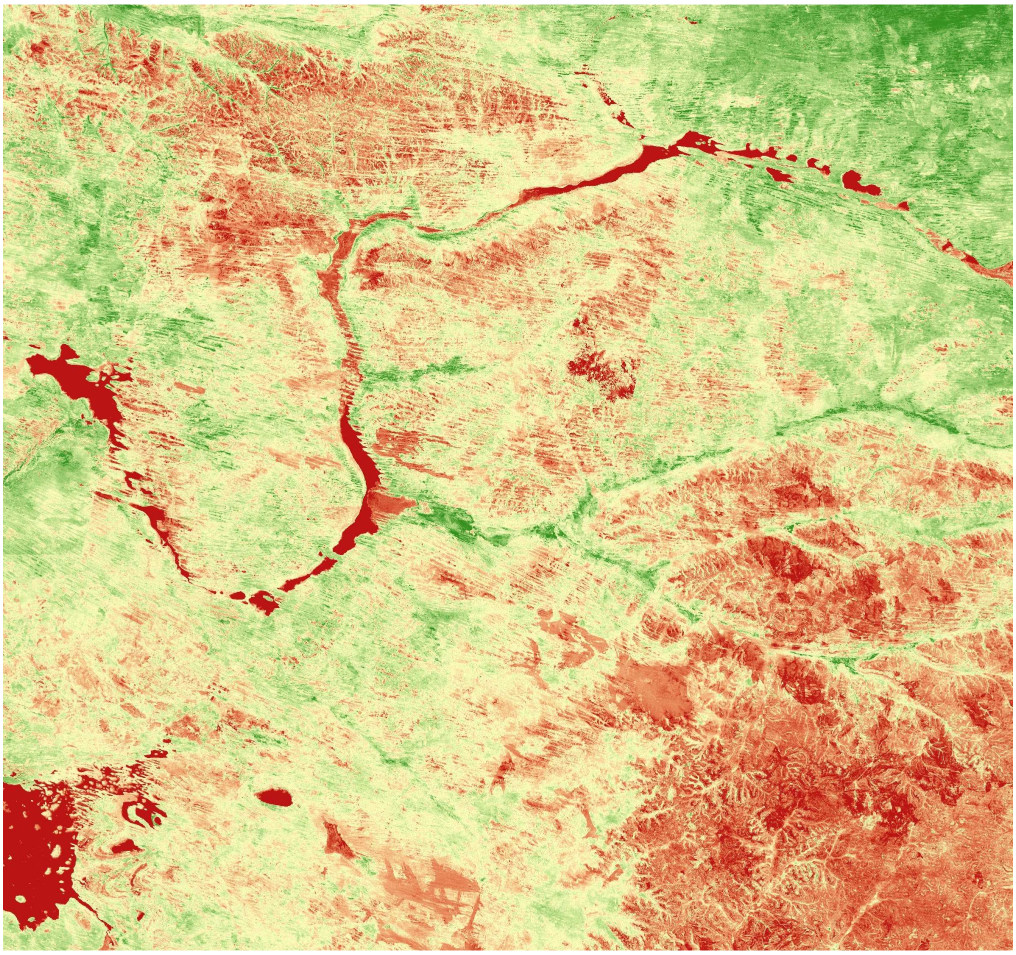

Figure 15 Normalised Difference Vegetation Index (NDVI) as applied to Landsat TM. Green colours represent high NDVI values (vegetation greenness) while browns correspond with low greenness.

Enhanced Vegetation Index (EVI) (Figure 16) is similar to NDVI but corrects for some distortions in reflected light caused by atmospheric haze as well as ground cover below the vegetation canopy. The EVI formula (

Equation 2) is given below where ρ_{red}, ρ_{nir} and ρ_{blue} are the reflectance values of MODIS bands 1, 2 and 3 respectively, G is a given gain factor, L is a canopy background adjustment factor, and C1 and C2 are coefficients of aerosol resistance, which use the blue band to correct aerosol influences in the red band. The coefficients used are assumed to be L=1, C1=6, C2=6, G=2.5 (Zhao *et al*., 2009).The EVI may provide a more direct relationship with the transpiring, greenness component of a canopy in moderate to high leaf area index canopies (LAI = 1–7) by relying on the more sensitive NIR canopy reflectance which remains linear with increasing foliage density after most of the red band has been absorbed (Gao *et al*., 2000; Huete *et al*., 2002). MODIS has been demonstrated to be very useful for regional assessment of vegetation health, and also for multi-temporal monitoring (e.g. Potgieter *et al*., 2007).

Equation 2 $$EVI = G \times ((\rho_{nir} - \rho_{red}) / (\rho_{nir} + C1 \times \rho_{red} - C2 \times \rho_{blue} + L))$$

