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Australian groundwater-dependent ecosystems toolbox part 2: assessment tools

Sinclair Knight Merz

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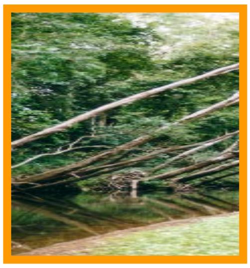

Waterlines

A SERIES OF WORKS COMMISSIONED BY THE NATIONAL WATER COMMISSION ON KEY WATER ISSUES

Waterlines

This paper is part of a series of works commissioned by the National Water Commission on key water issues. This work has been undertaken by Sinclair Knight Merz on behalf of the National Water Commission.

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Contents

Abbreviations and acronyms

ASRIS	Australian Soil Resource Information System
ASTER	Advanced Spaceborne Themal Emission and Reflection Radiometer
AVHRR	Advanced Very High Resolution Radiometer
CFC	chlorofluorocarbons
CWI	climate wetness index
CWSI	Crop Water Stress Index
DEM	Digital Elevation Model
DNA	deoxyribonucleic acid
DOC	dissolved organic carbon
ECW	Enhanced Compressed Wavelet (Image compression format created by Earth Resource Mapping)
EM	electromagnetic
ET	evapotranspiraiton
EVI	enhanced vegetation index
EWR	ecological water requirement
FAPAR	Fractional of Absorbed Photosynthetically Active Radiation
GEMI	Global Environmental Monitoring Index
GDE	groundwater-dependent ecosystem
GDE toolbox	Australian groundwater-dependent ecosystems toolbox
GIS	Geographical Information System
GRACE	Gravity Recovery and Climate Experiment
LAI	leaf area index
Landsat	Land Remote Sensing Satellite
ψ_{leaf}	leaf water potential
MODIS	Moderate Resolution Imaging Spectroradiometer
METRIC	Mapping Evapotranspiration at high Resolution with Internalized Calibration
NanoTEM	Nano Transient Electromagnetic

NDVI	Normalised Difference Vegetation Index
NDWI	Normalised Difference Water Index
nm	nanometres
NOAA	National Oceanic and Atmospheric Administration
PAR	photosynthetically active radiation
PAWC	plant available water capacity
PVI	Perpendicular Vegetation Index
SARVI	Soil and Atmospherically Resistant Vegetation Index
SEBAL	Surface Energy Balance Algorithm for Land
SPOT	Systeme Pour l'Observation de la Terre (French remonte sensing satellite)
T1, T2 etc.	GDE toolbox assessment framework Tool 1, Tool 2 etc.
TC	tasselled cap
TDS	total dissolved solids
VITT	Vegetation Index/Temperature Trapezoid
WUE	water use efficiency

1. Introduction

This document comprises part 2 to the Australian groundwater-dependent ecosystem (GDE) toolbox. The document presents a suite of practical and technically robust ‘tools’ that will allow water resource, catchment and ecosystem managers, and their advisers, to identify GDEs and determine environmental water requirements as closely as practicable within the constraints imposed by technology, budgets and available time frames.

The tools are based on a review of established methods reported in national and international literature. In addition to providing details of the various techniques for identifying GDEs and estimating their environmental water requirement, the *assessment tools* consider the data requirements and an indication of the level of effort and expense required in use and in results analysis for each tool.

The target audience for these *assessment tools* includes professionals responsible for water resource and GDE management, and for regional natural resource management planning. Users need not be specialists in groundwater, surface hydrology or ecosystem management; the information is provided in such a way that allows users to commission appropriate specialist studies.

1.1. Report structure

The tools are presented in the order in which they are encountered in *part 1: assessment framework* of the GDE toolbox. A total of 14 tools are presented in the order in which they are encountered in the assessment framework and are presented in the context of major stages of the assessment framework: (i) tools for GDE classification and identification; (ii) tools for verification of groundwater use; and (iii) tools for understanding GDE response to change. Links between the tools, stages of assessment and types of GDEs for which they are useful is presented in Table 1.

1.2. Tool content

The information provided for each tool is presented in a common template (page 3). The principles behind each tool’s application to GDE/ecological water requirement (EWR) assessments are described to provide the user with an understanding of the tool to be applied. A short discussion, outlining the tool components and how they are used in GDE assessments, follows. Methods used to interpret the data used by the tools, such as presentation options or specialist software required, has been included to ensure the user obtains the greatest benefit. Any major limitations of the tool, along with any advantages or disadvantages in its use, are listed together with a representative range of costs. The main types of specialist skills and resources required to apply the tool have been listed along with the data requirements.

Each tool identifies links with other tools within the toolbox and indicates whether it may provide inputs or require outputs from the related tool. This can assist in GDE management by providing opportunities to support findings and build knowledge of the system. A list of key references, Australian case studies and where to find further information is provided for each tool, in order of relevance.

Table 1: Links between the GDE toolbox assessment framework, GDE type and tools useful to each assessment stage and GDE type

Assessment framework	*Aquifer and cave ecosystems (Type 1)*	*Ecosystems dependent on the surface expression of groundwater (Type 2)*	*Ecosystems dependent on the subsurface presence of groundwater (Type 3)*
Stage 1: GDE location, classification and basic conceptualisation 1.1 Where are the ecosystems that use groundwater? 1.2 What is the broad type of GDE and functional grouping?	← T1 Landscape mapping T2 Conceptualisation →		
Stage 2: Characterisation of groundwater reliance 2.1 Is groundwater part of the ecosystem? 2.2 How reliant is the system on groundwater?	T9 Stygofauna sampling T10 Evaluation of groundwater-surface water interactions T11 Environmental tracers T12 Analysis of introduced tracers	T10 Evaluation of groundwater-surface water interactions T11 Environmental tracers T12 Analysis of introduced tracers	T3 Pre-dawn leaf water potentials T4 Plant water-stable isotopes T5 Plant water use modelling T6 Root depth and morphology T7 Plant groundwater use estimation T8 Water balance – vegetation
Stage 3: Characterisation of ecological response to change 3.1 What are the threats to the groundwater system / ecosystem? 3.2 How might the current ecosystem change if the groundwater system changes? 3.3 What is the predicted long-term ecosystem state due to the change?	← T3–T12 as appropriate (see Stage 2) T13 Long-term observation of system response to change T14 Numerical groundwater modelling →		

Tool number and title		
Description	A brief description of how the tool works and the information and insights it may provide	
Application to components of EWR studies	Applicability of the tool to the stages of GDE assessment as described in *Part 1: Assessment Framework* For applicability: ✓ low applicability; ✓✓ moderate applicability; ✓✓✓ high applicability; blank – not applicable. For level of certainty: ✓ low applicability; ✓✓ moderate applicability; ✓✓✓ high certainty; blank – not applicable	
Scale of measurement	Usefulness of the tool at common scales of application ✓ poor suitability; ✓✓ moderate suitability; ✓✓✓ high suitability; blank – not suitable	
Principles	Principles behind the application to GDE assessments	
How the tool is applied in GDE assessments	Outlines tool components and how they are used	
Analysis approach	An outline of the methodological approach	
Limitations	Any limitations associated with the tool	
Advantages	Specific strengths of the tool	
Disadvantages	Any weaknesses of the tool	
Costs	Indicative costs for application of the tool	
Specialist skills and resources	Outline of specialist skills and resources required to apply the tool	
Main data types required	*Data*	*Likely source(s)*
	Data requirements	Indication of likely sources of existing data or process to obtain new data
Complementary tools	Other tools for which the tool may provide data or require data ✓ indicates relevance	
Key references and Australian case studies	Summary of Australian or international case studies where the tool has been applied in order of relevance	
Further Information	Links to resources that contain further information on tool application	

2. Assessment tools

T1 Landscape mapping

Description	Locating and identifying ecosystems that are potentially groundwater-dependent based on a number of biophysical parameters such as depth to watertable, soils and vegetation type. Assessing primary productivity, water relations and/or condition of vegetation communities using remotely sensed images to infer use of groundwater.

Application to components of EWR studies

	Applicable	*Level of certainty*
Location, classification and basic conceptualisation	✓✓✓	✓✓
Characterisation of groundwater reliance		
Characterisation of response to change		
Monitoring and evaluation	✓	✓✓

Scale of measurement

Regional: ✓✓✓ Catchment: ✓✓✓ Site: ✓

Principles

Landscape-scale mapping is used to determine the spatial distribution of GDEs over a relatively large area. The approach involves analysis of landscape/regional datasets and is based on the principle that biophysical characteristics can, in combination, be used as indicators to identify potential GDEs. Where an ecosystem is known to be groundwater dependent in one location, site specific knowledge or conceptual understanding of particular vegetation and/or a common combination of physical attributes may be used to infer the location of similar GDEs in other areas.

Various tools, including aerial photography, ground survey, satellite imagery and geographical information dystem (GIS) modelling, can be used to develop regional or finer-scale maps of potential GDEs using this approach. The spatial resolution of data used for landscape mapping needs to reflect the scale of the ecosystems being mapped.

A national example of how landscape-mapping tools can be used to identify potential GDEs is the GDE Atlas, developed as part of a National Water Commission project. When complete, the GDE Atlas will form a readily available spatially based tool able to help identify and classify potential GDEs. The approaches being undertaken to create the atlas relevant to this tool are discussed below in the 'Analysis approach' section.

How the tool is applied in GDE assessments

GIS and remote-sensing analysis are two common approaches to landscape mapping.

GIS approaches

GIS modelling works by overlaying and linking existing spatial datasets, including topographic, soil and geological maps, vegetation maps, ground or airborne geophysical surveys, aerial photography and/or satellite imagery etc. GIS analyses are best used when there is good information on specific characteristics of existing GDEs, which can then be extrapolated to infer the location of similar GDEs in other areas. Ideally, this process is supported by a conceptualisation (see T2) of where GDEs may exist within the landscape. Examples include:

- spring-based GDEs formed at the edge of basalt flows
- spring-based and baseflow GDEs formed by the discharge of groundwater along fault lines
- vegetation close to permanently flowing rivers (i.e. riparian

vegetation).

Typical overlays include depth-to-water, soil water-holding capacity, geology, elevation and vegetation type (structure and/or floristics), wetlands and drainage mapping. The coincidence of a GDE, such as a given vegetation community, with particular geomorphic, hydrogeological or hydrological features that have been shown to correlate with groundwater dependence in one area may then be used to infer the presence and distribution of GDEs over larger spatial scales. This approach has been applied to many areas across Australia in the mapping of terrestrial vegetation and wetland GDEs.

Similarly, river baseflow GDEs can be detected over large areas using mapping of hydrological connectivity. Surface water and groundwater data are collated to create a watertable elevation surface. The shape of the watertable surface along the river indicates the nature of any surface-water/groundwater connections (i.e. contours contorted down the river indicate losing conditions, contours contorted up the river indicate gaining conditions, and contours approximately normal to the river indicate hydraulically neutral conditions).

As well as the spatial intersects, many spatial data sets contain attributes that, when combined, can allow the inference of the presence of groundwater use and or groundwater discharge. This approach is often used in the absence of key data sets such as watertable maps. For example:

- Permanent or near-permanent saline wetlands often indicate a groundwater source.
- Permanent or near-permanent surface water in arid regions may indicate a groundwater source.

Remote sensing

Remote sensing data are typically collected by satellites or aircraft. Sensors record the radiation absorbed or emitted by the earth surface (including by vegetation). Depending on design, the radiation sensed can be visible (e.g. light) or invisible (e.g. infrared); multiple wavelengths can also be detected.

The information is then processed (using different algorithms, see Table T1-2) to develop images of the earth surface that highlight particular landscape features, such as areas of open water, moist or dry soil, presence or absence of vegetation, leaf-area index, and plant productivity (since photosynthesis leads to an absorption of red light).

Time-series remotely sensed images are used to spatially and temporally assess characteristics of vegetation and water features which may allow inferences to be made about groundwater dependence and/or surface water interactions.

Application to GDE studies is typically based around the premise that, if vegetation is active, or wetlands and surface-water features persist, during dry periods they are likely to be using or contain water other than surface runoff or rain-fed infiltration. Common applications include:

- surface characteristics of GDE vegetation which contrast with nearby non-GDE vegetation (particularly during dry periods or seasons), such as leaf-area index or greenness
- higher rate of evapotranspiration (ET) where vegetation has access to groundwater, compared with nearby non-GDE vegetation
- constant activity rate of vegetation, suggesting a continuous supply of water
- permanent high water levels within wetlands, possible presence of springs or seeps
- thermal anomalies related to a direct effect of groundwater on surface temperature in groundwater discharge zones (including within water features).

More recently, algorithms have been developed to estimate the *in situ* evapotranspiration of vegetation and, when combined with other data sets, can predict the amount of water transpired by vegetation.

There are several different platforms (satellites and aircraft) and sensors (Table T1-1, page 12) that capture remotely sensed data; they have various spatial and temporal resolutions, bandwidths, and associated benefits and limitations to their application. Once collected, and before application, the data are processed using a variety of algorithms that account for anomalies that can confound the ability of the data to act as surrogates for biophysical features on the ground. Unless these anomalies are corrected, the data are difficult to interpret.

A long-standing and commonly used algorithm is the NDVI (Normalised Difference Vegetation Index), which uses the ratio of red and infrared bandwidths to produce an NDVI (value between -1 and +1) for each pixel of the area being sensed. This then results in a new processed image in which the different visual and thermal properties of surfaces can be readily distinguished. NDVI is strongly correlated with primary productivity and therefore is used as an indicator of live, green vegetation. Leaves absorb photosynthetically active radiation (PAR, bands 400–700 nm which they use as an energy source when they are photosynthetically active and scatter (reflect or transmit) near-infrared radiation (>700 nm). Other biophysical characteristics of vegetation also have been estimated using NDVI, including canopy coverage, photosynthetic capacity of canopies (through detection of chlorophyll or 'greenness') and leaf-area index (LAI).

There are acknowledged limitations to using NDVI. For example, contributions from the soil and vegetation understorey can influence the relationship between NDVI and other measures of vegetation, such as LAI. These have led to the development of several derivatives and alternative algorithms for data analysis/interpretation; each was developed to account for anomalies in remotely sensed data and/or allow application of the data for other purposes (listed in Table T1-2, page 13).

An additional common application of remotely-sensed data is the use of thermal infrared bands in the resolution of surface energy balances, which can be used to estimate evapotranspiration (ET). A comparison of ET rates of different vegetation types can suggest possible groundwater use, as well as provide a quantitative measure of ET, which can then inform assessments of environmental water requirements for those ecosystems or communities.

More generally, remote sensing can be used to detect areas where GDEs may be likely to occur. For example, mapping of surface wetness, based on the known reflectance of other surfaces or land types (including both open water and that in soil and vegetation), can be useful in identifying wetlands and likely areas of groundwater discharge across large spatial scales. Thermal imagery can help detect areas of groundwater discharge and hence river/coastal reaches or wetlands that may receive groundwater inputs.

The different bandwidths and electromagnetic spectrum (or region) of satellite data available (non-exhaustive) and their potential applications (examples based on Landsat data) are given in Table T1-3 (page 14).

Analysis approach

Landscape-mapping studies typically combine and compare different techniques to further refine the assessment of likely groundwater dependence. For example, aerial photography (black and white, colour or infrared) can be analysed to map vegetation communities, geology and geomorphology. Interpretations based solely on aerial photographs, however, can often be misleading, and extensive ground-truthing is often needed to clarify areas of uncertainty. Unsupervised interpretation, using image analysis software, can translate data from satellites or aircraft into maps of vegetation type, LAI, vegetation condition and/or evapotranspiration. Overlaying spatial ET estimates derived from remote sensing techniques with reliable depth-to-watertable data in GIS will help to identify locations where groundwater is likely to be within reach of roots of at least some components of the ecosystem. Soil water-holding capacity can be used to identify where groundwater is more likely to be the main source of water for vegetation during dry periods.

T1 Landscape Mapping	
	The GDE Atlas takes the above-described approach. Initially eco-hydrogeological landscape units are established through GIS analysis by combining datasets of climate, geomorphology, hydrogeology, geology, elevation and previously mapped extents of terrestrial vegetation, wetlands and rivers. Many of these data sets are readily available (Table T1-4). The eco-hydrogeological landscape units derived are essentially zones of similar hydrogeology and ecology that are assumed to have similar groundwater processes and ecological use of groundwater. Remote sensing is then used to identify ecosystems that are potentially dependent on water in addition to infiltration from rainfall.
Limitations	• Spatial resolution is dependent on scale of imagery collected and mapping. Coarse-scale imagery and mapping may not allow detection of small (subpixel) GDEs. • There are inherent errors and uncertainty in deriving values of physical properties (such as LAI) from remotely sensed data and algorithms. • Remote sensing and other landscape mapping tools can be used only as a first pass in GDE assessment process; that is, in identifying potential GDEs. Further work is required to confirm groundwater dependency and determine EWRs, and ground-truthing should be considered in all applications in this context. Some data of this type can assist with other tools. • Some components rely on prior knowledge that may or may not be available, for example: - rooting depth of vegetation communities - particular ecosystems or vegetation communities in other locations that are groundwater dependent - coincidence of vegetation communities or ecosystems and particular topographical and geological settings indicates groundwater dependency. • Some applications require relatively complex computation and the availability of ancillary data (e.g. surface temperature). The successful application of remotely sensed data to potential GDE delineation requires a clear understanding of their relationship with groundwater systems and spectral signatures in surface images.
Advantages	• Allows consideration of GDEs at a management-unit scale. • The approach is repeatable. With access to archived satellite imagery, assessments can be made retrospectively to assess changes over time. • Errors associated with ET estimates using SEBAL (application using remote sensing imagery) are generally around 10%, significantly lower than errors associated with upscaling point-based field measurements.
Disadvantages	• Snapshot of potential GDEs at one time means that results will probably change with land use, across seasons, and across climate cycles and with climate variability. • Despite the range of methods that have been developed, there are few available on a commercial basis or published as clear prescriptions. • Requires skills in processing of satellite images; knowledge of application and limitations of associated algorithms and how they relate to spectral signatures and biophysical characteristics.
Costs	Costs in landscape mapping methods relate to the acquisition, post-processing and interpretation of data and vary with the resolution of the mapping and image analysis, the scale of the assessment, the extent of ground-truthing and the level of expertise required. Remote sensing data and aerial photography costs vary depending on the data source used.

T1 Landscape Mapping

MODIS, some Landsat images and aerial photography are freely available; other data sources require purchasing. Indicative costs are:

- Imagery $500 to $4000 per scene (depending on data source).
- Single-parameter modelling (i.e. vegetation analyses with depth-to-watertable mapping) < $25 000.
- Interpretation of small catchment with integrated GIS analyses and remote sensing $25 000 to $50 000.

Interpretation of time-series data with analyses of specific processes to identify GDEs at a catchment scale > $50 000.

Specialist skills and resources

- Vegetation survey for ground-truthing.
- Interpretation of aerial photographs and satellite imagery.
- Geological, geophysical and soils surveys.
- GIS analyses—integration of data sets within spatial data models.
- Digital elevation model (DEM) of ground for watertable surface development.
- Knowledge of vegetation water-use patterns to define remote sensing metrics.