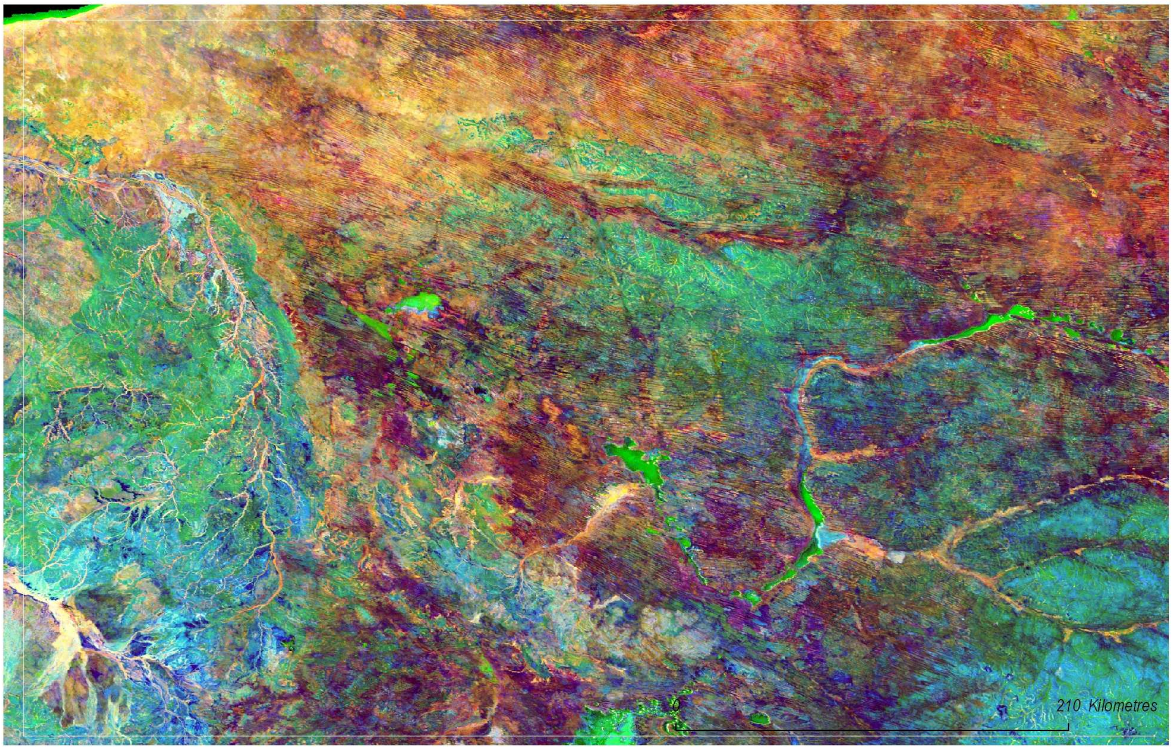

Figure 16 MODIS EVI image for the Paterson Province, Western Australia. This RGB colour composite combines mean EVI (red), standard deviation (green) and flatness (blue).

Leaf Area Index (LAI) is a measure of the total leaf area per unit area of ground surface and can be determined directly from plant canopy foliage samples however this is labour intensive and sampling methods not always comparable. LAI can be applied to a number of satellites, including Landsat TM, NOAA-AVHRR and MODIS. An assessment of MODIS LAI in Australian ecosystems (Hill *et al*., 2006) found a reasonable estimation of LAI for most cover types and land use types, however there were some inaccuracies and limitations. Gitelson *et al*. (2007) evaluated the use of MODIS data for estimating the LAI in crops, with positive results. Silberstein (2010) found that recharge declines with increasing LAI amongst other variables.

NOAA-AVHRR, Landsat and MODIS sensor details are provided in Appendix A

5.5. Topography

DEMs can be derived from a range of different sources or platforms with differing resolution and accuracy. From a national perspective two principle datasets are available, including the 9 sec DEM at approximately 250m resolution and the Shuttle Radar Topography Mission (SRTM) DEM data. The former has been constructed from contours, spot heights and drainage (i.e. drainage enforcement). The latter is available at two resolutions, 3 sec (90m) and 1 sec (30m). A number of products are available at 1 and 3 second resolution, including digital surface model (i.e. bare ground plus vegetation and built structures; Figure 17), bare-earth model (vegetation heights removed) and a hydrologically enforced model.

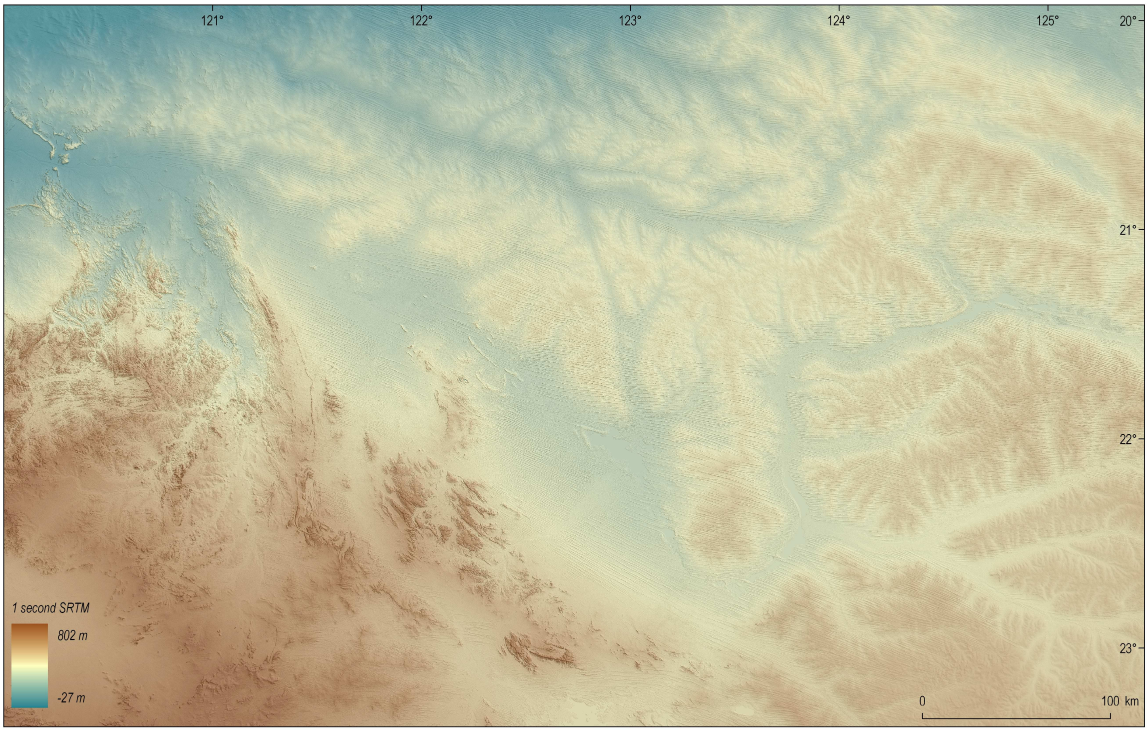

Figure 17 1 second Digital Elevation Model for the Paterson Province, Western Australia.

Using DEMs for GIS-based spatial modelling allows for the estimation and generation of the spatial distribution of hydrological parameters (e.g. slope gradient, flow accumulation, landscape position indexes, form and aspect) using different interpolation techniques (e.g. kriging, trend surface analysis, moving average and flow accumulation). An understanding of terrain, aspect and landscape is also important for estimating the spatial variability of recharge. In upland areas (mountains and hills) recharge appears to occur by seepage from streams, diffuse recharge into regolith materials covering slopes and valley floors, and groundwater through bedrock (Cook 2003, Smerdon *et al*. 2009). Although recharge can occur in a number of landscape positions, discharge typically occurs along break of slope and involves lateral flow of groundwater. Saraf *et al*. (2004) used a DEM generated from contour maps to identify drainage lines, and zones of water accumulation that could be equated with increased recharge rates. These areas were flat, and occurred in the lower parts of the landscape.

Cardenas (2008) reports simulations of surface water-groundwater exchange at increasing scales across bed forms, bars and bends, and basins. These show that temporal and spatial scales are important for rates of recharge, and that geomorphic features are an important aspect of these relationships. This shows that there is potential for the development of models that use landform features, among others, as surrogates for some aspects of recharge and discharge.

Francke *et al*. (2008) reviewed various means of spatially discretizing the landscape into modelling units including fully distributed, semi-distributed and lumped schemes. For use in large-scale models, hydrological response units are usually derived by mere intersection of GIS map layers such as land use, management and soil data (Francke *et al*., 2008). This method naturally cannot preserve the intra-slope distribution of properties or topological information. Francke *et al* (2008) suggested the Landscape Unit Mapping Program (LUMP) algorithm as an alternative, which allows for the automated delineation of landscape units (LU). For each LU, representative toposequences are computed and decomposed into terrain components (TCs - area, slope, length, soil and vegetation properties, etc.).

Landscape index model such as FLAG (Roberts *et al*., 1997) or MrVBF (Gallant and Dowling, 2003) (Appendix B) can also be used to predict likely locations of discharge, particularly when paired with wetness or soil moisture indicators. The Multi-resolution Valley Bottom Flatness (MrVBF) index is a terrain analysis tool primarily discriminates depositional landforms (valley bottoms) based on their distinctive topographic signature as flat, low-lying areas (Figure 18; Gallant and Dowling, 2003). MrVBF also has the potential to identify valley constrictions where groundwater discharge is likely to occur (Gallant and Dowling, 2003) and matched with thermal imagery, MrVBF has the potential to indicate actual locations of discharge areas. FLAG is a minimal model based solely on elevation data and provides a 'fuzzy' discharge index that can be applied widely for rapid assessment in data poor areas. Dowling *et al*. (2003) used the UPNESS index in FLAG to predict the location of wet and dry soil classes in a small catchment in NSW, with some success. Landscape datasets are often used in conjunction with soil, geology and regolith datasets to provide secondary datasets such as regolith-landform and soil landscape maps.

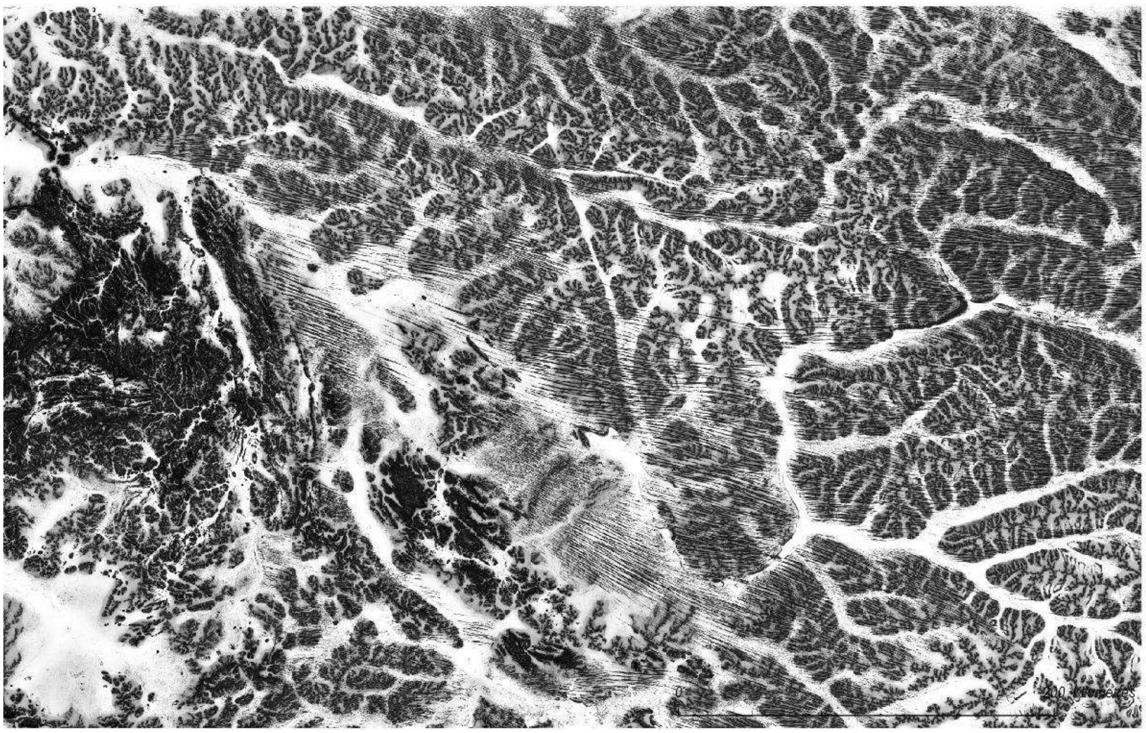

Figure 18 Output image from the Multi-resolution Valley Bottom Flatness (MrVBF) index algorithm (intermediate product 6). The areas shown here in white define flat and low valley bottoms, which may correspond with the location of palaeovalley landform features and drainage patterns.

5.6. Hydrology

Evapotranspiration

Evapotranspiration (ET) is the second largest term in the terrestrial water budget after precipitation. Terrestrial ET has two components, direct evaporation of water (E) and transpiration of water by vegetation (T), with over 80% of terrestrial ET due to transpiration of plants. E occurs from wet and moist soil, from rain water interception and by sublimation of water vapour from ice and snow. T occurs through stomata on plant leaves and stems. T is controlled by both physical and biological processes and is tightly coupled to the rate of photosynthesis as stomata provide the pathway by which carbon dioxide enters leave (Glenn *et al*., 2007). ET requires a source of heat energy to convert water from the liquid to the vapour phase. This is ultimately supplied by net radiation (R_n), the amount of incident solar radiation (R_s) that is absorbed at the Earth's surface; a simplified formula for the surface energy balance (SEB) is shown in Equation 3 where λ is the latent heat of evaporation of water; R_n is the net radiation flux (R_s minus outgoing short wave and long wave radiation); G is soil heat flux; and H is sensible heat flux to the atmosphere (units are W m^{-2}).