Main data types required

Data	*Likely source(s)*
Native vegetation cover, wetlands and drainage maps	Maps, ground surveys, aerial photographs, satellite imagery
Vegetation composition	Maps, reports, ground surveys
Root depth	Reports, site assessments
Geology and geological structure	Maps, reports, ground survey, geophysical survey
Groundwater flow systems and elevations, depth to watertable and surface water level	Maps, reports, observation bore records, DEM, river gauge data
Land use	Maps, reports, aerial photograph, satellite imagery
Soils	Maps, geophysical survey, ground survey, site assessment
Vegetation condition	Maps, reports, site assessments, satellite imagery
Leaf area index	Reports, site assessments, satellite imagery

Complementary tools

Tool may:	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14
provide inputs for		✓				✓		✓					✓	✓
require outputs from		✓				✓							✓	✓

T1 Landscape Mapping	
Key references and Australian case studies	Dresel PE, Clark R, Cheng X, Reid M, Fawcett J and Cochraine D 2010, *Mapping Terrestrial Groundwater Dependent Ecosystems: Method Development and Example Output,* Victoria Department of Primary Industries, Melbourne, Vic., 66 pp. NDVI derived from Landsat and MODIS images, collected at different times of year, are used to assess growth patterns of terrestrial vegetation. The data are incorporated into a groundwater interactive map to delineate regions likely to have shallow groundwater accessible to vegetation. Final outputs contained maps of terrestrial vegetation, wetlands and streams or landscapes likely to contain ecosystems that are, at least in part, dependent on groundwater. Woodgate M, 2004, Burnett Basin WRP *Amendment. Coastal Burnett Groundwater Project, Groundwater Dependent Ecosystems Desktop Report*. Department of Natural Resources and Mines, Queensland, September 2004. Potential GDEs are identified from vegetation mapping on the basis of vegetation structure, inferred rooting depth, position in the landscape, inferred depth to watertable, vegetation health and proximity to baseflow dependent river systems. Howe P, Cook P, O'Grady A and Hillier J 2005, *Pioneer Valley Groundwater Consultancy Report 3. Analysis of Groundwater Dependent Ecosystem Water Requirements*. Department of Natural Resources and Mines. Queensland, April 2005. Uses GIS to describe information management systems that are linked to physical geographic data (e.g. topographical, geological, hydrological) and demographic (e.g. land use, population). The various data sets that describe the attributes of an area are linked together geographically to provide spatial context. Münch Z and Conrad J 2007, 'Remote sensing and GIS based determination of groundwater dependent ecosystems in the Western Cape, South Africa', *Hydrogeology Journal*, 15:19–28. Mapped potential GDEs using combination of LANDSAT imagery and GIS modelling in South Africa. Land cover classification from the satellite imagery helped exclude obvious non-GDE areas and subsequently processed using NDVI, wetness and greenness indices to identify likely GDEs. Classification of the image was derived from known values of certain features such as open water or wetlands. GIS modelling, used to determine wetness potential based depth to watertable, topographic features and hydrogeological data, was combined with the remote-sensing outputs.

T1 Landscape Mapping	
Further information	Jiang Z, Huete AR, Didan K and Miura T 2008, 'Development of a two-band enhanced vegetation index without a blue band', *Remote Sensing of Environment*, 112(10):3833–3845. Discusses the development of the two-bank Enhanced Vegetation Indices (EVI, see Table T1-2) and provides background on EVI in general. Abstract available at: *http://www.sciencedirect.com/science/article/B6V6V-4T2J18X-2/2/88cddcb7d4350eea72af503ee19e73d2*. Bo-cai G 1996, 'NDWI-A normalized difference water index for remote sensing of vegetation liquid water from space', *Remote Sensing of Environment*, 58 (3):257–266. Discusses theory and use of NDWI (see Table 1-2) to assess changes in vegetation water content. Abstract available at: *http://www.sciencedirect.com/science/article/B6V6V-3VVT5PP-B/2/b6ca2db31b6fbfb55f91a795fa08468f*. SKM 2010, *Evapotranspiration measurement: Informing water management in Australia*, Waterlines Report Series No 35, November 2010. Discusses use of SEBAL (see Table 1-2) in the application of remotely sensed evapotranspiration measurement. Available at: *http://www.nwc.gov.au/resources/documents/Waterlines_no_35.pdf*. Contreras S, Jobbagy EG, Villagra PE, Nosetto MD and Puigdefábregas J, 2011, 'Remote sensing estimates of supplementary water consumption by arid ecosystems of central Argentina', *Journal of Hydrology*, 397(2011):10–22. Introduces an ecological and satellite based approach to explore the impacts of external water supplies on arid ecosystems. Abstract available at: *http://www.sciencedirect.com/science/article/pii/S0022169410007109.* Further information regarding Australian satellite and sensor capabilities is available on the Geoscience Australia website at: *http://www.ga.gov.au/earth-observation/satellites-and-sensors.html*.

Table T1-1: Common satellites and sensors available for remote sensing

Platform or sensor	*EM regions captured (spectrum detected)*	*Spatial scale and image resolution (area covered by the sensors, and pixel size of the data collected)*	*Temporal scale (frequency of data collection)*	*Comments*
Landsat satellite series (multiple satellites and sensors)	Visible, near infrared and infrared (including thermal)	15–120 km (depending on sensor—visible, near infrared and infrared bands) 30 m resolution (thermal infrared)	16 days	Data from 1972 to present (of various resolutions, improving as newer sensors were introduced) Only Landsat 5 and 7 are still operational
MODIS sensor	Visible and near infrared	250 km, 500 km, 1 000 km	1–2 days	Data from 1999 to present Available free of charge
ASTER	Visible, near infrared and infrared (including thermal)	15 m, 30 m (visible, near infrared and infrared bands) 90 m (thermal bands)	On demand	Data from 1999 to present High quality but on-demand nature means temporally and spatially discontinuous. Carries MODIS sensor
SPOT	Visible and near infrared	2.5 –20 m	High revisit capability	Data from 1998 to present
NOAA satellite series carrying AVHRR sensors	Visible, near infrared and infrared (including thermal)	>1000–4000 m	Daily (from particular regions)	Data from 1979 to present Available free of charge
Resourcesat-1	Visible and near infrared	23.5 m; 50 m and 70 m	5–24 day revisit respectively (depending on sensor)	Data available 2003 to present

Note: EM = Electromagnetic; more-detailed explanation of satellites and sensors commonly used, including pricing and acquisition, is available on the Geoscience Australia website (http://www.ga.gov.au/earth-observation/satellites-and-sensors.html).

Table T1-2 Common algorithms and methods used in application of remotely sensed data

Algorithm / method	*Application*
EVI (enhanced vegetation index)	Two- or three-band measure of vegetation greenness (composite measure of leaf chlorophyll, leaf area index, canopy cover and canopy architecture), optimised for improved sensitivity in high biomass regions. Feedback based, soil and atmospheric resistant.
NDVI (normalised difference vegetation index) [Derivatives of NDVI include: SARVI = soil and atmospherically resistant vegetation index; TC = tasselled cap; green and wetness indices; PVI = perpendicular vegetation index; GEMI = global environmental monitoring index]	Identification of live green vegetation Leaf area index (LAI) Biomass Chlorophyll concentration Primary productivity Vegetation cover
NDWI (normalised difference water index)	Uses near infrared and shortwave infrared to measure vegetation water content. It is less sensitive to atmospheric scattering than NDVI.
SEBAL (surface energy balance algorithm for land) / METRIC (mapping evapotranspiration at high resolution with internalised calibration)	Uses thermal infrared imagery to resolve a surface energy balance in order to estimate evapotranspiration (ET).
FAPAR (fractional of absorbed photosynthetically active radiation)	Directly related to primary productivity which may be more accurate that NDVI.
VITT (vegetation index/temperature trapezoid) [Adaptation of CWSI (crop water stress index)]	ET estimations through a water availability index based on an energy balance theory relating water to transpiration.

Table T1.3 Example applications of different band widths and spectral ranges. Based on Landsat satellite series (Geoscience Australia cited April 2011)

Band number	*Spectral range (in Microns)*	*Electromagnetic spectrum*	*Typical applications*
1	0.45–0.52	Visible blue	Coastal water mapping, differentiation of vegetation from soils
2	0.52–0.60	Visible green	Assessment of vegetation vigour
3	0.63–0.69	Visible red	Chlorophyll absorption for vegetation differentiation
4	0.76–0.90	Near infrared	Biomass surveys and delineation of water bodies; soil moisture assessment
5	1.55–1.75	Middle infrared	Vegetation and soil moisture measurements; differentiation between snow and cloud; delineation of water bodies
6	10.40–12.50	Thermal infrared	Thermal mapping, soil moisture studies and plant heat stress measurement
7	2.08–2.35	Middle infrared	Hydrothermal mapping
8	0.52 –0.90 (panchromatic)	Green, visible red, near infrared	Large-area mapping, urban change studies

Table T1-4: Data sets available to assist with landscape mapping

Dataset	*Source*	*Comments*
Imagery		
Landsat mosaic	Geoscience Australia	National mosaic (ECW format). Can be used to identify the activity of vegetation and presence of water.
MODIS (since 1999)	Geoscience Australia	
Inflow Dependent Ecosystems (derived product from GDE Atlas)	National Water Commission	Highlights vegetation and water bodies that are maintained by water in excess of rainfall.
Hydrology		
Rivers / watercourses	Geoscience Australia Geodata v3	National (1:250 000)
Water bodies	Geoscience Australia Geodata v3	National (1:250 000)
River basins	Geoscience Australia	National (1997)
Ecohydrological regions	Land and Water Australia	National (1:250 000)
Ecology		
Bioregions	Department Sustainability, Environment, Water, Population and Communities	National (v6.1). Provides context on the dominant ecology within regions.
Integrated vegetation cover (2003 and 1788)	Australian Bureau of Agriculture and Resource Economics and Sciences	NVIS National (2003)
Groundwater		
Groundwater provinces	Australian Bureau of Agriculture and Resource Economics and Sciences	National
Groundwater flow systems	Australian Bureau of Agriculture and Resource Economics and Sciences	National
Landscape		
Digital elevation models	Geoscience Australia	
Geology	Geoscience Australia	
Soils	CSIRO	Australian Soil Resource Information System (ASRIS) soil datasets

T2 Conceptual modelling

Description	Documentation of a conceptual understanding of the location of GDEs and interaction between ecosystems and groundwater.

Application to components of EWR studies

	Applicable	*Level of certainty*
Location, classification and basic conceptualisation	✓✓✓	✓✓
Characterisation of groundwater reliance	✓✓✓	
Characterisation of response to change	✓✓✓	
Monitoring and evaluation	✓✓	

Scale of measurement	Regional: ✓✓	Catchment: ✓✓	Site: ✓✓

Principles	Conceptual modelling involves giving informed consideration to groundwater systems, soils and climate information and the links to the dependent ecosystem. The investigation leads to a statement of relationships and interactions of ecosystem elements and processes.
How the tool is applied in GDE assessments	Conceptual models are non-quantitative tools that formalise an understanding of the major components of a given system, their interactions, and how external changes can modify the system. They are often represented as stylised oblique aerial views but can in fact be expressed in a large number of ways, including written narratives, tables and schematic diagrams such as box-and-arrow models. A conceptual model developed for the purposes of a GDE assessment may be ecological, hydroecological (a conceptualisation of how the ecosystem is reliant on and interacts with groundwater sources) or purely hydrogeological (an assessment of how the relevant hydrogeological systems function) in nature depending on need. The method involves a review of information available on the area of interest, which can include climate, geology, soils, hydrogeology, surface-water systems, and flora and fauna as components. Possible interactions among these various components are often very diverse, and can include processes or impacts such as primary production, herbivory, predation, competition and extraction. From this background information, a systematic view of how the system is structured and functions is developed. Sites or areas of interest can be compared with other, similar locations in which there are groundwater-dependent ecosystems to inform this process. The initial conceptualisation may then be used as the basis for developing approaches for more detailed investigations using other tools. Quantitative modelling is one such extension. Conversely, any and all information relating to a system can help to inform the development and further refinement of conceptual models. Conceptual models are a critical element of the adaptive management framework, as they formalise existing knowledge and allow predictions to be made as to the likely effectiveness of different management interventions. Models can assist in communication with stakeholders.
Analysis approach	Development of the conceptual model relies heavily on the professional judgement of experienced operators who need to be able to conceptualise, mostly with limited information, how the ecosystem and the relevant hydrogeological system function. There is no 'one size fits all'

T2 Conceptual modelling	
	conceptual model as different models must be tailored to different systems, for different end users and for different types of analysis. The involvement of specialists from several disciplines is often necessary to fully understand the system.
Limitations	• Does not provide quantitative information on groundwater dependence or EWRs.
Advantages	• An essential precursor to numerical models, such as outlined in T14. • Relatively low cost, especially in comparison with detailed groundwater modelling. • Captures and incorporates knowledge and hypothesis from a range of experts and disciplines. • Formalises existing information, leading to identification of knowledge gaps and extent of agreement among different experts/user groups as to the most important components and the critical interactions operating in a given system. • Allows for some degree of scenario planning and prediction of different management interventions.
Disadvantages	• Heavily reliant on experience and skills of operator, the degree to which ecosystem dependence on groundwater is obvious or there being existing documentation of groundwater dependence in similar settings at other locations. • Often require a hydrogeologic basis which may be limited by the amount of information available.
Costs	Costs could range between $1000 to $30 000 depending on the level of data available, accessibility of the site and the detail of conceptualisation required.
Specialist skills and resources	• Conceptualisation of groundwater processes and ecosystem interaction with groundwater. • Ecological, hydrogeological and hydrological expertise. • Knowledge of the ways that conceptual models can be developed for different purposes and for different end users. • Drafting for pictorial representations.

Main data types required	*Data*	*Likely source(s)*
	Site or study area description	Literature and maps on geology, hydrogeology, soils, vegetation, land use, climate, topography.

Complementary tools

Tool may:	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14
provide inputs for	✓				✓	✓		✓		✓		✓	✓	✓
require outputs from	✓							✓		✓			✓	

T2 Conceptual modelling	
Key references and Australian case studies	Howe P, Cook P, O'Grady A and Hillier J 2005, *Pioneer Valley Groundwater Consultancy Report 3 Analysis of Groundwater Dependent Ecosystem Water Requirements*, Department of Natural Resources and Mines, Queensland, April 2005. Provides a simple conceptualisation of GDE linkages to the biophysical setting of the Pioneer Valley, Queensland. Reid M A, Cheng X, Banks EW, Jankowski J, Jolly I, Kumar P, Lovell DM, Mitchell M, Mudd GM, Richardson S, Silburn M and Werner AD 2009, *Catalogue of conceptual models for groundwater–stream interaction*, eWater Technical Report, eWater Cooperative Research Centre, Canberra. Available at: *www.ewater.com.au/uploads/files/Reid_et_al-2009-Model_Catalogue.pdf*. Provides a useful guide for natural resource managers on the fundamentals and conceptualisation of groundwater–stream interaction, and its relevance in eastern Australian settings to stream and catchment management. It includes 10 case studies of connected groundwater–stream systems. Key sites for hydrology salinity and model validation: A local Groundwater Flow Systems perspective. Available at: *http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0017/140525/D-Mitchell.pdf*. Provides detail of the conceptualisation of catchments in NSW for the purpose of investigation hydrology salinity and model validation. SKM 2010, *Conceptual Diagrams of Groundwater Dependent Ecosystems*, report prepared for the Department of Water, South Australia. Presents hydrogeologic conceptualisations of numerous groundwater dependent wetlands in the south-east of South Australia.
Further information	Queensland Department of Environment and Resource Management (DERM) website provides many examples of conceptual models in different landscape settings. Available at: *http://www.epa.qld.gov.au/wetlandinfo/site/ScienceAndResearch/ConceptualModels/Conceptintromore.html*. Brodie R, Sundaram B, Tottenham R, Hostetler S and Ransley T 2007,. *An adaptive management framework for connected groundwater–surface water resources in Australia*, Bureau of Rural Sciences, Canberra. Provides detail on the key elements of a groundwater – surface water conceptual model including baseline information required and the broad array of methods that exists to assess the connectivity and degree of interaction between streams and groundwater.

T3 Pre-dawn leaf water potentials

Description	Identification of groundwater uptake by vegetation, or components of vegetation assemblages, on the basis of pre-dawn measurements of leaf water potential.		
Application to components of EWR studies		*Applicable*	*Level of certainty*
	Location, classification and basic conceptualisation	✓✓	✓✓
	Characterisation of groundwater reliance	✓✓✓	✓✓
	Characterisation of response to change	✓	✓
	Monitoring and evaluation	✓✓	✓✓
Scale of measurement	Regional: ✓	Catchment: ✓	Site: ✓✓✓

Principles

Leaf water potential (ψ_{leaf}) is a measure of the resistance of the pathway to water movement and is a function of the soil water availability, evaporative demand and the conductivity of the soil to leaf pathway. Groundwater use is indicated for vegetation where ψ_{leaf} values exceed (are less negative than) than vadose zone soil water potential (ψ_{soil}) values. At the watertable, ψ_{soil} is close to zero. Leaf water potential must be less (more negative) than the soil water potential at the root-soil interface in order for water to move into the plant: conversely, if soil water potential is more negative than leaf water potential, then water has the potential to move from the plant into the soil. ψ_{leaf} changes on a diel basis (i.e. over a 24-hour cycle) as the transpiration rate changes throughout the day and from day to night. There is little or no transpiration of water during the night from most types of plants and so the movement of water through the stem approaches static conditions over night. For this reason, ψ_{leaf} before dawn is generally in equilibrium with the matric potential of the soil (the tension with which water is held to soil particles) at the main depth at which the plant takes up water.

By matching pre-dawn ψ_{leaf} with the matric potential of the soil profile, it is possible to identify the main depth(s) of water uptake. Water uptake will generally occur from the shallowest layer with the highest (less negative) water potential.

How the tool is applied in GDE assessments

A comparison of leaf and soil water potential provides a rapid, field-based method of identifying possible sources of water uptake for plant transpiration and determining whether plants use groundwater.

A time-series of leaf and soil water potential data is preferred. Measurements should concentrate on the drier season, when the unsaturated soil zone is depleted of water and groundwater uptake is most likely.

Soil-profile water potential is either measured directly or estimated from water-content measurements. Pre-dawn ψleaf measurements are taken and compared with the ψsoil of the soil profile. Depending on the rooting depth, the upper depth at which pre-dawn ψleaf matches ψsoil is likely to be the main depth of water uptake. High ψleaf values in dry soils suggest that vegetation is using groundwater.

Leaf water potential

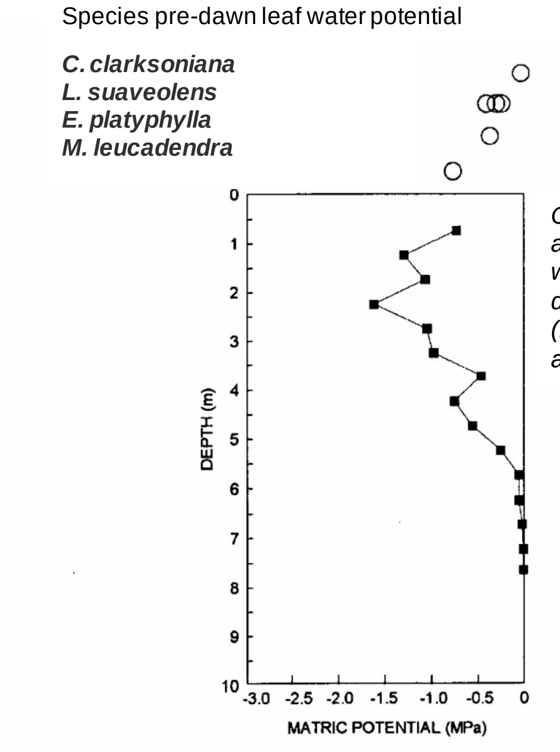
A small twig with leaves is collected from the plant in the pre-dawn period and the height above the ground recorded. The leaf water potential is most commonly measured by using a Scholander 'pressure bomb', a metal cylinder into which the twig is inserted via a rubber bung. High-pressure air or nitrogen is then applied to the cylinder, and the pressure recorded at which xylem fluid is forced from the vascular tissue.

Soil water potential

Soil matric potential can be measured directly in the field using thermal heat sensors, gypsum blocks, tensiometers and equitensiometers. It can also be measured in the laboratory using pychrometers or the filter paper method. Soil matric potential and water content only change slowly if stored appropriately and do not need to be measured at exactly the same time as ψleaf.

Analysis approach

Groundwater use at the time of sampling is determined by comparing pre-dawn ψ_{leaf} with soil-profile matric potentials. The figure below compares soil matric potentials determined using the filter paper technique on core samples with pre-dawn leaf water potentials measured on four different overstorey species, from an open woodland ecosystem in the Pioneer Valley, Queensland. The watertable at this site occurs at approximately 7 m depth. The predawn leaf water potential of *C. clarksoniana* was -0.03 MPa, which clearly indicates a water source within the capillary fringe below 6 m depth. In contrast, the low predawn leaf water potential of *M. leucadendra* is consistent with water extraction from the soil profile.



Comparison of soil and pre-dawn leaf water potentials for different species (from O'Grady et al, 2006)

Limitations

- Multi-year measurement programs may be needed to detect groundwater use if plants or vegetation only use groundwater episodically (e.g. during prolonged dry periods when soil water reserves have been exhausted).
- Method can yield inconclusive results in one-off assessments and where there is a high variability in retention capacity of vadose zone soil strata and shallow groundwater.
- Soil coring to depth can be problematic in some soil types.
- The assumption of pre-dawn equilibrium may need to be tested for each species as some species can have partial stomatal opening at

T3 Pre-dawn leaf water potentials

night.

- Bulky equipment (Scholander Bomb, high-pressure gas cylinders) presents some logistical and safety difficulties in field-based surveys.

Advantages

- Well-established approach, widely used by plant physiologists.
- The tool is best suited to investigating groundwater dependency of specific vegetation associations in specific locations.
- The tool can be used to determine whether, and at what time of year, groundwater is being used by vegetation.
- Inexpensive (see below), at least for instrumentation if not for extensive field surveys.
- Provides good data to assess how dry soils need to be to induce water stress in vegetation.
- Can be used to survey many species relatively easily.

Disadvantages

- Multiple field measurement sites would be required for broader scale assessments.
- Although application of the tool is in itself cheap, large sampling campaigns can be labour intensive and are consequently expensive.
- The tool does not, by itself, indicate the amount of groundwater use.

Costs

Costs vary with the duration of the sampling campaign and number of plants and sites assessed:

- Leaf water potential measurements: $5000 to $50 000 with moderate to high confidence.
- Soil matric potential or water content measurements: $20 000 to $50 000, depending on time, method and number of sites.

Costs do not include the purchase price of any instruments that may be required.

Specialist skills and resources

- Operation of the instruments used to measure leaf water potential and soil water content/matric potential.
- Understanding of the biophysical plant and soil processes involved.

Main data types required

Data	*Likely source(s)*
Pre-dawn leaf water potential	Site measurements with pressure bomb
Soil profile water potentials	Site measurements using gypsum blocks, tensiometers, laboratory analysis of soils from field site.
Soil profile water content	Site measurements using neutron probes, time or frequency domain reflectometry, laboratory analysis of soils from field site

Complementary tools

Tool may:	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14
provide inputs for				✓	✓	✓		✓					✓	
require outputs from				✓		✓								

T3 Pre-dawn leaf water potentials	
Key references and Australian case studies	Howe P, Pritchard J, Carter J and New C 2009, 'Addressing the potential effects of mine dewatering on terrestrial groundwater dependent ecosystems – Pilbara region WA', in *Proceedings of the First International Seminar on Environmental Issues in the Mining Industry,* Wiertz J and Moran C (eds), Enviromine2009, Chile. Eamus D, Hatton T, Cook P and Colvin C 2006, *Ecohydrology: Vegetation function, water and resource management*, CSIRO Publishing. 360 pp. Describes and provides a synthesis of the different disciplines required to understand the sustainable management of water in the environment in order to tackle issues such as dryland salinity and environmental water allocation. O'Grady A P, Cook, P G, Howe P and Werren G 2006, 'Groundwater use by dominant tree species in tropical remnant vegetation communities', *Australian Journal of Botany*, 54(2):155–171. Use of pre-dawn leaf water potential measurements and other techniques for assessment of groundwater use by terrestrial vegetation. Thorburn P J and G R Walker 1994, 'Variations in stream water uptake by *Eucalyptus camaldulensis* with differing access to stream water', *Oecologia*, 100: 293–301. Use of pre-dawn leaf water potential measurements and other techniques for assessment of stream water, soil water and groundwater use by riparian vegetation. O'Grady A P, Eamus D, Cook P, Lamontagne S, Kelly G and Hutley L 2002, *Tree Water Use and Sources of Transpired Water in Riparian Vegetation along the Daly River, Northern Territory*. Available at: *http://www.nt.gov.au/nreta/water/drmac/pdf/OGrady_Ma.pdf*. Provides an example of the way in which an EWR-type assessment using pre-dawn leaf water potentials (in combination with other methods) can be undertaken, and the type and level of information that is derived.
Further information	Background information on soil matric potentials (including field analysis methods) are available in: Marshall T J, Holmes J W and Rose C W 1999, Chapter 3 'Measurement of water content and potential' in *Soil Physics*, Cambridge University Press, 453 pp. Or D and Wraith J M 1999, 'Soil Water Content and Water Potential Relationships' in Sumner, ME (ed) *Handbook and Soil Science*, A53-A83, CRC Press.

T4 Stable isotopes of water in plants

Description	Naturally occurring stable isotopes of water can be used to identify sources of water used for plant transpiration.		
Application to components of EWR studies		*Applicable*	*Level of certainty*
	Location, classification and basic conceptualisation	✓	✓✓✓
	Characterisation of groundwater reliance	✓✓✓	✓✓✓
	Characterisation of response to change	✓	✓
	Monitoring and evaluation		
Scale of measurement	Regional:	Catchment:	Site: ✓✓✓

Principles

The isotopes of water, oxygen-18 (^{18}O) and deuterium (^{2}H) are used to delineate sources of water used by terrestrial vegetation. ^{2}H and ^{18}O occur naturally, they are not radioactive (e.g. ^{14}C and ^{32}P and ^{235}U). Natural isotopes differ merely in the number of neutrons in the atom. Thus they behave the same way chemically, but in different ways physically because of their different atomic mass. Isotopic fractionation of the water therefore occurs through transport processes and phase transitions in the atmosphere, soils and plants. As the relative influence of fractionating processes is likely to be different for the various sources of water (groundwater, surface water and soil water), they will often have different isotopic values. However, as there is no further fractionation of the isotopic signature in the process of plant uptake, comparison of potential source waters (i.e. surface water, soil water, groundwater) isotopic compositions with the plant xylem water composition can be used as an indicator of the source of the water and whether the plant is using groundwater.

How the tool is applied in GDE assessments

The stable isotopic (^{2}H and ^{18}O) composition of xylem water is a combination of the water sources the plant uses. The xylem 'signature' is compared with the various potential source waters to identify the relative contribution of each. The comparison is carried out using a mixing model.

The ability of the mixing model to identify the proportion of water from different sources is dependent on the number of sources and the difference in the stable isotopes of water signatures of each. Greatest success is achieved when the signature of each water source is distinctly different, and there are few possible sources.

If used in conjunction with some other tools (especially T3 and T8), this tool can provide an indication of the amount of groundwater use by the individual plants under investigation.

The analysis of the nature of groundwater dependence is improved if data can be collected under various seasonal conditions, in order to compare xylem and source water under different conditions of water stress.

T4 Stable isotopes of water in plants	
Analysis approach	Stable isotopes of water analyses are performed on plant xylem water and the various potential sources of water to establish the proportion provided by groundwater, surface water and soil water. Ideally, sampling for plant xylem water and soil water should occur following one to two weeks of relatively stable weather conditions without significant rainfall. Rainfall can cause changes in the stable isotopes values in soil and plant water, and may mean that the two cannot be readily correlated. Best results are obtained when the technique is used in conjunction with complementary methods (e.g. pre-dawn leaf water potential, soil water measurement) and there are no more than three (and preferably only two) sources of plant water. Sampling should at least be carried out during drier conditions or seasons when soil water is most likely to be in short supply to plants. Repeated sampling will provide a better understanding of the nature of groundwater dependency and help to detect groundwater use that is only episodic. *Sampling approach* • Plant xylem water chemistry Xylem water is generally extracted from small twigs, although could be taken (more destructively) from other parts of the plant. It should not be taken from leaves, as evaporation can cause enrichment of the heavy water isotopes. • Soil water chemistry Soil samples are collected from representative depths using an auger, core or test pit. Sufficient soil must be collected to extract approximately 10 mL of water. • Surface water The stable isotopes of water composition of surface water is required for wetland ecosystems and riparian ecosystems. Water can be sampled directly from a representative part of the water body. Where different surface water conditions exist (e.g. flowing river with adjacent cut-off wetlands), sampling from both sources would be necessary as the stable isotopes of water composition is likely to vary between them. • Groundwater chemistry Groundwater can be sampled from piezometers located within several hundred metres of the vegetation being sampled (preferably closer). The piezometers also provide information on the groundwater level at the sample interval, assisting in the assessment of the capillary zone and its location relative to the root zone of the vegetation. The piezometer should be screened as close to the watertable as possible if groundwater samples are to be representative of plant water sources
Limitations	• Although it can be used to indicate groundwater uptake, the tool does not provide any clear indication of the EWR. • Can provide inconclusive results where the probable water sources have similar isotopic signatures. • Multi-year measurement programs may be needed to detect groundwater use if plants or vegetation communities only use groundwater episodically (e.g. during prolonged dry periods when soil water reserves have been exhausted). • Distinct differences in the isotopic signature of the water sources not always possible
Advantages	• A good tool for investigating groundwater dependency of specific vegetation in specific locations.

T4 Stable isotopes of water in plants

Disadvantages

- Large sampling campaigns can be labour intensive and are consequently expensive.
- Results are site specific. Without validation, results and interpretations from one location cannot be transferred to another. Multiple field measurement sites are required for broader scale assessments.

Costs

Costs vary with the duration of the sampling campaign and the number of plants and sites assessed:

- Use of groundwater: $30 000 to $50 000, with moderate to high confidence.
- Proportion of groundwater use: $25 000 to $50 000, not including water balance measurements, with low to moderate confidence.

Specialist skills and resources

- Plant, soil and water sampling techniques and equipment.
- Understanding of the biophysical processes involved.
- Access to an isotope ratio mass spectrometer. A number of instruments are available in Australia and New Zealand.
- Interpretation requires some knowledge of plant physiology or hydrogeology and isotope behaviour if simplistic/false conclusions are to be avoided.

Main data types required

Data	*Likely source(s)*
Stable isotopes of water composition of xylem water and potential water sources	Laboratory analysis of samples collected from field sites
Watertable depth	Piezometers in field
Soil water content and/or matric potential, plant transpiration	Site measurements using soil water content and/or matric potential techniques

Complementary tools

Tool may:	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14
provide inputs for			✓		✓	✓		✓					✓	
require outputs from			✓								✓			

T4 Stable isotopes of water in plants

Key references and Australian case studies	Costelloe JF, Payne E, Woodrow I E, Irvine EC, Western AW and Leaney FW 2008, ' Water sources accessed by arid zone riparian trees in highly saline environments, Australia', *Oecologia,* 156:43–52. Use of stable isotopes of water in association with other techniques for assessment of groundwater use and dependency of riparian *E. coolabah* in a remote arid setting. O'Grady AP, Cook PG, Howe P and Werren G 2006, 'Groundwater use by dominant tree species in tropical remnant vegetation communities', *Australian Journal of Botany*, 54(2):155–171. Use of stable isotopes of water and other techniques for assessment of groundwater use by terrestrial vegetation. Zencich SJ, Froend RH, Turner JV and Gailitis V 2002, 'Influence of groundwater depth on the seasonal sources of water accessed by *Banksia* tree species on a shallow, sandy coastal aquifer', *Oecologia*, 131: 8–19. Uses deuterium (^{2}H) to determine changes in seasonal water use (precipitation, soil water, and groundwater) of banksia spp. in the Swan Coastal Plain, southwest Western Australia. Thorburn PJ and Walker GR 1994, 'Variations in stream water uptake by *Eucalyptus camaldulensis* with differing access to stream water', *Oecologia*, 100: 293–301. Use of stable isotopes of water and other techniques for assessment of stream water, soil water and groundwater use by riparian vegetation. Mensforth LJ , Thorburn PJ, Tyerman SD and Walker GR 1994, 'Sources of water used by riparian *Eucalyptus camaldulensis* overlying highly saline groundwater', *Oecologia* 100: 21–28. Case study used a combination of stable isotopes of water analysis and water balance methods to assess groundwater use and dependency of riparian *E. camaldulensis* trees. Howe P, Pritchard J, Carter J and New C 2009, 'Addressing the potential effects of mine dewatering on terrestrial groundwater dependent ecosystems – Pilbara region WA', in *Proceedings of the First International Seminar on Environmental Issues in the Mining Industry*, Wiertz J and Moran C (eds), Enviromine2009, Chile.
Further information	Eamus, D 2009, *Identifying groundwater dependent ecosystems. A guide for land and water managers*, Land & Water Australia, 15 pp. This booklet provides an overview of techniques, including the stable isotopes of water, available to identify terrestrial groundwater dependent ecosystems. Available at: http://lwa.gov.au/files/products/innovation/pn30129/pn30129_1.pdf. Dawson T E and Ehleringer J R 2006, 'Plants, isotopes and water use: A catchment-scale perspective', in *Isotope Tracers in Catchment Hydrology* (eds) C Kendall and JJ McDonnell, Elsevier

T5 Plant water-use modelling

Description	Identification of sources and volumes of water used for plant transpiration, by using mathematical simulations of plant function.

Application to components of EWR studies

	Applicable	Level of certainty
Location, classification and basic conceptualisation		
Characterisation of groundwater reliance	✓✓	✓✓
Characterisation of response to change	✓✓	✓✓
Monitoring and evaluation	✓✓	✓

Scale of measurement

Regional: ✓ Catchment: ✓ Site: ✓✓

Principles

Plant water-use modelling is potentially an effective way to assess possible plant responses associated with changes in access to water. Numerical and analytical models are formulated which represent natural systems. Simulations are then run to explore responses to change in water regime.

Provided the model accurately represents the natural system under investigation, the approach/tool can provide estimates of groundwater use and EWR. Modellers would typically rely on conceptualisations and data from other tools to construct or calibrate their models. Moreover, a qualitative conceptual model needs to have been developed earlier in order to identify critical components and their likely interactions (see T2).

How the tool is applied in GDE assessments

Where possible, the model is developed around physical data from the site being evaluated. Once established, the model can be used to simulate conditions prior to changes in water availability.

Transpiration and climate data

Modelling of a plant's water use requires site-based measurements of transpiration. Rainfall and potential evaporation data may be required for modelling of plant water use and estimating the plant available water capacity (PAWC), depending on the model requirements. The data can be obtained from regional monitoring stations or on-site micro-climate stations.

Source of transpiration water

Ideally, information on the source of plant transpiration water is required. This can be obtained by the use of stable isotopes of water (T4) or pre-dawn leaf water potentials (T3).

Plant-soil-atmosphere interaction

Use of plant water-use models in GDE assessments depends on having a model that accurately reflects the interaction between plants, soils, various water sources, and the atmosphere. Numerous models of various levels of complexity are available. Most require estimates to be made of various input parameters to describe the plant and soil system (e.g. leaf area, rooting depth and intensity, soil hydraulic properties) and its interaction with the environment. Parameters may be estimated from literature or site measurements. Modelling for GDEs must reflect interactions between groundwater, soil water and surface water regimes and the availability of groundwater to plants. These interactions can be predicted through conceptual models (T2), groundwater modelling (T14) or observations of groundwater regime.

T5 Plant water use modelling

	Models may be run using historical or synthetic climate regimes and a range of management scenarios to explore plant response to change in water regime.
Analysis approach	Models are used to estimate plant water requirements and/or groundwater uptake. Groundwater uptake can be inferred where measured water use greatly exceeds the modelled value. If sufficient data are available that allow the model to adequately represent the plant system, it may be used to directly estimate groundwater use. The model may also be used to explore plant responses to changes in the water regime in ways that allow the EWR to be determined, particularly if combined with a probabilistic assessment of the capacity of the soil water reservoir to meet plant water requirements on a seasonal basis.
Limitations	• Requires comprehensive information on site conditions and the characteristics of the vegetation to be modelled. This information will rarely be available prior to any new GDE assessment. • The usefulness of the model is limited by its success in representing the vegetation being investigated.
Advantages	• The tool is best suited to investigating groundwater dependency of specific vegetation associations in specific locations.
Disadvantages	• Large sampling campaigns can be labour and data intensive and are consequently expensive. • Results are site specific. Without validation, results and interpretations from one location cannot be transferred to another. Multiple field measurement sites are required for broader scale assessments.
Costs	Total cost will vary with the scale at which the tool is applied and the degree of accuracy required. The likely range is $30 000 to $50 000 for a small-scale, low-confidence modelling effort using existing data to well over $100 000 for a more complex model and modelling process, with additional new site data being collected.
Specialist skills and resources	• Numerical skills associated with developing and/or operating models. • Understanding of plant-soil-atmosphere interactions. • Field data collection.

Main data types required

Data	*Likely source(s)*
Climate data	Regional monitoring stations, Bureau of Meteorology records, on site weather stations
Transpiration	Sap flow studies, eddy covariance studies, ventilated chambers
Source water	Measured using stable isotopes of water or pre-dawn leaf and soil water potentials
Plant-soil-atmosphere interactions	Literature, models, field measurements

Complementary tools

Tool may:	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14
provide inputs for								✓						✓
require outputs from		✓	✓	✓		✓		✓					✓	✓

T5 Plant water use modelling

Key references and Australian case studies	Howe P, Cook P, O'Grady A and Hillier J 2005, *Pioneer Valley Groundwater Consultancy Report 3 Analysis of Groundwater Dependent Ecosystem Water Requirements*, Department of Natural Resources and Mines, Queensland, April 2005. Presents a case study that utilised a simple hydraulic model of plant water uptake calibrated using stable isotopes of water and water potential data, along with a water balance approach, to determine the probability of vegetation reliance on groundwater in any one year. Dye P J, Jarmain C, Le Maitre, Everson CS, Gush M and Clulow A 2006, *Modelling vegetation water use for general application in different categories of vegetation*, South African Water Research Commission, July 2006. This study models the response of native vegetation to changes in water availability. Methods used in this study could be applied to examine vegetation response to changes in watertable depth. Deery DM 2008, *Plant water uptake at the single plant scale: experiment vs. model*, PhD Thesis, Charles Sturt University, August 2008. This study researches the flow of water to a plant route and compares field experiments with mathematical modelling. Available at: *http://www.irrigationfutures.org.au/imagesDB/news/Deery_Thesis_29Aug_08.pdf*. *http://irrigationfutures.org.au/imagesDB/news/CRCIF-IM0109-web.pdf*. Froend R H and Sommer B 2010, 'Phreatophytic vegetation response to climatic and abstraction induced groundwater drawdown: Examples of long-term spatial and temporal variability in community response', *Ecological Engineering*, 36: 1191–1200. Investigates the influence of climatic drought and groundwater abstraction on phreatophytic vegetation dynamics over a period of 33 years in the south-west of Western Australia.
Further information	Eamus D 2009, *Identifying groundwater dependent ecosystems. A guide for land and water managers*, Land & Water Australia, 15 pp. This booklet provides an overview of techniques, including leaf area index, depth to groundwater and root depth, to identify groundwater dependent ecosystems. Available at: *http://lwa.gov.au/files/products/innovation/pn30129/pn30129_1.pdf*. Eamus D, Hatton T, Cook P and Colvin C 2006, *Ecohydrology: Vegetation function, water and resource management*, CSIRO Publishing. This book introduces and explains the fundamentals of several disciplines—plant physiology, hydrology, ecology, environmental science—required to successfully understand vegetation and groundwater interactions and management.