Equation 3 $$\lambda ET = R_n - G - H$$

Equation 3 is the basis by which ET is estimated by ground flux towers and by physically-based remote sensing methods however there are many different formulas for calculating ET (e.g. Penman, 1948; Monteith and Unsworth, 1990; Priestley and Taylor, 1972 – cited in Glenn *et al*., 2007). A number of review papers have been written, comparing the various approaches (e.g. Remote sensing methods estimate H through measurements of radiometric surface temperature by sensors sensitive to radiation in the thermal IR bands, and R_n and G by a combination of remote sensing or ground measurements.

It has become apparent that remote sensing is the only feasible means for projecting ET over large landscape units (Glenn *et al*., 2007). Two types of methods have been developed to scale ET: 1) empirical methods that project ET measurements/estimates on the ground to larger scales using vegetation indices (VIs), and 2) physical models that are based on solving the Surface Energy Balance (SEB) equation through remotely-sensed estimations of land surface temperature (LST) and other terms in SEB (Kustas and Norman, 1996; Schmugge *et al*., 2002; Kustas *et al*., 2003; Overgaard *et al*., 2006 – cited in Glenn *et al*., 2007). Both approaches have benefited from recent improvements in ground methods of measure ET at plot scales (Campbell and Norman, 1989) and in new remote sensing platforms with improved spatial and temporal coverage (e.g. MODIS and ASTER). Ground ET measurements, typically from flux towers, serve as ground-truth plots to validate or calibrate remote sensing methods. The error bounds of the flux towers (10–30% uncertainty) currently set limits on the accuracy with which remote sensing methods can be validated or scaled from ground data (Glenn *et al*., 2007).

Water table surface

Depth to water table is a key dataset for estimating recharge and discharge. Detailed studies across Australia often produce a water table surface from point data however the approach can be widely varied, making it difficult to compare (or combine) surfaces between different studies. Consequently there is currently no nationally consistent approach to generating a depth to water table surface. The Bureau of Meteorology now has responsibility for compiling and delivering Australia's water information, including groundwater information such as depth to water table. One of the outputs of the program will be the generation of a depth to water table mapping approach that can be applied on a catchment or regional scale and will provide groundwater managers with a water table surface that can be incorporated into an assessment of recharge and/or discharge (this output is unlikely to be publically available before 2012; Daamen, 2010, pers. comm.). Groundwater recharge and discharge estimates are both strongly affected by depth to water table.

The Groundwater Flow System (GFS) framework (discussed in more detail below) described in Coram *et al*. (2000) provides a framework that classifies all aquifers as being 'groundwater flow systems' in one of three scales for salinity management purposes:

Local groundwater flow systems – Flow systems 5 km or less across;

Intermediate groundwater flow systems – Flow systems between 5 and 50 km across;

Regional groundwater flow systems – Flow systems greater than 50 km across

The scale of the groundwater flow system is critical in determining groundwater response times, and therefore forms a logical basis for the depth to groundwater assessment.

Various methods have also been developed to generate potentiometric surfaces from limited hydrologic data. This allows predicted water table surfaces to be compared with stream level data, so that an estimation of hydraulic connection between the stream and aquifer can be gauged. Fourier-series spectral analysis by Worman *et al*. (2006) derived a 3-D solution to groundwater flow based on surface topography, applied at both the regional and stream-reach scale. Salama *et al*. (1996) generated watertable surfaces based on DEM data. They did this by recognising the relationship between surface form and the water table – the latter is a spatially smoothed replica of the surface. A water table surface created in this way was then checked using sparse bore data.

Hydrogeomorphic units (HGU)

England and Stephenson (1970) discussed the use of hydrologic response units for mapping areas with homogeneous hydrologic characteristics, including recharge rates. As with many of these types of units, soil character was considered to be very important. A recent report for the National Water Commission (GA/BRS, 2007) outlines a new hydrogeomorphic approach developed for mapping potential groundwater – surface water connectivity in Australian catchments, recognising that data availability is generally poor across most of the country. This report suggests a number of hydrogeomorphic settings for Australia (Figure 19) – hydrogeomorphic units (HGUs).

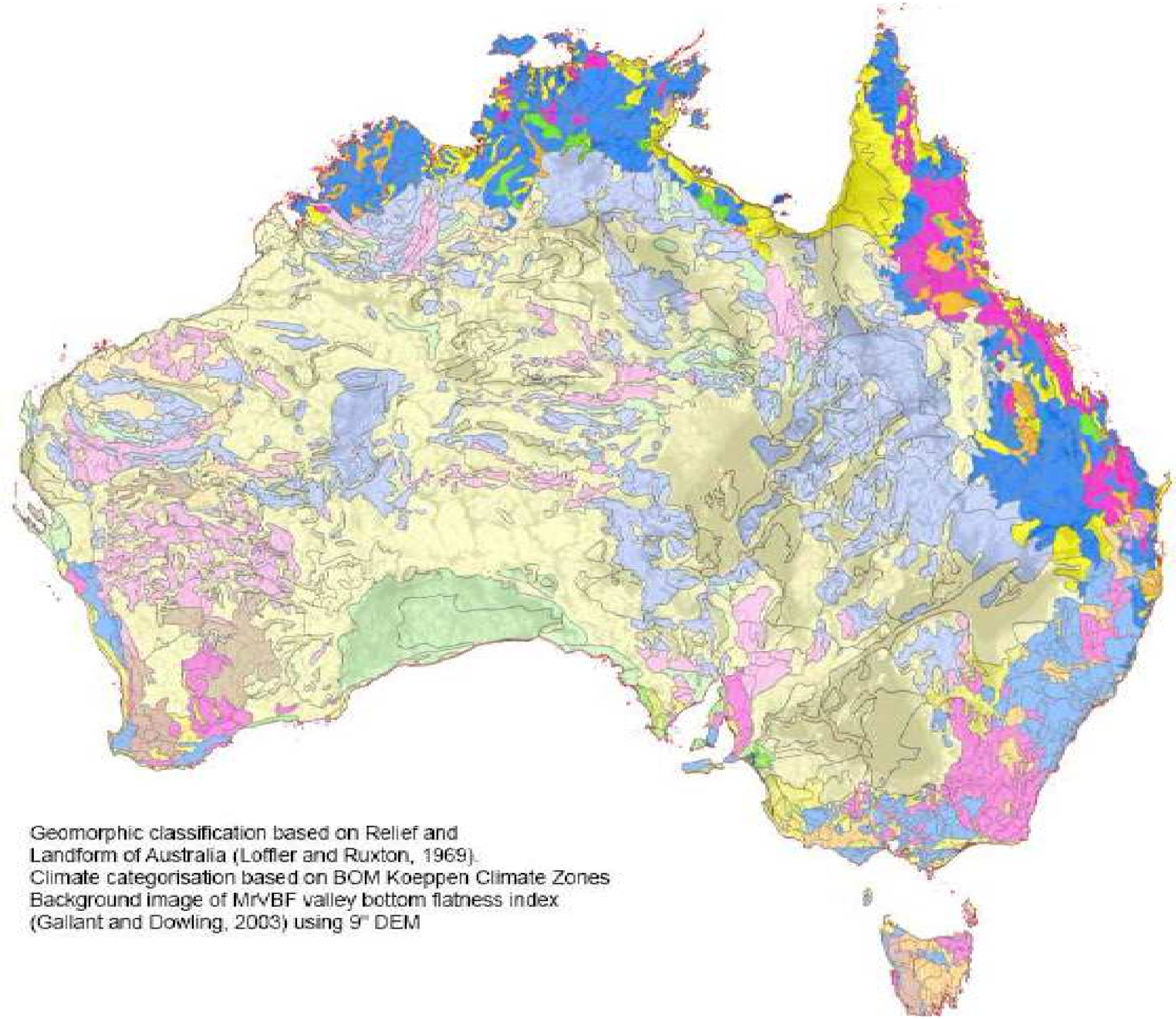

Figure 19 Draft hydrogeomorphic units from GA/BRS (2007).

Hydrogeological-Landscapes (HGL)

The Hydrogeological-Landscape framework integrates information on lithology, climate, vegetation, bedrock structure, regolith (including soils) and landforms to delineate areas with similar hydrological characteristics (Wilford *et al*., 2008). Hydrogeological-Landscape units are placed within a hierarchical mapping system to address the importance of landscape scale, both from a hydrological and management perspective. It was originally develop to address salinity in upland settings but has much broader application in understanding and predicting landscape hydrology. Terrain based indices (e.g. MRVBF, FLAG), weathering intensity (mapping soil/regolith), geology and climate surfaces are used in defining individual HGL units (Figure 10).

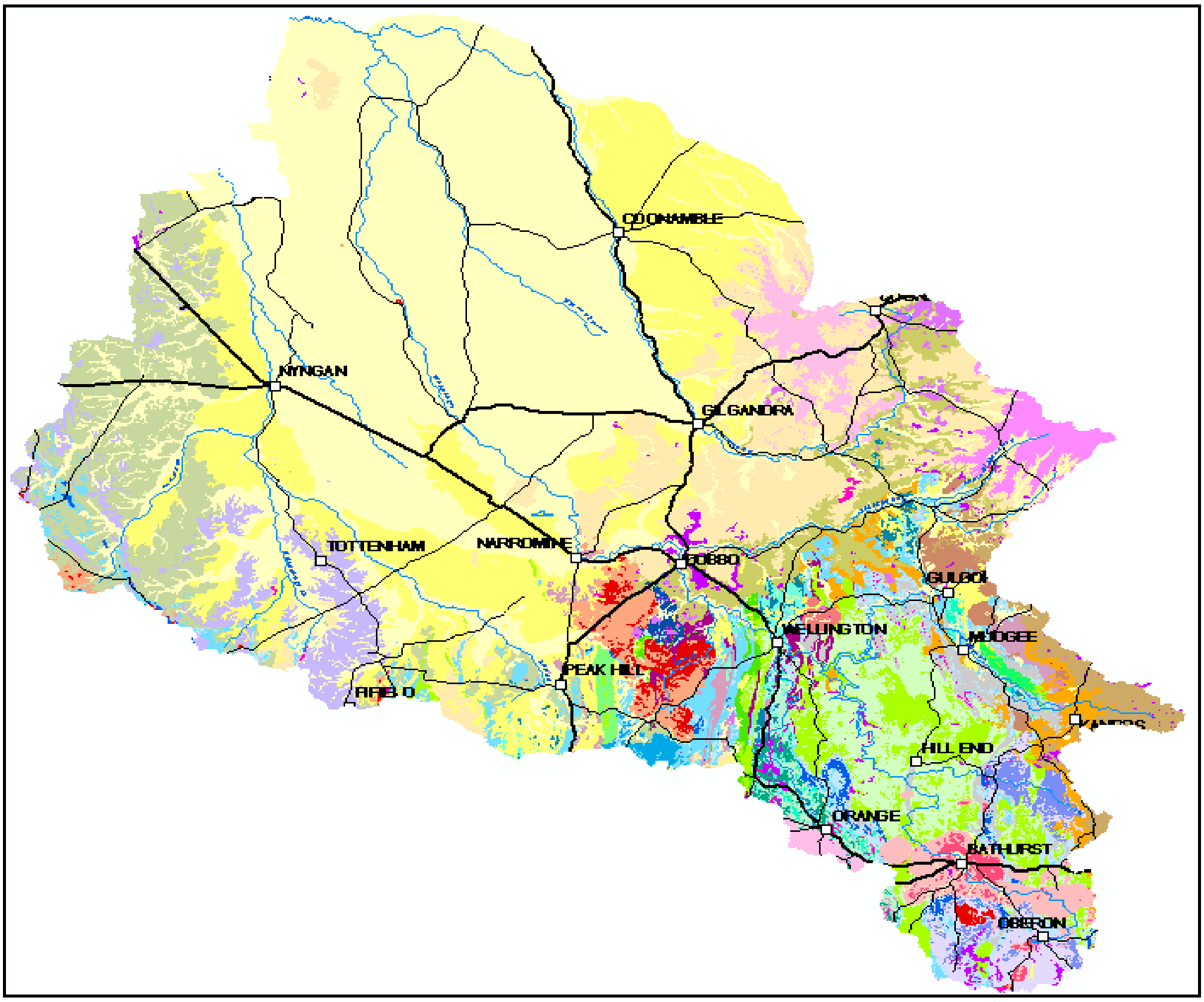

Figure 20 Hydrological-Landscape units over the central west catchment in NSW.