T6 Root depth and morphology

Description	Comparison of the depth and morphology of plant root systems with measured or estimated depth to the watertable, in order to assess the potential for groundwater uptake.		
Application to components of EWR studies		*Applicable*	*Level of certainty*
	Location, classification and basic conceptualisation	✓✓	✓✓
	Characterisation of groundwater reliance	✓✓✓	✓
	Characterisation of response to change		
	Monitoring and evaluation		
Scale of measurement	Regional: ✓✓	Catchment: ✓✓	Site: ✓✓✓
Principles	The tool assumes that, where plant roots are deep enough to interact with groundwater (in terrestrial vegetation communities, wetlands and/or riparian vegetation along baseflow streams) there may be some reliance on groundwater by the vegetation.		
How the tool is applied in GDE assessments	A depth-to-watertable map is prepared for the area under investigation and intersected with a vegetation map. The vegetation map is attributed with the depth-of-rooting of the main species, based on literature reports and, where possible, earlier site-specific investigations. Potential GDEs are identified where root depth is within 1–2 m of the watertable. The watertable map is prepared from measurements (or monitoring) of groundwater levels in a network of piezometers or bores. An accurate ground surface digital elevation model (DEM) is required to translate the watertable elevation DEM into a depth-to-watertable DEM. Given adequate bore coverage and topographic information, watertable maps can be prepared by hand-contouring or the application of geostatistical approaches such as kriging. Vegetation maps are based on field survey, aerial photography or satellite imagery, or can be made as GIS layers. Root depth would typically be assessed from the literature, or experience in previous field studies or, best of all, actual measurements at the field site. Depth can be estimated in the field by excavation or by the use of down-hole cameras to locate roots that intrude into observation boreholes (noting that boreholes can sometimes form a preferential pathway for root growth).		
Analysis approach	Depth-to-watertable maps may be prepared manually or using automated geostatistical approaches. In areas of variable topography and geography, any depth-to-watertable map represents just one of a large number of possible realisations. The map should be accompanied by indications of reliability. Analysis involves intersecting the depth to watertable and attributed vegetation map in a GIS. Watertable maps could be prepared seasonally if there is strong intra-annual variation. Such maps could be used to identify seasons of potential groundwater use.		
Limitations	• The quality of depth-to-watertable map is highly dependent on the adequacy of the piezometer network and ground surface DEM and		

T6 Root depth and morphology	
	method of development. Higher densities of piezometers are required in topographically or geologically variable landscapes than in flat or geologically uniform landscapes. • The tool provides no indication of the EWR. • The method may be inaccurate if significant heterogeneity exists (e.g. duplex soils, hardpans, rock layers). • Rooting depths of most tree species are poorly known, and vary between site.
Advantages	• Provided the depth-to-watertable map is of suitable quality, this method provides a good first-pass indication of potential for groundwater dependence.
Disadvantages	• The method is based simply on the association of roots and depth to groundwater and without validation (e.g. using T4) may be unreliable and overestimate a terrestrial ecosystem's dependence on groundwater.
Costs	Total costs vary with the amount of existing information. If watertable and vegetation mapping already exist, costs will generally be less than $20 000. Costs of vegetation mapping, piezometer network construction and watertable mapping vary with the scale of the assessment and landscape variability. Investigations on a totally greenfield site may be $50 000 to $250 000, depending on size and variability.
Specialist skills and resources	• Hydrogeological assessment, watertable mapping • Vegetation mapping

Main data types required

Data	*Likely source(s)*
Groundwater level	Site measurements from piezometers, existing watertable maps
Topography	DEM, topographic maps
Vegetation types	Vegetation maps
Rooting depth	Literature, field studies

Complementary tools

Tool may:	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14
provide inputs for	✓			✓	✓								✓	
require outputs from	✓				✓								✓	

T6 Root depth and morphology	
Key references and Australian case studies	Jackson RB, Canadell J, Ehleringer JR, Mooney HA, Sala OE and Schulze ED 1996, 'A global analysis of root distributions for terrestrial biomes', *Oecologia* 108:389–411. Jochen Schenk H and Jackson RB 2002, 'The global biogeography of roots', *Ecological Monographs*, 72:311–328. Analysed structure of vegetation by determining the biotic and abiotic factors that influence vertical root distributions in the soil, including soil, climate, and plant properties.
Further information	Eamus D 2009, *Identifying groundwater dependent ecosystems. A guide for land and water managers*, Land & Water Australia, 15 pp. This booklet provides an overview of techniques, including root depth, to identify groundwater dependent vegetation. Available at: *http://lwa.gov.au/files/products/innovation/pn30129/pn30129_1.pdf*.

T7 Plant groundwater-use estimation

Description	Measures of leaf area index (LAI) and climatic data are used to estimate groundwater discharge from terrestrial ecosystems that have access to groundwater.

Application to components of EWR studies		*Applicable*	*Level of certainty*
	Location, classification and basic conceptualisation	✓✓✓	✓✓✓
	Characterisation of groundwater reliance	✓✓	✓✓
	Characterisation of response to change	✓✓✓	✓✓
	Monitoring and evaluation	✓✓✓	✓✓✓

Scale of measurement	Regional: ✓✓	Catchment: ✓✓	Site: ✓✓✓

Principles	This tool builds on the theory of ecological optimality as first presented by Eagleson (1982), who proposed that in water-limited environments the productivity of vegetation is maximised in a manner that minimises water stress. In terrestrial ecosystems, the LAI (the combined area of all the leaves per unit ground area) is a good measure of vegetation biomass. Thus the LAI can be a good indicator of the water availability regime an ecosystem is experiencing. The underlying principle is that for a given climatic regime, LAI is strongly correlated to the ratio of rainfall and pan evaporation-known as the climatic wetness index (CWI) (e.g. Ellis et al. 2005; Ellis & Hatton 2008). O'Grady et al. (2010) have since demonstrated that the LAI of communities with access to groundwater is higher than that predicted from CWI and have developed an approach for estimating the volume of groundwater discharge associated with this increased LAI.
How the tool is applied in GDE assessments	Can be used in desktop and more detailed ecosystem assessments to better understand the functioning and productivity of groundwater-dependent ecosystems. As a desktop exercise, an estimate of LAI may be derived using the MODIS LAI product (see T1). In combination with readily available climate data, the spatial extent of potential GDEs in the area of interest can be defined and an estimate of the volume of water, above that supplied by rainfall required to maintain the LAI can be mapped. In more detailed assessment of GDEs a better understanding of the temporal dynamics of LAI would provide insights into whether the systems was under stress from, for example, declining watertable, and thus develop an understanding of ecosystem responses.
Analysis approach	Information on LAI can be collected using a number of approaches that vary in complexity. These approaches include deriving LAI from remotely sensed imagery, using digital cover and hemispherical photography, or using specialised plant-canopy analysers. Canopy cover and hemispherical photography require post-processing of photographs to determine LAI. There have been a number of attempts to automate them, but with various levels of success.
Limitations	• The tool is built on steady state assumptions that apply over long time periods; thus, using 'snapshots estimates' of LAI or having an insufficient climate record could lead to erroneous interpretation. • Obtaining accurate estimates of LAI can be extremely difficult, particularly from species that have small, fine leaves such as many

T7 Plant groundwater use estimation

	melaleucas and thin cladodes or phyllodes, such as casuarinas and acacias.
Advantages	• It is often assumed that the LAI of terrestrial ecosystems that have access to groundwater should be higher than those that do not, and this approach provides a sound conceptual case for that argument. It also provides a simple empirical approach that can be used in estimating the water requirements for a terrestrial ecosystem. • A better understanding of the temporal dynamics of LAI helps to better understand the water requirements of an ecosystem or vegetation type. Furthermore, monitoring spatial and temporal leaf area dynamics would form the basis of valuable monitoring tools that may go some way to the understanding the ecosystem response functions to altered water regimes. • There are continual improvements in remote sensing algorithms and in the spatial and temporal resolution of remotely sensed data. Additionally, the required climatic information is readily available for much of Australia. Together these factors suggest that this approach may become an increasingly powerful tool for monitoring and detecting change in ecosystem function. • This approach can be readily integrated with the other tools in this toolbox.
Disadvantages	• The method, although developed on Australia data, has not been extensively tested and is highly reliant on accurate estimates of LAI. • LAI can vary considerably seasonally and on longer inter-annual time frames. High LAI is not itself an indicator of access to groundwater or groundwater dependency, and needs to be considered in the context of the CWI. The approach is best suited to terrestrial ecosystems and has limited application for other GDE types.
Costs	Indicative costs for LAI analysis: $5000 to $25 000 depending on scale of assessment. Costs for interpretation in the context of CWI additional to this amount.
Specialist skills and resources	LAI is a simple concept but difficult to accurately quantify. Measurement techniques require a reasonable technical competency; for example, GIS and remote sensing skills. Competencies for on-ground measurements vary from low to high, depending on the methods being used to collect the information. Interpretation of LAI data requires a high level of technical competency.

Main data types required

Data	*Likely source(s)*
Climatic data, rainfall and evaporation	Remotely sensed data (e.g. MODIS)
LAI	Existing national climatic coverage of climatic variables such as potential evaporation, Bureau of Meteorology

Complementary tools

Tool may:	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14
provide inputs for	✓				✓			✓					✓	
require outputs from	✓	✓			✓								✓	

T7 Plant groundwater use estimation	
Key references and Australian case studies	Eagleson, PS 1982, ‘Ecological optimality in water limited natural soil-vegetation systems 1. Theory and hypotheses’, *Water Resources Research*, 18: 325–340. Ellis T, Hatton T and Nuberg I 2005, ‘An ecological optimality approach for predicting deep drainage from tree belts of alley farms in water-limited environments’, *Agricultural Water Management*, 75:92–116. Ellis TW and Hatton TJ 2008, ‘Relating leaf area index of natural eucalypt vegetation to climate variables in southern Australia’, *Agricultural Water Management*, 95:743–747. O’Grady A P, Carter J and Holland K 2010, *Review of Australian groundwater discharge studies of terrestrial systems*, CSIRO Water for a Healthy Country. O'Grady AP, Carter JL, and Bruce JL 2011, ‘Can we predict groundwater discharge from terrestrial ecosystems using ecohydrological principals?’ *Hydrology and Earth Systems Science*, 2011. Published online-in discussion.
Further information	Further information regarding Australian satellite and sensor capabilities is available on the Geoscience Australia website. Available at: *http://www.ga.gov.au/earth-observation/satellites-and-sensors.html*. Fuentes S, Palmer AR, Taylor D, Zeppel M, Whitley R and Eamus D 2008, ‘An automated procedure for estimating the leaf area index (LAI) of woodland ecosystems using digital imagery, MATLAB programming and its application to an examination of the relationship between remotely sensed field measurements of LAI’, *Functional Plant Biology* 35(10): 1010–1079. This journal paper describes various methodologies available to determine LAI.

T8 Water balance: vegetation

Description	Use of water balance measurements and/or calculations to assess whether and to what extent plant water use is dependent on groundwater uptake.		
Application to components of EWR studies		*Applicable*	*Level of certainty*
	Location, classification and basic conceptualisation	✓	✓
	Characterisation of groundwater reliance	✓✓✓	✓✓✓
	Characterisation of response to change	✓✓✓	✓✓✓
	Monitoring and evaluation	✓	✓✓✓
Scale of measurement	Regional: ✓ Catchment: ✓✓ Site: ✓✓✓		

Principles

Groundwater use is determined from water balance measurements and/or calculations. It is assumed that any plant water use that exceeds availability from rainfall and soil water (and surface water for vegetation fringing rivers and wetlands) is based on the use of groundwater.

Water-balance studies are typically based on field measurements undertaken on small-scale sites. Field sites may be replicated across landscapes to provide a larger-scale view of water balance and groundwater use.

Recent developments have enabled the use of remote sensing technologies in water-balance studies, specifically in the mapping of evapotranspiration. Remotely sensed data on surface energy balance and evaporation can be used to extend the spatial scale of water-balance studies, but can have reduced accuracy in comparison with direct on-ground methods

In general, water-balance studies should be undertaken over several years in order to properly characterise groundwater dependency for ecosystems with episodic or highly variable use. In the first instance they can be used to provide a preliminary indication of the potential for groundwater dependency.

How the tool is applied in GDE assessments

Groundwater dependence is inferred where there is a deficit between plant water use and the size of the soil water reservoir. These values are determined from measurements, calculation and/or modelling of the water balance.

Benyon and Doody (2004) expressed the water balance for an area of vegetation as follows:

$$Q_{wt} = P - I - T - E - \Delta S$$

Where:

Q_{wt} = drainage (positive value) beyond or water uptake (negative value) from the maximum depth of soil water measurement or the watertable, whichever is shallower

P = gross total precipitation

I = evaporation of water intercepted by plant canopies; calculated as the deficit between rainfall and the sum of throughfall (rain passing through the vegetation canopy and infiltrating into the soil) and stemflow (water that drains down the stem of the tree)

T = transpiration or water taken up by vegetation and evaporated from leaf surfaces

E = evaporation from the soil surface and any leaf litter

ΔS = change in soil water storage between two measurement periods.

All terms are converted to millimetres depth of water over the defined area of land.

Negative values of Q_{wt} indicate that the vegetation is satisfying some of its water requirements by taking up an additional source of water, potentially groundwater. In water-limited environments, those plants (taxa or individuals) that utilise groundwater are likely to have some competitive advantage over those that do not have access to groundwater.

Howe et al. (2005) developed a water-balance approach that considers historical rainfall records to estimate the probability that the soil water reservoir is sufficient to supply vegetation transpiration requirements in any particular year. The water balance is expressed as:

$$\Delta S = P - Q_{WS} - Q_{DS}$$

Where:

Q_{WS} = wet season water use

Q_{DS} = dry season water use

P = precipitation, and the dry season precipitation is assumed to be negligible.

The water-use terms include soil evaporation and understory transpiration.

The magnitude of the soil moisture storage is constrained according to:

$$0 \leq S \leq z_r \times PAWC$$

Where:

z_r = maximum rooting depth of the vegetation

PAWC = plant available water capacity of the soil (mm/m)

The water balance is calculated on an annual basis. The timing of groundwater dependence of vegetation is calculated where there is a deficit between plant water use and the soil water reservoir. Transpiration rates are the basis for calculating Q_{WS} and Q_{DS}.

Various instruments or techniques are used to either directly measure or estimate one or more of the terms in the water balance equation. Most are applied at a field-site scale. Some ground-based techniques for measuring surface evaporation (e.g. eddy covariance) provide measurements that are representative of up to a few hectares in area. Changes in soil moisture can be directly measured using neutron moisture meters, soil capacitance probes or gravimetrically or remotely via emerging technologies such as Gravity Recovery and Climate Experiment (GRACE) satellite data. Satellite imagery can be used to determine surface energy balances and evaporation at a range of scales, from site to regional, but must be supported by other field-site techniques for accurate estimation of groundwater use. Throughfall is measured directly at site with a series of troughs, and interception losses are calculated from the difference between precipitation and throughfall.

T8 Water balance - vegetation	
Analysis approach	Groundwater dependence is inferred where there is a deficit in the water balance between water inputs and outputs.
Limitations	• The tool is best suited to investigating groundwater dependency of specific vegetation in specific locations. Multiple field-measurement sites would be required for broader scale assessments. • Groundwater uptake is inferred from differences in relatively large numbers whose values incorporate a level of uncertainty and measurement error. These errors may mask groundwater uptake where rates are quite small; that is, low levels of groundwater uptake may not be detected by water-balance techniques because of measurement errors and uncertainty in the underlying values. Similarly, error propagation within the calculation of water balances may allow the inference of groundwater use where there is, in fact, none. • Multi-year measurement programs may be needed to detect groundwater use if plants or vegetation only use groundwater episodically (e.g. during prolonged dry periods when soil water reserves have been exhausted). A probabilistic approach is recommended in any water-balance approach. • The amount of groundwater used by vegetation, as indicated by water-balance modelling, is not necessarily the EWR. Additional work is required to estimate it.
Advantages	• Water-balance techniques are very applicable for terrestrial systems and some specific vegetation types such as broad-leaf eucalypt species. • Water-balance systems are most suited for site-scale applications.
Disadvantages	• Intensive sampling programs are often required to obtain the level of data precision required for these types of study. • Intensive sampling programs are usually very costly due to (extended) duration of observations required and the instrumentation involved. • Water balance techniques often require high level scientific and technical skills. • Time frames can be very long in order to properly characterise groundwater dependency. • Can be difficult to transpose site-scale results to larger scales because of high variability in catchment conditions. • Groundwater use is inferred by deduction of all other parameters in the water balance, not by direct measurement, and incorporates error inherent from measuring/estimating all other parameters.
Costs	Costs vary according to the level of confidence required: • To confirm use of groundwater: $25 000 to $50 000, with moderate to high confidence. • To determine the amount of groundwater use: $50 000 to $500 000, with low to high confidence. Costs do not include the purchase of instrumentation.
Specialist skills and resources	• Operation of the instruments used to measure water-balance components and to process and analyse the data obtained. • Understanding of the biophysical plant, soil and atmospheric processes involved in the water balance. • Significant financial resources for long-term or multi-site studies.

T8 Water balance - vegetation

Main data types required

Data	*Likely source(s)*
Daily and seasonal precipitation	Site weather station, Bureau of Meteorology records
Interception	Site measurements
Transpiration	Site measurements using sap flow techniques, ventilated chambers
Soil evaporation	Site measurements of below canopy rainfall and change in surface water content using mini-lysimeters
Surface evaporation (transpiration and soil evaporation)	Site measurements using micrometeorological techniques, energy balances (ground or satellite) or laser scintillometry, Bureau of Meteorology estimates of potential or actual evaporation, evaporation formulae
Soil water content	Site measurements using neutron probes, time or frequency domain reflectometry
Plant available water capacity (PAWC)	Soil matric potential, depth of vadose zone

Complementary tools

Tool may:	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14
provide inputs for		✓			✓		✓							✓
require outputs from	✓	✓	✓	✓	✓	✓	✓						✓	✓

T8 Water balance - vegetation	
Key references and Australian case studies	Cook PG, Hatton TJ, Eamus D, Hutley L and Pidsley D 1998, *Hydrological investigation at Howard East, N.T. 4. Executive summary and recommendations. CSIRO Land and Water Technical Report* 41/98. This document and its supporting technical documents outline a major water-balance study for a terrestrial vegetation community and a seasonal wetland in the Howard River catchment NT. The study identified that dry season water use by both communities was from stored soil water rather than groundwater. Benyon RG and Doody TM 2004 *Water use by tree plantations in south east South Australia,* CSIRO Forestry and Forest Products Technical Report No. 148. Report on water-balance studies of groundwater uptake by blue gum plantations in south-east South Australia. Useful description of water balance methods and their application. Howe P, Cook P, O'Grady A and Hillier J 2005, *Pioneer Valley Groundwater Consultancy Report 3 Analysis of Groundwater Dependent Ecosystem Water Requirements,* Department of Natural Resources and Mines, Queensland, April 2005. This report used a probabilistic water-balance approach to determine the likelihood of the soil moisture storage being able to supply the transpiration requirements of the vegetation, based on observed variations in annual rainfall over 100 years of record. The dependence of the vegetation on groundwater was estimated from the frequency with which the soil moisture storage was insufficient. Eamus D 2009, *Identifying groundwater dependent ecosystems. A guide for land and water managers*. Land & Water Australia, 15 pp. The report discusses field methods to evaluate the groundwater dependency of ecosystems. Recommendations for determinations based on the use of vegetation and hydrologic measurements are provided, including water balance calculations. The report discusses two simple case studies to illustrate the water balance approach. Benyon R G, Therveyanthan S and Doody TM 2006, Interactions between groundwater and tree plantations in south-eastern Australia, *Australian Journal of Botany*, 54:181–192. Whitley R, Zeppel M, Armstrong N, Macinnis-Ng C, Yunusa I and Eamus D 2008, A modified Jarvis-Stewart model for predicting stand-scale transpiration of an Australian native forest. *Plant and Soil*, 305: 35–47. The booklet is available at: *http://lwa.gov.au/files/products/innovation/pn30129/pn30129_1.pdf*.
Further information	SKM 2010, *Evapotranspiration measurement: informing water management in Australia,* Waterlines Report Series No 35, November 2010. Available at: *http://www.nwc.gov.au/www/html/2951-waterlines-no-35.asp?intSiteID=1*. O'Grady AP, Carter J and Holland K 2010, *Review of Australian groundwater discharge studies of terrestrial systems*, CSIRO Water for a Healthy Country, Canberra, 56. Reviews existing water-balance studies in Australia and explores this data for generalisations that can be used for estimating groundwater discharge in data poor areas.

T9 Stygofauna sampling

Description	Techniques available to observe, monitor and measure biological activity within the groundwater system		
Application to components of EWR studies		*Applicable*	*Level of certainty*
	Location, classification and basic conceptualisation	✓✓✓	✓✓✓
	Characterisation of groundwater reliance	✓✓✓	✓✓✓
	Characterisation of response to change		
	Monitoring and evaluation	✓✓✓	✓✓✓
Scale of measurement	Regional: ✓✓ Catchment: ✓✓✓ Site: ✓✓✓		
Principles	Measuring the presence and composition of communities of aquatic fauna that occur in groundwater (known as stygofauna), can be used to describe the biodiversity values of aquifer ecosystems. Based on ecological affinity, there are three broad types of stygofauna: stygoxene (accidentally or facultatively present in groundwater); stygophile (completes part of life cycle in groundwater); and stygobites (obligate inhabitant of groundwater throughout the life cycle).		
How the tool is applied in GDE assessments	Investigation of groundwater taxa can be undertaken to identify subsurface GDEs and/or, in the more advanced stages of GDE assessment, to understand the relationship of the ecosystem to the groundwater regime. Analysis approaches may involve survey, observation or monitoring and analysis of system response to change. In the subsurface environment, the presence of stygofauna demonstrates the presence of a GDE. In the hyporheic zone, the presence of stygofauna indicates groundwater upwelling.		
Analysis approach	Sampling stygofauna entails standard methods of field survey and a variable level of taxonomic skills, depending on whether taxa need to be identified on the basis of morphological similarity (morphotype) or to a family, genus or species level. Stygofauna can be sampled by plankton netting, pump-sampling, or trapping from wells and by pumping from piezometers in the hyporheic zone. Sampling of stygofauna can be undertaken at any time of the year; however, where groundwater inputs to a surface water system are suspected, recommended timing is the driest time of the year or late in a drought. Where trapping or sampling is undertaken, a first pass assessment as to the presence or absence of stygofauna can be made in the field through visual inspection (although this method does not account for microbial biota). Collected samples can be preserved in 100% ethanol for further laboratory analysis if required. Water quality variables should be recorded in the field at the time of faunal sampling, and water samples should be retained for nutrient and dissolved organic carbon (DOC) analysis. In the laboratory, stygofauna classification on the basis of morphotype can be sufficient for the purposes of GDE analysis. For more detailed assessments (e.g. biodiversity conservation) a higher level of taxonomic classification may be required and this can involve DNA analysis. Results of stygofaunal sampling can be represented spatially on the basis		

T9 Stygofauna Sampling		
	that the presence of stygobitic species in groundwater demonstrates the presence of a subsurface GDE. In the surface water environment, superimposing maps of stygofauna on potentiometric maps of a streambed will reveal matched occurrences with upwelling/outwelling zones.	
Limitations	• Gaps in taxonomic descriptions of many stygofauna. • The nature of groundwater dependence of many stygophiles is presently unknown.	
Advantages	• Provides direct evidence of ecosystem dependence on groundwater. • Stygofaunal sampling can be cost effective as it can be less expensive in comparison to other tools and does not require lengthy training of field staff.	
Disadvantages	• Site- and field-based method. Results can only be extrapolated to the catchment or regional scale after extensive field investigation.	
Costs	Where only a presence/absence of stygofauna is required, sampling and analysis is relatively cheap (<$1000 per site). Costs increase relative to the level of taxonomic identification required.	
Specialist skills and resources	• Taxonomic identification of aquatic fauna. • Sampling equipment and techniques.	
Main data types required	*Data*	*Likely source(s)*
	Sampling locations	Drilling records, bore locations, groundwater level records, water quality records
	Knowledge of taxa with strong dependence on groundwater	Literature, previous experience
	Presence and composition of stygofaunal assemblage	Field survey

Complementary tools

Tool may:	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14
provide inputs for		✓								✓			✓	
require outputs from		✓								✓	✓	✓	✓	✓

T9 Stygofauna Sampling

Key references and Australian case studies	Tomlinson M and Boulton AH 2010, 'Ecology and management of subsurface groundwater dependent ecosystems in Australia – a review', *Marine and Freshwater Research*, 61:936–949. Discusses the state of knowledge, research needs and management implications of the stygofauna in Australia. Hancock PH and Boulton AJ 2009, 'Sampling groundwater fauna: efficiency of rapid assessment methods tested in bores in eastern Australia', *Freshwater Biology*, 54: 902–917. This paper compares sampling methods and makes recommendations for sampling program design. Tomlinson M and Boulton AH 2008, *Subsurface Groundwater Dependent Ecosystems: a review of their biodiversity, ecological processes and ecosystem services,* Waterlines Occasional Paper No 8, October 2008. Reviews knowledge of the biodiversity, ecological processes and ecosystem services of subsurface GDEs in Australia and identifies research directions. Tomlinson M, Boulton A J, Hancock PJ and Cook PG 2007, 'Deliberate omission or unfortunate oversight: should stygofaunal surveys be included in routine groundwater monitoring programs?', *Hydrogeology Journal*, 15:1317–1320. Provides a background to stygofauna in Australia and presents a staged approach to stygofaunal sampling. Boulton AJ 2001, 'Twixt two worlds: Taxonomic and functional biodiversity at the surface water/groundwater interface. *Rec. West. Aust. Mus. (Suppl.)*, 64: 1–13. Reviews published literature on the fauna of the hyporheic zone of Australia's rivers and draws on overseas research to explore functional significance. Boulton AJ and Hancock PJ 2006, 'Rivers as groundwater dependent ecosystems: degrees of dependency, riverine processes, and management implications', *Australian Journal of Botany*, 54(2):133–144. Explores the functional dependency of river base flow systems on groundwater at channel reach, catchment, and landscape (regional) scales. Assesses hydrological, physical, chemical, and biological features of groundwater dependency and gives examples of direct and indirect effects of these features on the aquatic ecology of surface streams and rivers. Georges A, Webster I, Guarino E, Thoms M, Jolly P and Doody S 2002, 'Modelling dry season flows and predicting the impact of water extraction on a flagship species', *Final Report for Project ID 23045*. Applied Ecology Research Group and CRC for Freshwater Ecology, University of Canberra, Canberra. A study that demonstrated springs create environments of relatively stable temperature where they discharge directly through the bed of the river, creating favourable nesting sites for the endangered pig-nosed turtle. Lategan MG, Korbel K and Hose GC 2010, 'Is cotton-strip tensile strength a surrogate for microbial activity in groundwater?', *Marine and*

	Freshwater Research, 61: 351–356. Discussed the ability of cotton strips to be used as a proxy for microbial activity in groundwater. Tomlinson M and Boulton A 2008, *Subsurface groundwater dependent ecosystems: a review of their biodiversity, ecological processes and ecosystem services*, National Water Commission Waterlines Occasional Paper No. 8, October 2008. This report summarises what is known about biodiversity in groundwater, the ecological processes in groundwater environments and the ecosystem goods and services provided by subsurface groundwater-dependent ecosystems in Australia. Available at: *http://www.nwc.gov.au/www/html/398-waterlines-8.asp?intSiteID=1* (Note that this paper has been updated and published as Tomlinson M, Boulton AJ 2010, ‘Ecology and management of subsurface groundwater dependent ecosystems in Australia: a review’, *Marine and Freshwater Research*, 61:1–14. University of New South Wales – Groundwater dependent eco-systems studies at Maules Creek. This page describes a project where field study of stygofauna in alluvial aquifers, the hyporheic zone and riparian zone is being used to increase understanding of these GDEs. Available at: *http://www.connectedwaters.unsw.edu.au/technical/research/projects/projects_maules.html*.
Further information	Groundwater fauna – State of the Environment 2006. This page provides a brief introduction to stygofauna. Available at: *http://www.environment.gov.au/soe/2006/publications/emerging/fauna/index.html*. PASCALIS (Protocols for the Assessment and Conservation of Aquatic Life In the Subsurface) Project. PASCALIS is a research project supported by the European Commission to investigate subsurface ecology. The project website hosts summaries of project tasks and milestone and links to relevant literature. Available at: *http://www.pascalis-project.com/*.

T10 Evaluation of groundwater–surface water interactions

Description	Analysis of the hydraulics of groundwater – surface water interactions. The processes by which groundwater discharges into a surface water system provides insight into the nature of groundwater dependency in wetlands, baseflow river ecosystems and in the marine environment.

Application to components of EWR studies

	Applicable	*Level of certainty*
Location, classification and basic conceptualisation	✓✓✓	✓✓✓
Characterisation of groundwater reliance	✓✓✓	✓✓✓
Characterisation of response to change	✓✓	✓✓
Monitoring and evaluation	✓	✓

Scale of measurement	Regional: ✓✓	Catchment: ✓✓✓	Site: ✓✓✓

Principles

Groundwater – surface water interactions are governed by hydraulic principles relating to the relative level of the two water 'bodies'. Components of the hydraulic system are evaluated to establish the timing, direction and volume of water movement. This establishes the extent to which a surface water body is supported by groundwater. Groundwater dependence of aquatic and fringing ecosystems is established where the surface water body is either continuously or intermittently supported by groundwater discharge.

Groundwater – surface water hydraulics can be applied at scales ranging from individual sites to entire regions.

How the tool is applied in GDE assessments

Local scale application

The detailed analysis of the hydraulic relationship between surface water and groundwater systems is most valuable when applied at a site scale, given that appropriate piezometer networks are available. Manual or, preferably, high frequency automated monitoring of surface water and groundwater levels provide the critical information for establishing the hydraulic linkages and direction of water movement. High frequency monitoring enables short term responses to barometric pressure changes and rainfall events to be captured for analysis. Supporting information on aquifer properties (e.g. hydraulic conductivity) and the degree of connectivity of the aquifer and surface water body is also required. Piezomanometers (Boulton 1993; Kennedy et al. 2007), and seepage meters (Rosenberry 2005) can also be used in lieu of or complementary to piezometer networks.

Regional scale application

Catchment and regional scale analyses require data on bed level and stage height along drainage lines and/or across wetland systems and tidal levels in the marine environment. Water levels in streams would typically be provided from stream gauging and topographic data. Hourly sea level data is available for 16 sites around Australia (hosted by BOM; *http://www.bom.gov.au/oceanography/projects/abslmp/data/index.shtml*). Similar data would be required for wetlands, although water level data are often lacking for these types of sites. Provided there is good topographic information around the wetlands' margins, water elevation can be estimated from air photos or other remotely sensed images.

Regional groundwater data would be sourced through existing hydrogeological mapping or records from groundwater observation bore networks.

If regional groundwater data are absent or sparse, assessments of the nature of groundwater and surface water interactions can be made interpreting hydrogeomorphologic conditions (geology, soils, topography) and there are developed methodologies to classify the nature of interactions along stream sections (see Parsons et al. 2008 and Ivkovic 2009).

The same type of 'specialist' assessment can also be made with respect to regional patterns in groundwater surface water interactions based on the position of waterbodies within a landscape (see Webster et al. 1996; Smith and Townley 2002).

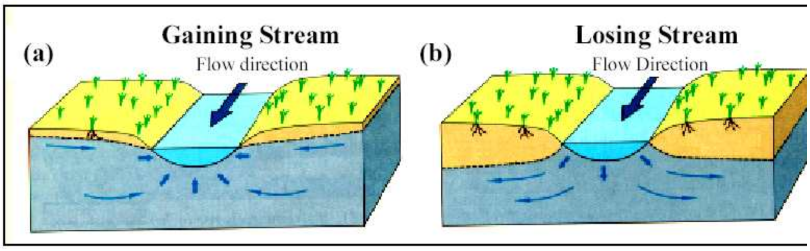
Baseflow separation

Baseflow separation is a rapid assessment tool for determining the contribution of (groundwater derived) baseflow to total stream flow in rivers. Baseflow is estimated from daily stream flow data from unregulated streams. The method is not reliable in regulated streams. This technique has also been extrapolated to the marine environment (e.g. Burnett et al. 2006).

Analysis approach

Groundwater – surface water hydraulics

The relative elevation of groundwater and surface water indicates the direction of water movement and whether or at what times groundwater contributes to the surface water body. For example, if the watertable or groundwater level in an aquifer is higher than the running level in a stream, groundwater will flow or discharge to the stream. In this case the stream is defined as a 'gaining stream'. If the watertable or groundwater level is lower than the running level in a stream, water will flow from the stream and recharge the groundwater. In this case the stream is defined as a 'losing stream'. Some parts of a stream may be gaining and others may be losing, and this may change over time. Provided other data on aquifer properties are available, flow volumes may be estimated using flow nets and analytical equations based on Darcy's law.



From Winter et al., 1998

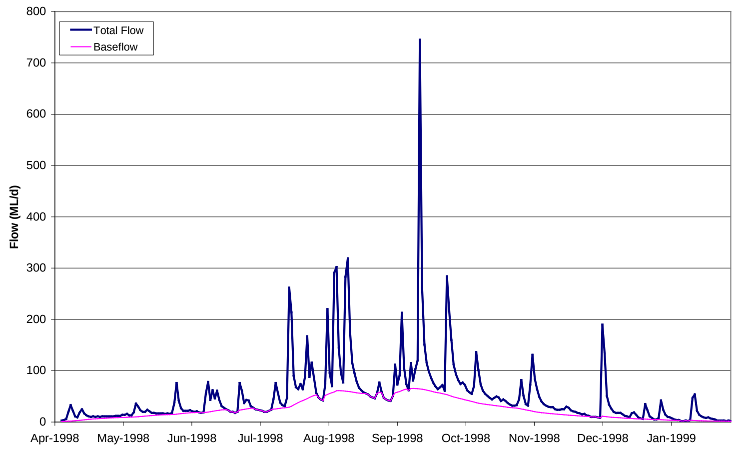
Information on groundwater and surface water hydraulics may also be used to construct two- or three-dimensional models (T14) that would provide further insight into groundwater – surface water interactions. They would provide estimates of groundwater contribution to surface water bodies and help to explore the impact of changes in the groundwater management regime.

Baseflow separation

The simplest method of baseflow separation involves using graphical methods to produce a baseflow hydrograph from daily stream flow data. In general, the shape of the baseflow hydrograph can be characterised by:

- continued baseflow recession after the rise of the total hydrograph due to the initial outflow from the stream into the adjacent stream banks
- baseflow peaking after the total hydrograph due to the storage-routing effect of the subsurface stores
- baseflow recession following an exponential decay function

- baseflow hydrograph rejoining the total hydrograph as direct runoff ceases.



Example baseflow hydrograph – baseflow in pink (after Nathan & McMahon, 1990).

Various mathematical techniques may be used to automate baseflow separation. Even the most sophisticated baseflow separation techniques are constrained by the need to identify the point at which surface runoff is assumed to cease. Regardless of the technique applied, baseflow estimates may include interflow during periods when stream flow is receding and overestimate the true baseflow component.

Limitations

- By itself, the tool only provides information on the contribution of groundwater to a surface water body. It provides limited information on the dependency of surface water ecosystems and does not directly indicate the EWR.
- Use of the tool relies on there being surface water level and groundwater monitoring in place in appropriate locations.
- Depends on accuracy of elevation data of piezometers and surface water levels and should consider the variation in gradient between surface water and the aquifer over time.
- To determine flux, hydraulic parameters of stream or seabeds, aquifers and aquitards are required and these may be unavailable or characterised by high levels of uncertainty.

Advantages

- Groundwater – surface water hydraulics can be applied at a variety of scales ranging from individual sites to entire regions. The technique is most valuable when applied at a site or catchment scale, when appropriate/targeted monitoring is in place.
- This technique is highly suited for systems dominated by groundwater discharge.

Disadvantages

- The larger-scale projects require longer time frames and greater costs. Monitoring needs to be targeted.

Costs

Total cost will vary with the scale at which the tool is applied and the comprehensiveness of groundwater and surface water monitoring. Estimated costs are:

Conceptualisation and analysis: $30 000 to $100 000, depending on data availability and required scale.

Specialist skills and resources

- Groundwater and surface water hydrology and their interactions.
- Construction and operation of surface water and groundwater monitoring infrastructure.
- Hydrologic data management and analysis.

T10 Evaluation of groundwater-surface water interactions

Main data types required

Data	*Likely source(s)*
Surface water levels in streams, wetlands and the marine environment	Site measurements—from stream gauges and water level recorders, remotely sensed images of wetland shorelines.
Elevation of streams or wetlands	Topographic surveys, digital elevation models, maps
Aquifer properties	Published reports of the same location or similar geologies, site investigations

Complementary tools

Tool may:	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14
provide inputs for		✓							✓		✓	✓		✓
require outputs from		✓									✓			✓

Key references and Australian case studies

Bonte M and Howe P 2004, 'Combining traditional hydrogeological approaches with tracer methodologies in the assessment of salt accession processes to the Gurra Gurra Wetland Complex, South Australia', *9th Murray–Darling Basin Groundwater Workshop*.

Provides a case study of various tools that can be effectively employed in estimating rates of groundwater inflow to surface water bodies, one of which includes flow net modelling.

Burnett W C, Aggarwal PK, Aureli A, Bokuniewicz H, Cable J E, Charette MA, Kontar E, Krupa S, Kulkarni KM, Loveless A, Morre WS, Oberdorfer JA, Oliveira J, Ozyurt N, Povinec P, Privitera AMG, Rajar R, Ramessur RT, Scholten J, Stieglitz T, Taniguchi M and Turner JV 2006, 'Quantifying submarine groundwater discharge in the coastal zone via multiple methods', *Science of the Total Environment*, 367:498–543.

Summarises case studies and tools trialled for estimating submarine groundwater discharge undertaken at various locations around the world, including a study in Cockburn Sound, Western Australia. Methods employed include seepage meters, naturally occurring environmental tracers, hydrograph separation, water balance and numerical modelling approaches.

Sophocleous M 2002, 'Interactions between Groundwater and Surface Water: The State of the Science', *Hydrogeology Journal*, 10:52–67.

Mechanisms of interactions between groundwater and surface water as they affect recharge–discharge processes are comprehensively reviewed.

Braaten R and Gates G 2003, 'Groundwater – surface water interaction in inland New South Wales: A scoping study', *Water Science & Technology*, 48(7): 215–224. Selected Proceedings of the 5th International River symposium, held in Brisbane, Australia, 3–6 September 2002.

Report investigates the hydraulic connection between rivers and aquifers in New South Wales and demonstrates that in highly connected reaches of the Murrumbidgee River losses and/or gains are closely related to groundwater levels.

Winter TC, Harvey JW, Franke OL and Alley WM 1998, *Ground Water and Surface Water. A Single Resource,* U. S. Geological Survey Circular 1139.

Presents current understanding of how natural processes and human activities affect ground water-surface water interaction as well as limitations in our knowledge and ability to characterise them.

Nathan RJ and McMahon TA 1990, 'Evaluation of automated techniques for base flow and recession analyses', *Water Resources Research*, 26(7):1465–1473, July 1990.

Provides a description and application of the recursive digital filter method for undertaking baseflow analysis.