IBRA bioregions

Bioregions described in the Interim Biogeographic Regionalisation for Australia (IBRA), identify vegetation communities and land systems over Australia across a range of spatial scales (Figure 21). The Australia continent was divided into 85 bioregions with each bioregion describing an area with similar climate, geology, landform, vegetation and animal communities. A further 403 sub-regions were identified to provide a finer scale delineation of the Australian landscape (http://www.environment.gov.au/parks/nrs/science/bioregion-framework/ibra/index.html).

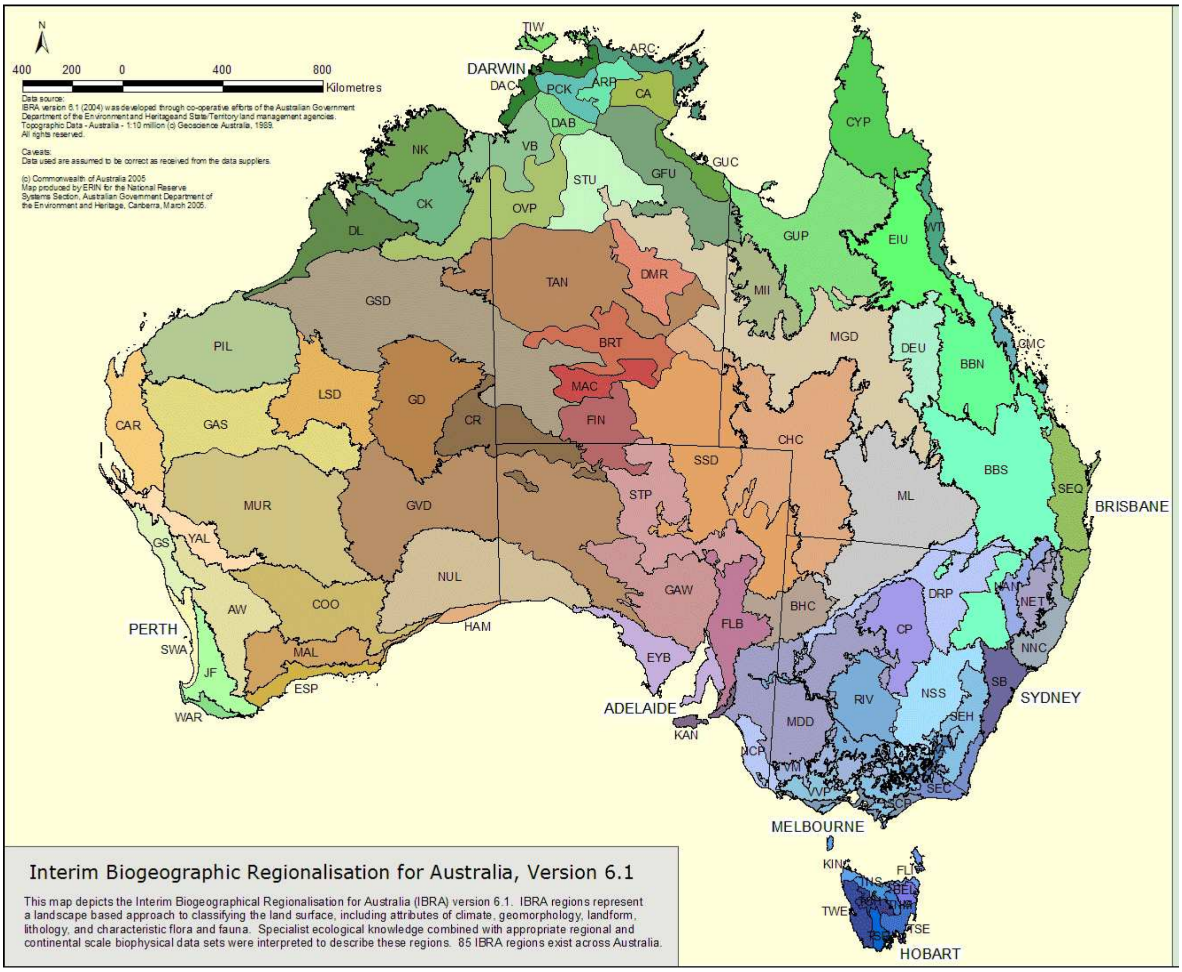

Figure 21 Interim Biogeographic Regionalisation for Australia for Australia.

Groundwater Flow Systems

Groundwater flow systems have been categorised as local, intermediate and regional (Toth 1963), depending on their size and the amount of time required for the system to react to change. The Australian national groundwater flow systems (GFS) mapping approach for dryland salinity management (Coram *et al*. 2000; Walker *et al*., 2003) is an Australian example of the application of GIS classification of conceptual models of groundwater processes at a national scale (Figure 22). Eleven types of settings where dryland salinity occurs were defined and mapped across different groundwater flow systems, and various geological and topographic settings. Four continental datasets were identified as surrogates for hydrogeological characteristics controlling groundwater flow – DEM (1-km raster image sampled from AUSLIG 250m 9 second DEM of Australia), bedrock geology (derived from BMR Geology of Australia in 1976), regolith (1: 500,000 scale Regolith Map of Australia (Chan *et al*., 1986)) and climate (1-km raster images of monthly rainfall and evaporation derived from ANUCLIM processing of climate data). These were combined to produce a national GFS map.

In a study of catchment-scale surface water and groundwater response to land-use change Dawes *et al*. (2002, 2004) used groundwater flow systems (GFS). George *et al*. (1999) used groundwater flow systems as a means of identifying recharge and discharge sites in Western Australia. Although they made no attempt to map the amount of recharge and discharge, the GFS approach would seem to offer potential as an input into such mapping.