Jolly ID and Rassam DW 2009, 'A review of modelling of groundwater-surface water interactions in arid/semi-arid floodplains', *18th World IMACS / MODSIM Congress*, Cairns, Australia 13–17 July 2009.

Provides a summary the advances that have been made in saturated zone, unsaturated zone and combined modelling methods.

Watt J and Khan S 2006, 'Do surface and groundwater interactions matter in irrigation sustainability?'

Describes a rapid assessment technique for irrigation studies, developed to enable managers to understand where groundwater-surface water interactions occur and what volumes of water are being exchanged. Available at: *http://www.csu.edu.au/research/icwater/publications/online-articles/docs/06WATTJacqueline.pdf*.

GHD 2010, *Groundwater and surface water interactions in the fractured rock areas of the south-west of Western Australia,* A report to Land and Water Australia and South West Development Commission.

Project undertaken as part of the National Program for Sustainable Irrigation to undertake investigations into surface water and groundwater interactions in the Wilyabrup and Warren Pemberton agricultural regions. Review of common methods used for investigating surface water and groundwater interactions. Available at: *http://lwa.gov.au/files/products/national-program-sustainable-irrigation/npsi510/groundwater-and-surface-water-interactions-fractur_0.pdf*.

Banks E 2010, *Groundwater – surface water interactions in the Cox, Lenswood and Kersbrook Creek catchments, Western Mount Lofty Ranges, South Australia*, Technical Report DFW 2010/19.

The investigation involved the analysis of hydrochemical indicators in a large number of groundwater and surface water samples from the Cox, Lenswood and Kersbrook Creek catchments. The hydrochemical indicators were used in conjunction with stream flow measurements and water level data from existing databases to determine where surface water and groundwater resources are connected. Available at: *http://www.skmconsulting.com/Knowledge-and-Insights/Technical-Papers/Tech-Paper-Baseflow-Analysis-as-a-Tool-for-Groundwater.aspx*.

Boulton AJ 1993, 'Stream ecology and surface-hyporheic exchange: Implications, techniques and limitations', *Australian Journal of Marine and Freshwater Research*, 44:553–564.

Discusses use of piezomanometers in groundwater – surface water interaction assessments.

Kennedy CD, Genereux DP, Corbett DR and Mitasova H 2007, 'Design of a light-oil piezomanometer for measurement of hydraulic head differences and collection of groundwater samples', *Water Resources Research*, 43: W09501.doi:10.1029/2007WR00590.

Rosenberg DO 2005, 'Integrating seepage heterogeneity with the use of ganged seepage meters', *Limnology and Oceanography: Methods*, 3: 131–142.

Ivkovic KM 2009, 'A top-down approach to characterise aquifer-river interaction processes', *Journal of Hydrology*, 365:145–155.

Parsons S, Evans R and Hoban M 2008, *Surface-groundwater connectivity assessment. A report to the Australian Government from the CSIRO Murray–Darling Basin Sustainable Yields project,* CSIRO, Canberra, 35 pp.

Webster KE, Kratz TK, Bowser C J, Magnuson JJ and Rose WJ 1996, 'The influence of landscape position on lake chemical responses to

drought in northern Wisconsin', *Limnology and Oceanography*, 41:977–984.

Smith AJ and Townley LR 2002, 'Influence of regional setting on the interaction between shallow lakes and aquifers', *Water Resources Research*, 38: 1170, doi:10.1029/2001WR000781.

Further information

REM 2007, *Impacts of groundwater-affecting activities on baseflow variability and ecological response: Scoping study*, report prepared for Land and Water Australia, 22 May 2007.

This study assesses the contribution of baseflow to selected rivers and the impact that 'groundwater affecting activities' may have on baseflow dependent ecosystems.

Brodie R, Sundaram B, Tottenham R, Hostetler S and Ransley T 2007, *An overview of tools for assessing groundwater-surface water connectivity,* Bureau of Rural Sciences, Canberra. Available at: *http://adl.brs.gov.au/brsShop/data/assessinggroundwatersurfacewaterconnectivity.pdf*.

Evans R 2007, *The effects of groundwater pumping on stream flow in Australia. Technical report*. Based on the Land & Water Australia Senior Research Fellowship Report by Dr Richard Evans, Principal Hydrogeologist, Sinclair Knight Merz. Available at: *http://www.mdba.gov.au/files/sdl-submissions/Submission%2069%20-%20Attachment%2015%20-%20Maria%20Riedl%20-%20VIC.pdf*.

The 'Connected Water' website, maintained by the Bureau of Rural Sciences contains further information regarding the connectivity of surface and groundwater. Available at: *http://www.connectedwater.gov.au/framework/investigate_assess.html*.

Further information on conceptualisation of surface water – groundwater connectivity is available from the Connectivity guidelines developed by the National Water Commission *http://www.nwc.gov.au/www/html/7-home-page.asp*.

T11 Environmental tracers

Description	Environmental tracers are physical or chemical properties of water, or any substance dissolved in water, that can be used to identify the origin or the age of groundwater. Environmental tracers can be used to identify groundwater contribution to dependent ecosystems.

Application to components of EWR studies

	Applicable	*Level of certainty*
Location, classification and basic conceptualisation	✓✓✓	✓✓✓
Characterisation of groundwater reliance	✓✓✓	✓✓
Characterisation of response to change	✓	✓✓
Monitoring and evaluation	✓✓✓	✓✓

Scale of measurement

Regional: ✓✓ Catchment: ✓✓✓ Site: ✓✓✓

Principles

Aquifers and surface water environments are subject to different physical, geochemical and biological conditions, often resulting in marked differences in temperature, salinity and other properties between surface water and groundwater. These properties, or environmental tracers, can be used for a number of purposes in GDE studies, including to:

- identify if and where groundwater discharge occurs in a surface water body
- estimate the proportion of different sources of water in a given water body
- estimate the age and velocity of groundwater
- quantify the groundwater flux to a surface water body.

How the tool is applied in GDE assessments

Most environmental tracers are only useful for specific tasks. For example, salinity can be used to evaluate mixing between different sources of water but is usually not suitable for dating groundwater. For a given task, the choice of tracer is also context-specific. For example, the different groundwater-dating environmental tracers are usually only applicable over a specific age-range. Thus, some prior conceptual knowledge of the groundwater system studied is required in order to select the best set of environmental tracers for a specific problem.

Temperature

The temperature of groundwater does not fluctuate widely throughout the year and is a particularly useful tool for identifying discreet discharge to water bodies. A river or wetland with a major groundwater component may exhibit less seasonal variability or spatial variability than a river or wetland fed entirely by surface runoff. The occurrence of mixing may also be identified through zones of differing surface water temperature which may indicate groundwater discharge.

Dissolved oxygen

Dissolved oxygen is a measure of the concentration of gaseous oxygen in an aqueous solution. Dissolved oxygen concentration in a water body is affected by a range of factors including salinity, altitude, water temperature, stratification, biological activity (respiration and photosynthesis) and the rate of groundwater inflow. Of these variables, temperature most directly affects the dissolved oxygen concentrations in wetlands and rivers. Groundwater, which has little contact with the atmosphere, can have a lower oxygen concentration relative to nearby surface water. In such cases, when groundwater discharges to a wetland or river system, the dissolved oxygen concentrations are initially lower near the discharge point.

pH

The pH of different water sources can vary markedly. Hence, the presence of comparatively higher or lower zones within or around a surface water body may be an ‘indicator’ of groundwater discharge.

Total dissolved solids / Electrical conductivity / Salinity

In instances where the salinity of surface water and groundwater differ sufficiently, the measurement of total dissolved solids (TDS) may be used to identify zones of mixing between the two water types. For example, zones of comparatively high surface water salinity along a particular reach of a river may represent areas of high salinity groundwater discharging as baseflow. Electrical conductivity is often used as a surrogate for TDS and/or salinity but the relationship breaks down at very high salinities and when the ionic composition is not like that of seawater.

Major ions

The calculation and analysis of major ion ratios (e.g. Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, CO_3^{2-}/HCO_3^{-}, SO_4^{2-}) can assist in interpreting surface water – groundwater mixing relationships. The analysis requires that the composition of groundwater and surface water contrast sufficiently that they and the mixing product may be identified. A conservative ion (a relatively non-reactive ion; e.g. chloride) may also be used to indicate mixing or to estimate the proportion of mixing, and ratios of chloride to the major ions can be useful to determine hydrochemical trends.

Stable isotopes

Stable isotopes of hydrogen, oxygen, carbon, nitrogen, and sulfur can be valuable tools for investigating groundwater – surface water interactions. In particular, the stable isotope ratios of hydrogen ($^{2}H/^{1}H$) and oxygen (usually $^{18}O/^{16}O$) in the water molecule are widely used. While stable isotope ratios of water are relatively conservative in aquifers, evaporation can cause changes in concentrations in surface water that will need to be considered.

In general, if the isotopic signatures of the groundwater and surface water are sufficiently distinct, the proportion or rate of groundwater flow to a river or wetland system can be calculated by way of a mixing ratio or mass balance approach.

Radionuclides

Most aquifer materials contain small quantities of heavy radioelements, in particular uranium-235, uranium-238 and thorium-232. Several decay products from these elements (in addition to these elements themselves) are useful environmental tracers in hydrogeology. These include the four radioisotopes of radium (Ra-223, Ra-224, Ra-226 and Ra-228, or the ‘radium quartet’), the radioactive noble gas radon-222, and the stable gas helium-4. Because of greater contact time with geological materials, groundwater is usually more enriched in these various decay products than nearby surface waters. Radon-222 and the radium quartet have been used to identify areas of groundwater discharge and, using more detailed mass-balance analyses, the magnitude of groundwater discharge. Helium-4 accumulates in groundwater at the millennia or greater timescale and is a marker for old regional groundwater (such as Great Artesian Basin groundwater).

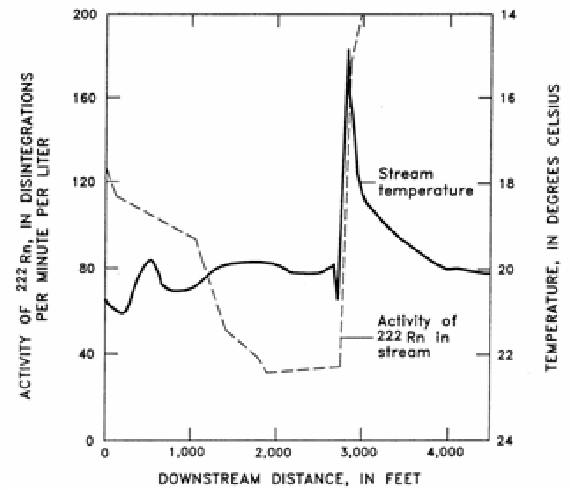
Naturally occurring and anthropogenic tracers for groundwater dating

The concentration of naturally occurring (^{14}C, ^{36}Cl, ^{4}He) and anthropogenic chlorofluorocarbons (CFCs) and sulfur hexafluoride (SF_6) tracers can provide information regarding groundwater age and thus information about rates of recharge and replenishment. The tracer used is dependent on the expected age range of the groundwater system under examination.

Analysis approach

Salinity, temperature, dissolved oxygen and pH

The salinity, temperature, dissolved oxygen and pH data will typically be monitored over a period of time at a particular site or at regular intervals along a river or stream. The time and spatial series data can be plotted graphically to enable the analysis of trends, comparison between the two water types, and identification of mixing points and relationships. The analysis is improved if seasonal data can be collected. This enables the contrast and comparison of source water for differing stress conditions. An example of the use of temperature to identify groundwater inflow points is illustrated below.



From Lee and Hollyday (1993)

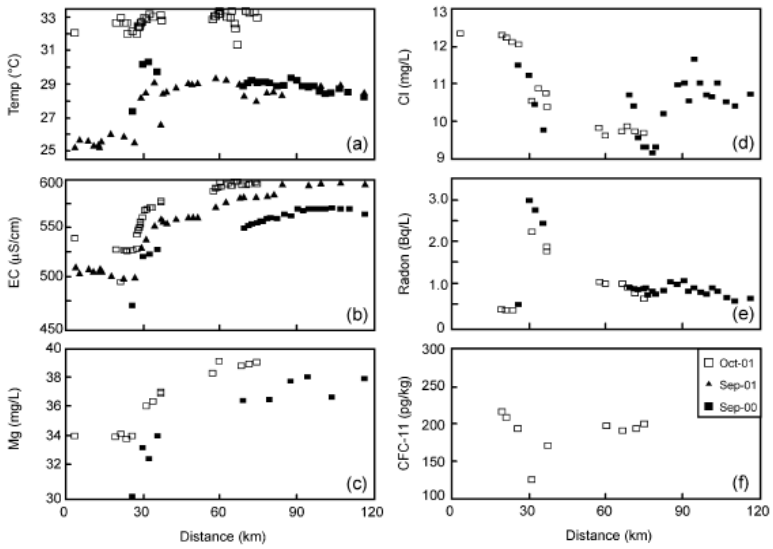
Stream temperature was measured over a 0.75-mile (~1.3 km) reach of Carters Creek, Tennessee, USA. A major point of groundwater inflow is apparent at 2900 feet (~885 m) from a sudden decrease in water temperature. This also coincides with an increase in radon activity (see T12).

Major ions

Water sampled at spatial intervals along a river or stream may be analysed and major ions plotted to identify groundwater discharge to a stream, as in the figure below. In this case Cook et al. (2003) measured radon and major ion chemistry along a 120 km section of the Daly River, Northern Territory. Locations of major points of groundwater inflow were apparent from increases in radon activity and from changes in ion concentrations. Using a simple model, they were able to use the data to quantify rates of groundwater inflow along the length of the river.

Chloride is a conservative ion; that is, it does not readily substitute for other anions (i.e. limited water–rock interaction) and may therefore be used in mass balance calculations concerning the mixing of surface water and groundwater. For example, by measuring the concentration of chloride in river water and groundwater (as baseflow), together with the rate of river flow, the rate of baseflow discharge to the stream may be determined by way of a simple mass balance.

Major ion ratios may also be viewed as Piper or Durov diagrams. The diagrams are constructed by calculating the relative concentrations of three cations and three anions (expressed in milliequivalents). Typically, Ca^{2+}, Mg^{2+} and Na^{+} are the cations, and Cl^{-}, HCO_3^{-}, SO_4^{2-} are the anions, although other combinations may be useful for different types of studies. The hybrid water samples (representing mixtures of the two waters) plot between these two end members (groundwater and surface water).



From Cook et al. (2003)

Stable isotopes of water

Most of the world's precipitation originates from the evaporation of seawater. As a result, the δ^{18}O and deuterium composition of precipitation throughout the world is linearly correlated and distributed along a line known as the 'meteoric water line'. The δ^{18}O and deuterium composition of a water sample relative to the meteoric water line, and to the composition of waters from other areas, provides a record of the source and evaporative history of the water. It can therefore be used as a tracer of the movement of surface water.

The proportion or rate of groundwater inflow to a surface water system may be estimated by applying an isotope mixing analysis or a mass balance approach.

Radon and radium

Radon and radium are typically higher in groundwater due to water–rock interactions than in surface water systems. Therefore, elevated radon and radium in rivers, wetlands and the marine environment are attributed to groundwater discharge.

The interpretation of radon-222 and the radium quartet data can be qualitative or quantitative. For qualitative use (such as identifying areas of groundwater discharge along a river reach), the key limitation is to define the signatures for different groundwater and surface water end members. For quantitative use (such as measuring the groundwater flux along a river reach), additional measurements may be required. For example, in the case of radon-222 in rivers, degassing removes while hyporheic exchange adds radon to surface water.

Naturally occurring and anthropogenic tracers for groundwater dating

Groundwater can be dated on the basis of one or more measurements, provided conditions are favourable (some tracers are unsuitable in some areas) and the appropriate tracer is used. CFCs and SF_6 are most useful for young groundwater (post-1970s recharge); ^{14}C for groundwater recharged between 50 and 40 000 years before present; and ^{36}Cl can be used to date groundwater with residence times of up to 1 000 000 years. Helium-4 has no upper time limit because it gradually accumulates in groundwater over geological timescales. However, several thousand years are required before significant helium-4 concentrations start to accumulate in groundwater.

Geophysical methods: salinity

Where the salinity of inflowing groundwater is different to that of runoff-

	generated surface water, resistivity or electromagnetic (EM) geophysical techniques may be used to identify points of groundwater discharge. The survey technique is deployed along the targeted length of river or wetland and the conductivity distribution of sediments under the surface water body is determined. These may then be related to points of saline groundwater discharge.
Limitations	• Different sources of water may have the same environmental tracer signature. Therefore, a suite of environmental tracers is usually monitored to characterise potential sources of water contributing to a surface water body. • Surface water temperature is affected by a number of factors, including season, time of day and shading. • The environmental tracer signature for all sources of water contributing to a given GDE must be characterised, which can be difficult. • Whilst useful as an 'indicator', water temperature cannot usually be used as a quantitative tool. • Limited usefulness in intermittent and ephemeral systems because long water residence times can significantly change the environmental tracer signature of the source water. • Requires strategically placed groundwater observation bores for high reliability. • Quantification of flows requires modelling and high level of expertise. • Although they can be used to estimate groundwater contribution to a GDE, environmental tracers are only a path towards establishing the EWR. • Quantitative interpretation of environmental tracers sometimes requires a significant investment in ancillary measurements.
Advantages	• Data may already be available from routine monitoring activities or previous studies. • A good tool for identifying locations of groundwater influx to surface water systems. • Can be a rapid assessment approach, particularly if using temperature and EC. • Environmental tracers allow identification and quantification of groundwater inputs to surface water systems where hydraulic approaches might otherwise fail, such as where the subsurface stratigraphy may be complex or poorly constrained, or where physical hydrometric data is unavailable. • Environmental tracers can provide an independent means to calibrate regional groundwater models and improve their reliability to predict impact of groundwater management on GDEs.
Disadvantages	• Water chemistry methods may only provide 'snapshot in time' outcomes for the period over which water sampling is undertaken. To account for seasonal or other temporal changes, multiple field campaigns must be undertaken. • Application can be field extensive and consequently expensive. • Results from either direct measurement or geophysical methods may not provide definitive assessment in isolation and may require inputs from other methods such as hydrogeological modelling.
Costs	Total cost per survey depends on the river length or wetland area studied and the number of samples taken and analysed. For a small-scale investigation (~ 2km reach) costs may range from $20 000 to $50 000. Larger scale investigations may cost up to $150 000. These cost estimates assume that groundwater monitoring bores are already appropriately located.

Direct measurement

Total cost will vary according to the number of samples taken. Estimated costs for sampling are $15 000 to $25 000. Data analysis and interpretation may range from $20 000 to $40 000.

Geophysical methods

Total cost will vary depending on the geophysical methods chosen. Indicative costs for NanoTEM are $2000 per 10 km river stretch, not including mobilisation.

Specialist skills and resources

- Rigorous water sampling and analytical laboratory protocols.
- Measurement of physical properties of water.
- Interpretation of measured parameters.
- Sound understanding of aquifer systems.
- Laboratory analysis of water samples.

Main data types required

Data	*Likely source(s)*
Water temperature, pH and dissolved oxygen	Site measurements, existing data may be available online
Total dissolved solids and major ions	Laboratory analysed water samples, water authorities and government managed databases
Stable isotopes and radioisotopes	Laboratory analysed water samples

Complementary tools

Tool may:	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14
provide inputs for				✓	✓				✓	✓		✓	✓	
require outputs from										✓		✓		✓

Key references and Australian case studies

Stieglitz TC, Cook PG and Burnett WC 2010, 'Inferring coastal processes from regional-scale mapping of ^{222}Radon and salinity: examples from the Great Barrier Reef Australia', *Journal of Environmental Radioactivity*, 101: 544–552.

In this study, concurrent mapping of radon and salinity allowed efficient, qualitative assessment of land–ocean processes, including submarine groundwater discharge.

Burnett WC, Aggarwal PK, Aureli A, Bokuniewicz H, Cable JE, Charette M A, Kontar E, Krupa S, Kulkarni KM, Loveless A, Morre WS, Oberdorfer JA, Oliveira J, Ozyurt N, Povinec P, Privitera AMG, Rajar R, Ramessur RT, Scholten J, Stieglitz T, Taniguchi M and Turner JV 2006, 'Quantifying submarine groundwater discharge in the coastal zone via multiple methods', *Science of the Total Environment*, 367: 498–543.

Summarises case studies and tools trialled for estimating submarine groundwater discharge undertaken at various locations around the world, including a study in Cockburn Sound, Western Australia. Radon and radium measurements were used to quantify groundwater discharge to the marine environment.

Lamontagne S, Le Gal La Salle C, Hancock GJ, Webster IT, Simmons CT, Love AJ, James-Smith J, Smith AJ, Kämpf J and Fallowfield HJ 2008, 'Radium and radon radioisotopes in regional groundwater, intertidal groundwater, and seawater in the Adelaide Coastal Waters Study area: Implications for the evaluation of submarine groundwater discharge', *Marine Chemistry*, 109:318–336.

Case study for the application of the radium quartet to estimate submarine groundwater discharge to a coastal area.

Cook PG, Wood C, White T, Simmons CT, Fass T and Brunner P 2008, 'Groundwater inflow to a shallow, poorly mixed wetland estimated from a mass balance of radon', *Journal of Hydrology*, 354:213–226.

Provides a case study of how ^{222}Radon can be used to determine groundwater inputs into a shallow wetland.

Cook PG, Lamontagne S, Berhane D and Clarke JF 2006, 'Quantifying groundwater discharge to Cockburn River, south-eastern Australia, using dissolved gas tracers ^{222}Rn and SF_6', *Water Resources Research*, 42 (10): 12pp W10411 doi:10.1029/2006WR004921.

Provides a case study of how ^{222}Radon, in combination with injected SF_6, can be used to delineate groundwater inputs to a stream.

Bonte M and Howe P 2004, 'Combining traditional hydrogeological approaches with tracer methodologies in the assessment of salt accession process to the Gurra Gurra Wetland Complex, South Australia', *9th Murray-Darling Basin Groundwater Workshop*.

Provides a case study of various tools that can be effectively employed in estimating rates of groundwater inflow to surface water bodies, including comparison between results of water chemistry and other tools.

Cook P G, Favreau G, Dighton J C and Tickell S 2003, 'Determining natural groundwater influx to a tropical river using radon, chlorofluorocarbons and ionic environmental tracers', *Journal of Hydrology*, 277: 74–88.

Measurements of ^{222}Radon, CFC-11, CFC-12, major ions and temperature of river water and springs are used to quantify rates of groundwater inflow to a tropical lowland river in the Northern Territory of Australia.

Andersen MS and Acworth RI 2009, 'Stream-aquifer interaction in the Maules Creek catchment, Namoi Valley, New South Wales, Australia', *Hydrogeology Journal*, 17: 2005–2021.

Temperature and the electrical conductivity distributions are used to identify zones of groundwater discharge in this ephemeral to quasi-perennial stream.

Lamontagne S, Herczeg AL, Dighton JC, Pritchard JL, Jiwan, JS and Ullman WJ 2003, *Groundwater – surface water interactions between streams and alluvial aquifers: Results from the Wollombi Brook (NSW) study (Part II – Biogeochemical processes)*, CSIRO Land and Water Technical Report 42/03, July 2003.

Provides some basic understanding on how groundwater – surface water interactions can impact on the load of nutrients to surface water in subtropical catchments.

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Further information

The 'Connected Water' website, maintained by the Bureau of Rural Sciences, contains further information regarding the use of water chemistry in surface water and groundwater studies. Available at: *http://www.connectedwater.gov.au/framework/hydrochemistry.html*.

Hatch M, Fitzpatrick A, Munday T and Heinson G 2007, 'An assessment of "in-stream" survey techniques along the Murray River, Australia', presented at the *Australian Society of Exploration Geophysicists 19th International Geophysical Conference and Exhibition*, Perth.

A review of in-stream geophysical methods used to indentify locations of saline groundwater inflow to a river. Available at: http://crcleme.org.au/NewsEvents/Events/ASEG%20Nov07/HatchMichael%20180.pdf.

More information to the background of the Murray project available at:http://crcleme.org.au/Research/p4projects/SA%20Murray%20Floodplains%2006-08.html.

Cook P G and Herczeg A L 1999, *Environmental Tracers in Subsurface Hydrology*. Kluwer Academic Press, Boston, 522 pp.

This book provides background information on using major ions, stable isotopes, radon and groundwater dating tools in groundwater studies.

T12 Analysis of introduced tracers

Description	Analysis of deliberately introduced hydrochemical tracers to identify water sources and groundwater-surface water mixing relationships.		
Application to components of EWR studies		*Applicable*	*Level of certainty*
	Location, classification and basic conceptualisation	✓✓✓	✓✓✓
	Characterisation of groundwater reliance	✓✓	✓✓✓
	Characterisation of response to change	✓	✓✓
	Monitoring and evaluation	✓✓✓	✓✓
Scale of measurement	Regional: ✓	Catchment: ✓✓	Site: ✓✓✓
Principles	Solutes, dyes, stable isotopes and radioisotopes may be added to surface water bodies to identify the occurrence of groundwater discharge and the flux of groundwater in or out of the system.		
How the tool is applied in GDE assessments	Introduced dyes and conservative tracers, typically to surface water, have a wide range of applications in GDE studies, including for the identification of groundwater discharge zones and the quantification of groundwater – surface water exchange rates. Tracers can be added either continuously or as a pulse depending on the circumstances and information required. While tracer additions are usually quite labour intensive and logistically complex, they can measure exchange processes very precisely over significant areas (whole river reaches, small lakes and wetlands). Bromide is one of the more commonly applied tracers because of its conservative behaviour, relative non-toxicity and low background concentrations. SF_6 injection is also commonly used to estimate degassing from surface water to constrain ^{222}Rn mass-balances. However, SF_6 injections are not recommended for systems where it may compromise the utilisation of this tracer for groundwater-dating purposes in neighbouring aquifers. Dyes (such as rhodamine), deuterated water (water enriched with the heavier stable isotope of hydrogen) and tritiated water (water labelled with ^{3}H, the radioisotope of hydrogen) have been used as tracers in surface and groundwater. The advantage of these tracers relative to bromide is that they can more easily label large water volumes for a longer period of time. However, the addition of dyes and radioisotopes may not be possible when the water body is used as a drinking or irrigation supply.		
Analysis approach	The changes in concentration over time and (in streams) distance are used to evaluate the rate at which groundwater moves in and out of the system.		
Limitations	• Technically and logistically complex. • Some tracers cannot be used in drinking and irrigation water supplies. • Although it can be used to estimate groundwater contribution to surface water, added tracers by themselves do not define the EWR for GDEs.		
Advantages	• Can quantify complex groundwater exchange processes at significant spatial scales.		

T12 Analysis of introduced tracers

	• Allows identification and quantification of groundwater inputs to surface water systems where hydraulic approaches might otherwise fail.
Disadvantages	• Tracer methods provide 'snapshot in time' outcomes for the period over which water sampling is undertaken. To account for seasonal or other temporal changes, multiple field campaigns must be undertaken. • Tracer methods can be field extensive and consequently expensive. • The interpretation of added tracer experiments is complex and requires a fair degree of expertise.
Costs	Total cost will vary according to the number of samples taken and are dependent upon time frames and complexity of sampling programs. Estimated costs for a small-scale investigation where the systems are well understood and time frames are short are around $25 000 to $40 000. If the system is not well understood and time frames are long then costs may exceed $80 000. These cost estimates do not include expenses associated with any monitoring infrastructure (e.g. installation of groundwater observation bores).
Specialist skills and resources	• Maintaining water sampling and laboratory protocols. • Groundwater and surface water hydrology and their interactions. • Construction and operation of surface water and groundwater monitoring sites. • Hydrologic data management and analysis.

Main data types required

Data	*Likely source(s)*
Background tracer concentrations	Site measurements from streams and aquifers
Surface water levels in streams and wetlands	Site measurements – from stream gauges and water level recorders, remotely sensed images of wetland shorelines
Groundwater level	Site measurements from piezometers, regional watertable maps
Elevation of streams or wetlands	Topographic surveys, digital elevation models, maps
Aquifer properties	Published reports of the same location or similar geologies, site investigations

Complementary tools

Tool may:	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14
provide inputs for									✓	✓	✓			
require outputs from		✓								✓	✓			✓

T12 Analysis of introduced tracers

Key references and Australian case studies	Cook P G, Lamontagne S, Berhane D and Clarke J F 2006, 'Quantifying groundwater discharge to Cockburn River, south-eastern Australia, using dissolved gas tracers ^{222}Rn and SF_6 ', *Water Resources Research* 42(10):12 pp. Provides a case study of how injected SF_6 is used in combination with other methods to delineate groundwater inputs to a stream. Lamontagne S, Herczeg A L, Dighton J C, Pritchard J L, Jiwan J S and Ullman W J 2003, *Groundwater – surface water interactions between streams and alluvial aquifers: Results from the Wollombi Brook (NSW) study (Part II – Biogeochemical processes),* CSIRO Land and Water, Technical Report 42/03, July 2003. Provides some basic understanding on how groundwater – surface water interactions can impact on the load of nutrients to surface water in subtropical catchments. Appendix 4 of this paper describes the use of environmental tracers to determine baseflow contributions to Parsons Creek. Cole JJ and Pace ML 1998, 'Hydrologic variability of small, Northern Michigan lakes measured by the addition of tracers', *Ecosystems*, 1:310–320. Becker MW and Coplen TB 2001, 'Use of deuterated water as a conservative artificial groundwater tracer', *Hydrogeology Journal*, 9:512–516. Payn RA, Gooseff MN, Benson DA, Cirpka OA , Zarnetske JP, Bowden WB, McNamara JP and Bradford JH 2008, 'Comparison of instantaneous and constant-rate stream tracer experiments through non-parametric analysis of residence time distributions', *Water Resources Research*, 44: W06404, doi:10.1029/2007WR006274.
Further information	*http://www.connectedwater.gov.au/framework/artificial_tracers.html*.

T13 Long-term observation of system response to change

Description	Long-term observations of GDEs to establish ecosystem responses to changes in groundwater regime due to climate or anthropogenic influences.		
Application to components of EWR studies		*Applicable*	*Level of certainty*
	Location, classification and basic conceptualisation	✓	✓
	Characterisation of groundwater reliance	✓	✓
	Characterisation of response to change	✓✓✓	✓✓✓
	Monitoring and evaluation	✓✓✓	✓✓✓
Scale of measurement	Regional: ✓✓✓	Catchment: ✓✓✓	Site: ✓✓✓
Principles	A long-term program of monitoring both groundwater regime and the condition and function of GDEs is implemented, generally after some change to the groundwater regime (i.e. water resource development, dewatering). Data are used to establish how ecosystem function and/or condition are influenced by particular elements of the groundwater regime. Once such relationships are established it should be possible to determine the water regime required to maintain a particular level of ecosystem function or condition, which is the EWR. Such relationships may be used to set the EWR for other ecosystems for which long-term monitoring data are not available. Long-term observations can contribute to an adaptive management approach for EWR determination. An initial EWR is set on the basis of limited information or analysis. Ecosystem and groundwater regime monitoring data are periodically evaluated and used to refine the EWR.		
How the tool is applied in GDE assessments	Monitoring should include observations of climate, extent and condition of the GDE, groundwater regime and the human activities and other impacts that potentially influence the GDE and its groundwater regime, as outlined below. • Climate—particularly rainfall and evaporation. • Observations of GDE condition and ecological function, including: - plant size and growth: stem height and diameter, stem basal area, crown diameter, leaf area, LAI, sapwood basal area, water use efficiency - vegetation condition: crown condition, species composition and abundance, weed ingress, structure - ecological function: recruitment, presence and abundance of fauna, species diversity, biomass. • Groundwater regime—observations of water level or pressure, flux and physical and chemical indicators of water quality. • Human activity—including records of groundwater extractions, artificial groundwater recharge, land use and management practice. The actual monitoring regime would depend on the ecosystem, its groundwater regime, the resources available and the particular issues to		

T13 Long-term observation of system response to change	
	be resolved through long-term ecosystem observation. Monitoring frequency would depend on the particular indicators. Duration of monitoring would need to be sufficient for the ecosystem to come into equilibrium with any changes in the groundwater regime initiated by human activity. Several years would be the minimum length of time over which monitoring would need to continue. This may include consideration of pests, weeds and fire.
Analysis approach	Analysis would take two forms: • time-series analysis to detect trends and/or patterns in ecosystem condition, groundwater regime and climate • statistical analysis to identify associations between ecosystem function, groundwater regime, climate and/or human activity. These surveys may be applied at the ecosystem or indicator species level and the tools and techniques used are often specific to the site. An example of how long-term ecosystem response to change can be linked to the changes in the associated groundwater system is provided in Froend and Sommer (2010). In that study, transect-based vegetation surveys and statistical analysis were used to determine the response of phreatophytic vegetation to groundwater drawdown. An example of indicators that can be used to assess ecosystem health response to change in subsurface groundwater dependent ecosystems is provided in Korbel and Hose (2011). Indicators include measures of microbial, invertebrate activity and diversity. In addition to traditional survey techniques, the use of the naturally occurring stable isotopes of carbon ($\delta^{13}C$ signatures) can be used as an indicator of plant water use efficiency (WUE) which, for an identified GDE, can indicate stress or change in water use habits that may be related to changes in the associated groundwater system (Farquhar et al. 1989; Arndt & Wanek 2002). WUE varies according to the degree and type of water stress, and plants that are prodigious in their usage of water show a lower WUE than those that are more conservative (e.g. Li 1999). There is a sizeable body of literature on the relationship between $\delta^{13}C$ and WUE in Australian vegetation, including for dominant genera such as eucalyptus and acacia (e.g. Akhter et al. 2005; Anderson et al. 1996; Li 1999; Miller et al. 2001). To undertake $\delta^{13}C$ studies, plant material (usually leaves) is collected, dried and ground. Dried material may be kept indefinitely before analysis. $\delta^{13}C$ is determined via mass spectrometry (<100 mg of dried sample required per analysis) and data reported in standard $\delta^{13}C$ delta units (parts per mill ‰). Typical C3 plants (e.g. most trees) will return values of ~ –27 ‰, whereas C4 plants (e.g. tropical grasses) will return values of ~ –12 ‰. Subtle variations across these broad values indicate variations in WUE. Unlike other ecological or physiological applications of stable isotope analyses there is no need to use a mixing model in the interpretation of $\delta^{13}C$ (e.g. *cf.* T4). Mixing models are not appropriate because the intention is not to estimate the relative contribution of different water or food sources, but rather to infer WUE on the basis of 'raw' $\delta^{13}C$ values.
Limitations	• Identifying primary factors in ecosystem decline may be difficult (e.g. pest and weed invasion versus grazing and clearing versus altered groundwater regimes). • Attributing cause and effect may be difficult, particularly in systems where there is long lag between change in groundwater regime and a corresponding alteration in ecological function in the GDE (e.g. regional groundwater flow systems). • The tool should only be applied to ecosystems with a very high likelihood of being groundwater dependent and subject to changes in groundwater regime. This will help to avoid investment in monitoring ecosystem function and groundwater dependency for ecosystems that are not groundwater dependent.

<table>
<tr><th colspan="2">T13 Long-term observation of system response to change</th></tr>
<tr><td>Advantages</td><td>General
Provides empirical observations as to how an ecosystem responds to changes in groundwater availability.
$\delta^{13}C$ analyses are cheap and require little sample preparation.
$\delta^{13}C$ is a stable isotope and so there are few occupational health and safety issues (e.g. radiation safety).
Strong and robust literature on the relationship between WUE and $\delta^{13}C$, based on well-understood biophysical and biochemical processes.
An existing (and growing) body of published data on $\delta^{13}C$ signatures for a wide range of plants in Australia, including vegetation in arid and semi-arid zones. If fundamental research shows the $\delta^{13}C$-WUE approach to have merit, this existing information would be easy to extract and reinterpret in terms of WUE.</td></tr>
<tr><td>Disadvantages</td><td>General
Repeated observations over an extended period may be required before this tool provides meaningful insight into groundwater dependency and the EWR. This will require sustained interest and investment by resource managers.
$\delta^{13}C$
$\delta^{13}C$ varies within a single plant according to leaf position (e.g. see Le Roux et al. 2001), among plants according to salinity stress and possibly micro-nutrient availability (e.g. Poss et al. 2000), and among species according to photosynthetic pathway (although the differences between C3 and C4 plants are greater than for WUE and presumably easy to differentiate).</td></tr>
<tr><td>Costs</td><td>General
Total cost will vary with the comprehensiveness and duration of monitoring. The following cost estimate relates only to annual operating costs and not to costs associated with any monitoring infrastructure (e.g. groundwater observation bores/piezometers). It is based on field monitoring of ecosystem condition and function and of groundwater and climate regime.
Estimated costs are:
annual monitoring cost of $10 000 to $100 000 per year
periodic evaluation of monitoring data of $10 000 to $50 000.
$\delta^{13}C$ Sample preparation is minimal (drying and grinding) and isotopic analyses cheap (<$50 per sample and likely to fall further). At a minimum, 50–100 samples would be collected per site (assuming 5 plant species of interest and 5–10 samples per species) leading to analytical costs of the order of ~$2500 to $5000 per site.</td></tr>
<tr><td>Specialist skills and resources</td><td>Monitoring and analysis techniques for ecosystems, climate and groundwater regime.
Long-term security of monitoring sites and financial resources.
Knowledge of sampling techniques and equipment.
Understanding of the biophysical processes involved.
Access to mass-ratio mass spectrometer. A number of instruments are available in Australia and New Zealand.
Interpretation requires some knowledge of plant physiology and isotope behaviour if simplistic/false conclusions are to be avoided.</td></tr>
<tr><td>Main data types required</td><td><table><tr><th>Data</th><th>Likely source(s)</th></tr><tr><td>Climate</td><td>Bureau of Meteorology record, site weather</td></tr></table></td></tr>
</table>

T13 Long-term observation of system response to change

		station
	Plant size and growth	Site measurements
	Vegetation condition	Site measurements
	Ecological function	Site measurements
	Groundwater regime	Site measurements
	Human activity	Public records and management plans, field observation
	$\delta^{13}C$ of leaf material for riparian and terrestrial vegetation	Measurements taken in field, published ecological papers on food-web structure, published papers on plant physiology and WUE, unpublished sources, such as proceedings of ecological conferences and student theses

Complementary tools

Tool may:	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14
provide inputs for	✓	✓			✓			✓	✓		✓			✓
require outputs from	✓	✓	✓	✓		✓			✓					

T13 Long-term observation of system response to change

Key references and Australian case studies

Froend RH and Sommer B 2010, 'Phreatophytic vegetation response to climatic and abstraction induced groundwater drawdown: Examples of long-term spatial and temporal variability in community response', *Ecological Engineering*, 36:1191–1200.

Investigates the influence of climatic drought and groundwater abstraction on phreatophytic vegetation dynamics over a period of 33 years in the south-west of Western Australia.

Groom PK, Froend RH and Mattiske EM 2000, 'Impact of groundwater abstraction on a Banksia woodland, Swan Coastal Plain, Western Australia', *Ecological Management and Restoration*, 1:117–124.

Monitoring of vegetation condition and groundwater regime to develop EWR guidelines for management of GDEs on the Swan Coastal Plain, WA.

Colvin C, Maitre D and Hughes S 2002, *Assessing terrestrial groundwater dependent ecosystems in South Africa – Final draft report*, Prepared for Water Research Commission, April 2002.

Presents an approach to determining the existence of terrestrial GDEs and describes various tools which may be used to determine dependency.