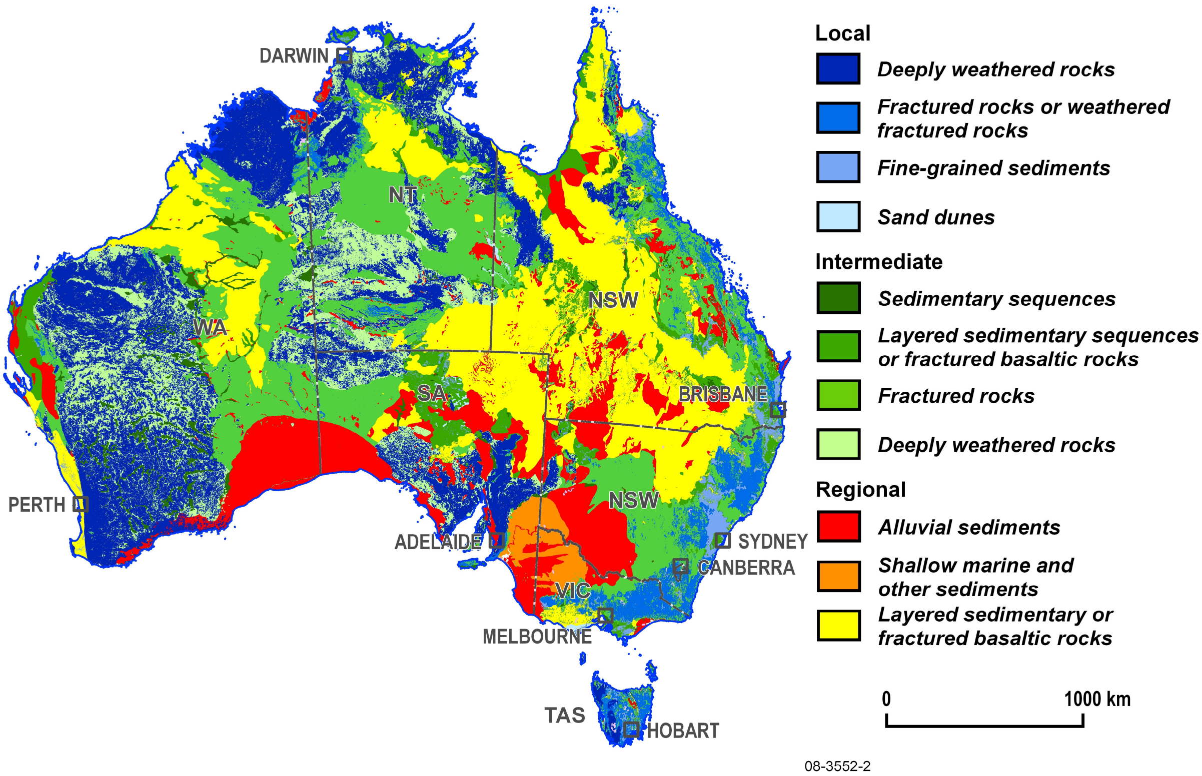

Figure 22 Groundwater Flow Systems map of Australia.

6. CONCLUSIONS

Recharge and discharge fluxes vary in sympathy with the geological and geomorphic character of groundwater systems. They are, in part, defined by the hydraulic properties of soils, but soil mapping alone seldom proves an adequate base to define the water balance of groundwater systems. Water passing through the soil zone may recharge surficial aquifers instead of a deeper aquifer that is of greater concern to the resource manager. Equally, target aquifers may be confined for much of the flow system.

Maps depicting soil/regolith character are an essential part of spatially defining areas of groundwater recharge and groundwater discharge but they need to be used in conjunction with sound conceptual models that describe groundwater behaviour. That is, target areas for recharge and discharge are best defined by knowledge of aquifer geometry and of functional relationships between soils and regolith and groundwater flow systems.

Where the relationship between soils landscapes and groundwater systems is defined there is considerable potential to use remote sensing, airborne geophysics and GIS as tools to support spatial assessments of groundwater recharge and discharge in Australian groundwater systems.

The next step in a national overview of groundwater recharge and discharge should involve consideration of what is known about the range of groundwater systems that exist throughout Australia, consistent with the principles and conceptual models defined in Coram *et al*. (2000). Armed with this knowledge it will then be possible to resolve what is mapped and the techniques most appropriate to use in the mapping. Table 4 however provides a short summary of digital datasets recommended for investigation in Phase Two.

Table 4 Digital datasets recommended for phase two of the project. The source location is also provided.

Key Themes	Datasets	Source
Climate	Climate surfaces	http://www.bom.gov.au/climate/
	ET	Penman - http://wwwdata.wron.csiro.au/ts/climate/evaporation/donohue/
Soil, regolith and geology	ASRIS	http://www.asris.csiro.au/index_ie.html
	Surface geology	https://www.ga.gov.au/products/servlet/controller?event=DEFINE_PRODUCTS
Vegetation and land cover	MODIS	Soon to be released by Geoscience Australia www.ga.gov.au
Landscape morphology	DEM	Soon to be released by Geoscience Australia www.ga.gov.au
	MrVBF	Email John.Gallant@csiro.au for algorithm

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APPENDIX A. SATELLITE/SENSOR DETAILS

Landsat TM

Landsat TM has a swath size of 185 kilometres and measures six bands of radiation in the visible and infrared (IR) range of the electromagnetic spectrum at a spatial resolution of 30 metres, as well as single band thermal data (120 metres resolution). Landsat TM data requires geo-referencing and correction for atmospheric attenuation and backscatter and can then usually be processed as false colour or greyscale images, as band ratios or as Directed Principal Component Analyses of band ratios (Wilford and Creasey, 2002). As depth penetration is near zero, Landsat TM is effectively an aerial photograph of the landform using spectral ranges including and beyond the visible wavelengths (Hou, 2004).

Landsat TM imagery is available from Geoscience Australia (for a small cost) or the US Geological Survey (free of charge). Ortho-rectified images are only available from Geoscience Australia.

MODIS

The TERRA satellite has an onboard Moderate Resolution Imaging Spectroradioter (MODIS) sensor which captures the entire surface of the Earth every one to two days. Its detectors measure 36 spectral bands covering the visible through to thermal infrared over a 2330 km swath (Kruse, 1999). The instrument acquires data at three spatial resolutions: 250 m (bands 1-2), 500 m (bands 3-7), and 1 km (bands 8-36).

MODIS data is freely available from NASA, CSIRO and Geoscience Australia.

ASTER

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) is a high spatial resolution radiometer, covers an area of 60 km^2, has a near polar, sun-synchronous orbit, with a repeat cycle every 16 days. This satellite was first launched in December 1999. This system consists of three separate subsystems: the visible and near infrared (VNIR), the short wave infrared (SWIR) and the thermal infrared (TIR) (Yamaguchi *et al*., 1998). Each subsystem operates in a different spectral region; when the three subsystems are combined they collect data from14 spectral bands. The VNIR subsystem operates in 3 bands and has a resolution of 15 m (Kruse, 1999). A backward-looking near-infrared band provides stereo coverage which can be used to construct DEMs. The SWIR subsystem operates in 6 spectral bands at 30 m resolution. The TIR subsystem has five spectral channels between 8 and 12 µm with spatial resolution of 90 m (Coll *et al*., 2007).

Selected archival ASTER imagery is available from Geoscience Australia (for a cost). A more comprehensive collection of imagery is available from ERDAS. Image acquisition can also be requested (for a cost).

NOAA-AVHRR

The National Oceanic and Atmospheric Administration (NOAA) of the USA operate a series of NOAA satellites which carry the Advanced Very High Resolution Radiometer (AVHRR) sensor. The first operation NOAA satellite was launched in 1979. The AVHRR sensor is a five to six channel scanner, sensing the visible, near-infrared, and thermal infrared portions of the electromagnetic spectrum (Kruse, 1999). It provides global on board collection of data over 2399 km swath, and orbits the earth 14 times each day from an altitude of 833 km. Spatial resolution is 1.1 km, which degrades to 3.3 kilometres as the view angle increases off-nadir, and is acquired twice daily (pre-dawn and afternoon).

Recent (last 7 days) AVHRR imagery is freely available (pre-processed) from Geoscience Australia. Archival imagery is available from CSIRO.

APPENDIX B. TERRAIN MODELS

Fuzzy Landscape Analysis GIS (FLAG)

FLAG is a minimal model based solely on elevation data and as a simple model requires significant assumptions about the way reality has been simplified (Roberts *et al*., 1997). It assumes that many parameters used as inputs to landscape/catchment models, or surrogates for unavailable inputs are often highly intercorrelated. Because many parameters are derived from the same DEM, they too will be correlated particularly with the accuracy of the DEM. FLAG is a raster-GIS based on fuzzy set theory. The derived DEMs were used to define fuzzy sets: HIGH, LOWNESS and UPNESS. HIGH is the first fuzzy set, identified as high elevation points; the highest in the study area was assigned a 1.0, the lowest point a 0.0 and all there points scaled linearly according to their relative elevation. The second fuzzy set is LOWNESS which was produced by identifying local low points in relation to the average local elevation. High LOWNESS values were assigned to locations which were low in the local landscape. Because it was assumed that the water table conformed to the landscape, areas with high LOWNESS were expected to be areas where the water table intersects the land surface to produce discharge (Robert *et al*., 1997). UPNESS is the fraction of the total landscape monotonically uphill.

FLAG employs a set of programs based on fuzzy set theory. Fuzzy set theory is a generalisation of classical set theory. Set theory is a branch of mathematics that defines a formal logic for describing and operating on objects which are defined according to the needs of the investigator. Details of fuzzy set theory can be found in Roberts (1986), Kaufmann (1975) and Roberts *et al*. (1997). As FLAG is a minimal model, it may be applied widely for rapid assessment in data-poor areas. FLAG outputs provide a fuzzy discharge index rather than potential discharge (Roberts *et al*., 1997).

Multi-resolution Valley Bottom Flatness (MrVBF)

The Multi-resolution Valley Bottom Flatness (MrVBF) index is a terrain analysis tool applied as an algorithm to digital elevation model data using GIS. This model identifies the lower and flatter parts of landscapes from DEM data. MrVBF imagery can be produced from any type of DEM, for example the 1-arc second and 9-arc second national DEM data (as derived from the SRTM). The MrVBF tool primarily discriminates depositional landforms (valley bottoms) based on their distinctive topographic signature as flat, low-lying areas (Gallant and Dowling, 2003). The identification of valley bottoms is assessed at multiple scales during data processing to ensure that finely detailed landform features are recognised as part of the analytical process. The final MrVBF product is a black, white and grey image with the flattest and largest valley bottoms highlighted in white and non-valley landforms (e.g., hillslopes and ridgelines) shown in black (Figure 18). The topographic markers of flatness (defined from slope) and valley bottom flatness (defined from combination of flatness and lowness) are carried throughout the processing stages. This allows for the broad-scale valley bottom flatness signature to override the fine-scale; thus, the broader features are shown without unnecessary detail. Smaller areas of steeper slope are also included in the generalised data (Gallant and Dowling, 2003). Consequently MrVBF is useful tool to model landscape attributes from DEMs and can be used in conjunction with other datasets such as soil type to assess potential recharge or discharge.

APPENDIX C. GLOSSARY

Aquifer:	Saturated permeable soil or geologic strata that can transmit significant quantities of groundwater under a hydraulic gradient.
Aquitard:	Saturated soil or geologic strata whose permeability is so low it cannot transmit any useful amount of water.
Discharge:	Loss of water from an aquifer (i) to the atmosphere by evaporation, springs and/or transpiration, or (ii) to a surface water body (in the case of rivers it is generally referred to as base flow) or the ocean, or (iii) by extraction.
Groundwater:	Sub-surface water in soils and geologic strata that have all of their pore space filled with water (i.e. are saturated).
Hydraulic gradient:	Change in hydraulic head in an aquifer with either horizontal or vertical distance, in the direction of groundwater flow.
Recharge:	Addition of water to an aquifer, most commonly through infiltration of a portion of rainfall, surface water or irrigation water that moves down beyond the plant root zone to an aquifer.
Vadose or unsaturated zone:	Zone between land surface and the water table within which the moisture content is less than saturation (except in the capillary fringe).
Water table:	Level of groundwater in an unconfined aquifer. The soil pores and geologic strata below the water table are saturated with water.