Akhtar J, Mahmood K, Tasneem MA, Malik KA, Naqvi MH, Hussain F and Serraj J 2005, 'Water-use efficiency and carbon isotope discrimination of *Acacia ampliceps* and *Eucalyptus camaldulensis* at different soil moisture regimes under semi-arid conditions', *Biologia Plantarum*, 49:269–272.

Anderson J E, Williams J, Kriedemann PE, Austin MP and Farquhar GD 1996, 'Correlations between carbon isotope discrimination and climate of native habitats for diverse eucalyptus taxa growing in a native garden', *Australia Journal of Plant Physiology*, 23:311–320.

Arndt SK and Wanek W 2002, 'Use of decreasing foliar carbon isotope discrimination during water limitation as a carbon tracer to study whole plant carbon allocation', *Plant, Cell & Environment*, 25(5):609–616.

Farquhar GD, Ehleringer JR and Hubick KT 1989, 'Carbon isotope discrimination and photosynthesis' *Annual Review of Plant Physiology and Plant Molecular Biology*, 40:503–537.

Le Roux X, Bariac T, Sinqoquet H, Genty B, Piel C, Mariotti A, Girardin C and Pritchard P 2001, 'Spatial distribution of leaf water-use efficiency and carbon isotope discrimination within an isolated tree crown', *Plant, Cell & Environment*, 24:1021–1032.

Li C 1999, 'Carbon isotope composition, water-use efficiency and biomass productivity of *Eucalyptus microtheca* populations under different water supplies', *Plant & Soil*, 214:165–171.

Poss JA, Grattan SR, Suarez DL and Grieve CM 2000, 'Stable carbon isotope discrimination: an indicator of cumulative salinity and boron stress in *Eucalyptus camaldulensis', Tree Physiology*, 20: 1121–1127.

Miller J M, Williams R J, Farquhar G D, 2001. 'Carbon isotope discrimination by a sequence of Eucalyptus species along a subcontinental rainfall gradient in Australia', Functional Ecology, 15: 222–232.

T13 Long-term observation of system response to change	
Further Information	Korbel KL and Hose GC 2011, 'A tiered framework for assessing groundwater ecosystem health', *Hydrobiologica*, 661: 329-349

T14 Numerical groundwater modelling

Description	Construction of mathematical models to simulate groundwater flow systems.		
Application to components of EWR studies		*Applicable*	*Level of certainty*
	Location, classification and basic conceptualisation	✓	✓
	Characterisation of groundwater reliance	✓	✓
	Characterisation of response to change	✓✓✓	✓✓
	Monitoring and evaluation	✓✓	✓✓
Scale of measurement	Regional: ✓✓	Catchment: ✓✓	Site: ✓✓

Principles

Models use numerical representations of aquifer systems to simulate changes in hydrogeological regime in response to climate and/or management. Their main use in GDE assessments is to explore the availability of groundwater to ecosystems in response to management actions.

Groundwater models can be used to estimate or predict the sources, volume and level of interaction of groundwater with surface water systems based on mathematical simulations of groundwater flow systems. They can also be used in a predictive context to examine impacts of management scenarios of systems subject to change; for example, through groundwater extraction, river regulation or land use change.

Groundwater models may be linked with plant-water use models to provide insights into plant responses to changes in groundwater regimes.

How the tool is applied in GDE assessments

Groundwater models can be used to assess the changes in the groundwater system that impact on ecosystem water availability. Groundwater models may be integrated with surface water and plant water use models to investigate the impacts of changes in water regimes over time.

Numerical models can be used to make quantitative assessments of ecosystem water availability (care should be taken to consider uncertainties related to simulated parameters). Qualitative assessments would be made where only an indication of groundwater availability is required and where data and other resources are limiting. Quantitative assessments can only be made where there is a sound conceptualisation of groundwater processes and good information on the properties of the groundwater flow system being modelled.

Groundwater conceptual model

In order to establish a mathematical representation for modelling, the dimensions, interactions and properties of the natural system need to be properly conceptualised. Conceptual models may utilise information derived from literature, expert knowledge, geological or hydrogeological maps, physical data from the site or defined groundwater flow systems. The conceptual model will define the thickness, distribution and extent of different aquifers and aquitards, and the ways in which they interact. In addition, it will establish the relative location of rivers, lakes, pumping bores and other features that affect groundwater systems and how the water balances of subsystems respond to different stresses. T2 provides

	further information on general uses of conceptual models. *Aquifer hydraulic parameters* Having defined the groundwater conceptual model, hydraulic parameters must be assigned that describe the way water moves through the ground. Essential parameters for input to a numerical model are hydraulic conductivity/transmissivity and specific yield (or storage coefficient for confined aquifers). These parameters can be estimated from published literature or (preferably) field studies. Spatial variability in aquifer properties can be large and so care must be taken in interpreting and using field measurements. Aquifer properties are measured by performing either slug or (preferably) pumping tests at groundwater bores. Some estimate of the aquifer properties can be determined from sieve analysis of sediment samples or laboratory analysis of soil cores collected from the site.
Analysis approach	In the majority of cases, groundwater models are constructed using commercially available modelling packages such as MODFLOW and FEFLOW and calibrated against observed and/or synthetic data. Models can consist of a vertical slice through the ground (a section or two-dimensional profile model) that examines flow in the vertical plane, or a three-dimensional model that examines vertical and horizontal flow components in a defined region. The choice of modelling approach and the actual modelling package used in the study can have a large influence on the model outputs and their interpretation. In addition to MODFLOW and FEFLOW, examples of some commonly used groundwater models are provided below: *WAVES* Correlates land use with recharge rates. Models moisture movement in the unsaturated zone, between the watertable and vegetation. Can include climate/plant type/root zone depth and soil moisture characteristics. Outputs from WAVES can be used as an input to MODFLOW and other numerical groundwater modelling packages (in place of RCH (recharge) and EVT (evapotranspiration) packages). *SUTRA* 'Finite-element simulation model for saturated-unsaturated fluid-density-dependent ground-water flow with energy transport or chemically-reactive single-species solute transport' and related programs (SutraSuite)- groundwater model and a number of utilities for pre- and post-processing (two or three dimensional). For information, go to *http://water.usgs.gov/nrp/gwsoftware/sutra.html*. *TOPOG* Terrain-based deterministic distributed parameter hydrological modelling package. Models how water moves through landscapes (over land, soil zone, groundwater and back as evaporation). Solute and sediment transport are also included. For more information, go to: *http://www.per.clw.csiro.au/topog/intro/intro.html*. *WATBAL Water balance/model* Water balance (direct runoff, surface runoff, subsurface runoff, maximum catchment water-holding capacity, and base flow) and potential ET modelled (see Yates 1994 and *http://nowlin.css.msu.edu/watbal.html*). *SWAP* 'Soil Water Atmosphere Plant' simulates transport of water, solutes and heat in unsaturated/saturated soils. *eWater Source Model Series (Catchments/Rivers/Urban)* Most applicable is eWater Source Catchments (previously named WaterCAST; *http://www.ewater.com.au/products/ewater-source/for-catchments/*). Models catchments, water quality/quantity of rainfall runoff and groundwater contribution to surface water systems, can model catchment changes (climate, land use changes, riverbank restoration, natural disasters).

T14 Numerical groundwater modelling

Limitations	• By itself, the tool only provides information on the contribution of groundwater to terrestrial vegetation or a surface water body. It does not directly indicate the EWR.
Advantages	• The effect of longer-term changes (such as changes in climate/water management practices) on groundwater availability to ecosystems can be modelled. • Numerical models provide a means to quantify spatial distributions of groundwater levels and flows. • Groundwater models enable analysis of system responses to a variety of changes in system stresses (e.g. recharge, groundwater extraction, manipulation of surface water regulators).
Disadvantages	• The reliability of model outputs reflects the accuracy of the initial conceptualisation and of model parameterisation. Where input data are limited, model outputs may be unreliable. • Use of the tool in a quantitative mode relies on there being adequate site information, on groundwater properties, and changes in level or pressure in response to climate and/or management action.
Costs	Total cost will vary with the scale at which the tool is applied and the information available for model input and calibration. A small-scale groundwater modelling activity using existing data may cost $50 000 to $75 000. A larger-scale activity that requires new data to be collected and an accurately calibrated model may cost $100 000 to $250 000.
Specialist skills and resources	• Numerical skills associated with developing and/or operating models. • Specialist skills in hydrogeology. • Groundwater investigation.

Main data types required

Data	*Likely source(s)*
Surface water levels and flows	Site measurements – from stream gauges and water level recorders, remotely sensed images of wetland shorelines
Groundwater level	Site measurements from piezometers, regional watertable maps
Elevation of streams or wetlands	Topographic surveys, digital elevation models, maps
Aquifer properties	Published reports of the same location or similar geologies, site investigations
Groundwater salinity	Site measurements - electrical conductivity (EC) or Total Dissolved Solids (TDS) from hand held instrumentation, remote sensing data
Vegetation type and health data	Vegetation map, remote sensing data

Complementary tools

Tool may:	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14
provide inputs for	✓	✓			✓			✓	✓	✓	✓	✓		
require outputs from	✓	✓			✓			✓		✓			✓	

T14 Numerical groundwater modelling

Key references and Australian case studies	Bonte M and Howe P 2004, *Combining traditional hydrogeological approaches with tracer methodologies in the assessment of salt accession process to the Gurra Gurra Wetland Complex, South Australia,* 9th Murray-Darling Basin Groundwater Workshop. Provides a case study of various tools that can be effectively employed in estimating rates of groundwater inflow to surface water bodies, including the comparison of groundwater model output against tracer methodologies. Aquaterra 2002, *Kemerton Water Study - Phase 2 Final Report,* report to Landcorp (Western Australia). Outlines an integrated study to develop a sustainable water management plan for an industrial park south of Perth, WA, in terms of: (a) groundwater abstractions for water supply (b) environmental constraints due to wetlands and fringing vegetation having conservation significance (c) conceptual drainage plans consistent with water sensitive urban design principles. The study involved hydrogeoecological data compilation, including vegetation mapping and wetland assessment, analysis of data on groundwater, climate and surface water systems, and development of a calibrated catchment-based numerical groundwater flow model. Smith A J, Turner J V, Herne D E and Hick W P 2003, *Quantifying submarine groundwater discharge and nutrient discharge into Cockburn Sound, Western Australia*. A technical report to Coast and Clean Seas Project WA9911. Quantifying submarine groundwater discharge and demonstrating innovative clean up to protect Cockburn Sound from nutrient discharge. CSIRO Land and Water, Perth. Technical Report 1/03, June 2003. Provides an Australian case study that tested various tools for estimating submarine groundwater discharge, including the development of a numerical groundwater flow model.
Further Information	Murray–Darling Basin Commission 2000, *Groundwater flow modelling guideline*, report compiled by Aquaterra Consulting. Describes general guidelines for groundwater flow modelling that are designed to reduce the level of uncertainty by promoting transparency in modelling methodologies and encouraging consistency and best practice. These guidelines are in the process of being updated for release in 2011–12 by the National Water Commission. More information about this project is available at: *http://www.nwc.gov.au/www/html/2835-development-of-national-groundwater-modelling-guidelines.asp?intSiteID=1*. Yates D 1994, *WatBal: An integrated water balance model for climate impact assessment of river runoff*, IIASA (International Institute for Applied Systems Analysis), WP-94-64, Laxenburg, Austria.

Appendix A—Glossary

abiotic	Non-living chemical and physical factors in the environment.
anion	Negatively charged ion. Source: Australian and New Zealand Guidelines for Fresh and Marine Water Quality (2000) *http://www.mincos.gov.au/__data/assets/pdf_file/0016/316123/wqg-apps.pdf.*
applied tracer	Non-natural constituent that is intentionally introduced to a hydrologic system to characterise groundwater flowpaths and estimate velocities.
aquifer	An underground layer of permeable rock, sand or gravel that absorbs water and allows it free passage through pore spaces. Source: Australian and New Zealand Guidelines for Fresh and Marine Water Quality (2000) *http://www.mincos.gov.au/__data/assets/pdf_file/0016/316123/wqg-apps.pdf.*
aquifer, confined	An aquifer that is overlain by a confining bed. The confining bed has a significantly lower hydraulic conductivity than the aquifer. Source: National Water Commission Water Dictionary *http://dictionary.nwc.gov.au/water_dictionary/pdf/WaterDictionary.pdf*
aquifer, perched	A region in the unsaturated zone where the soil or rock may be locally saturated because it overlies a low-permeability unit. Source: National Water Commission Water Dictionary *http://dictionary.nwc.gov.au/water_dictionary/pdf/WaterDictionary.pdf*
aquifer, unconfined	An aquifer in which there are no confining beds between the saturated zone and the surface. There will be a watertable in an unconfined aquifer. Source: National Water Commission Water Dictionary *http://dictionary.nwc.gov.au/water_dictionary/pdf/WaterDictionary.pdf*

aquitard	A confining unit that retards but does not prevent the flow of water to or from an adjacent aquifer. An aquitard is the less-permeable bed in the stratigraphic sequence. An aquitard does not readily yield water to wells or springs but may serve as a storage unit for groundwater and can transmit water slowly from one aquifer to another. Source: Poehls DJ and Smith GJ 2009, *Encyclopedic dictionary of hydrogeology*, Elsevier Inc., 517 pp.
baseflow	The component of streamflow supplied by groundwater discharge. Source: National Water Commission Water Dictionary *http://dictionary.nwc.gov.au/water_dictionary/pdf/WaterDictionary.pdf*.
biotic	A living component of a community, such as plants and animals.
capillary zone	The zone of soil moisture above the watertable where water is drawn upwards by capillary tension, in which the water is at less than atmospheric pressure.
cation	Positively charged ion.
conservative ion	A non-reactive ion; speciation does not change over a given process.
Darcy's law	A law that relates the rate of fluid flow to the flow path and hydraulic head gradient, assuming that the flow is laminar and that inertia can be neglected. Source: Poehls DJ and Smith GJ 2009, *Encyclopedic dictionary of hydrogeology*, Elsevier Inc., 517 pp.
diel	Occurring over a 24 hour cycle.
digital elevation model (DEM)	A depiction of relief using points and lines, which contain the elevation of each point or the elevation of each point in a line. The data may be in a regular grid or have an irregular spacing. Source: Geoscience Australia. Glossary to NTDB and NTMS Specifications (250K and 100K) *http://www.ga.gov.au/mapspecs/250k100k/appendix_l.jsp*.
dissolved oxygen (DO)	The measure of the amount of gaseous oxygen dissolved in an aqueous solution.
doline	Natural depression or hole in the Earth's surface caused by karst processes, commonly referred to as a 'sinkhole'.

drawdown	The distance between the static water level and the surface of the cone of depression.
duplex soil	A soil where there is a sharp texture contrast between the A and B horizons. A duplex soil is often characterised by a sandy or loamy surface horizon with a sharp to clear boundary to a clay subsoil. Source: adapted from the Department of Primary Industries *http://vro.dpi.vic.gov.au/dpi/vro/vrosite.nsf/pages/gloss_dg*
ecohydrogeological zone (EHZ)	Regions where similar processes are likely to determine the interaction between groundwater and ecology, due to similar ecology, geology, climate, groundwater/surface water connections.
ecosystem	A system that includes all living organisms (biotic factors) in an area as well as its physical environment (abiotic factors) functioning together as a unit.
ecosystem services	Fundamental characteristic of ecosystems related to conditions and processes necessary for maintaining ecosystem integrity, which implies intact abiotic components (e.g. soils and water), biodiversity and resilience to natural successional cycles (e.g. fire, flooding, predation). Ecosystem function will include such processes as decomposition, nutrient cycling and production. It is generally considered that maintenance of biodiversity is integral to ecosystem function.
ecological values	The natural ecological processes occurring within ecosystems and the biodiversity of these systems. Source: adapted from ARMCANZ & ANZECC 1996, *National principles for the provision of water for ecosystems*, Sustainable Land and Water Resources Management Committee Subcommittee on Water Resources Occasional Paper SWR No 3 July 1996. *http://www.environment.gov.au/water/publications/environmental/ecosystems/pubs/water-provision.pdf*.
ecological water provision (EWP)	Part of the environmental water requirement (or ecological water requirement) that can be met. Source: ARMCANZ & ANZECC 1996, *National principles for the provision of water for ecosystems*, Sustainable Land and Water Resources Management Committee Subcommittee on Water Resources Occasional Paper SWR No 3 July 1996. *http://www.environment.gov.au/water/publications/environmental/ecosystems/pubs/water-provision.pdf.*

ecological water requirement (EWR)	Descriptions of the water regimes needed to sustain the ecological values of water-dependent ecosystems at a low level of risk. Source: adapted from definition for *Environmental Water Requirements* in ARMCANZ & ANZECC 1996, *National principles for the provision of water for ecosystems*, Sustainable Land and Water Resources Management Committee Subcommittee on Water Resources Occasional Paper SWR No 3 July 1996. *http://www.environment.gov.au/water/publications/environmental/ecosystems/pubs/water-provision.pdf* .
eddy covariance	Technique that measures fine-timescale carbon and water fluxes between vegetation and the atmosphere.
electrical conductivity (EC)	Electrical conductivity (EC) measures dissolved salt in water. The standard EC unit is microSiemens per centimetre (µS/cm) at 25 °C. Source: National Water Commission Water Dictionary *http://dictionary.nwc.gov.au/water_dictionary/pdf/WaterDictionary.pdf*
environmental flow	A water regime provided within a river, wetland or estuary to improve or maintain ecosystems and their benefits where there are competing water uses and where flows are regulated. Source: National Water Commission Water Dictionary *http://dictionary.nwc.gov.au/water_dictionary/pdf/WaterDictionary.pdf*
environmental tracer	Naturally occurring indicator, usually physico-chemical, used to identify and constrain specific biotic or abiotic processes.
evapotranspiration (ET)	The combined loss of water from a given area during a specified period of time by evaporation from the soil or water surface and by transpiration from plants. Source: Australian and New Zealand Guidelines for Fresh and Marine Water Quality (2000) *http://www.mincos.gov.au/__data/assets/pdf_file/0016/316123/wqg-apps.pdf*
geophysical survey	A process of searching and mapping the subsurface structure of the earth's crust using geophysical methods such as seismic, magnetic, electromagnetic, gravity and induced polarisation techniques.
gaining stream	A stream where groundwater discharge contributes to stream flow.
groundwater	Subsurface water located in the zone of saturation in pores, fractures and cavities in rocks.

groundwater-dependent ecosystem (GDE)	Natural ecosystems that require access to groundwater to meet all or some of their water requirements on a permanent or intermittent basis so as to maintain their communities of plants and animals, ecological processes and ecosystem services.
groundwater flow system	The total system which describes the movement of water in the subsurface from the point where it enters the ground to where it leaves.
ground-truthing	The use of a ground survey to calibrate and/or confirm hypotheses relating to the interpretation of aerial survey, satellite imagery or other remote method.
gypsum blocks	Gypsum blocks consist of two electrodes embedded in a block of gypsum used to measure soil water tension, a reflection of the force that a plant must overcome to extract water from the soil. The resistance between the two electrodes varies with the water content in the gypsum block, which will depend directly on the soil water tension.
hardpan	A soil layer with physical characteristics that limit root penetration and restrict water movement. Source: Food and Agriculture Organisation of the United Nations *http://lprapp11.fao.org/problemsoils/index.php?option=com_glossary &Itemid=237*
hydraulic conductivity	A coefficient of proportionality describing the rate at which water can move through a permeable medium. Horizontal hydraulic conductivity (K_h) refers to the coefficient of proportionality in the horizontal direction, whereas vertical hydraulic conductivity (K_v) refers to the coefficient of proportionality in the vertical direction.
hydraulic gradient	The rate of change in total head per unit distance in a given direction. The direction of gradient is that yielding the maximum rate of decrease in head.
hydrograph	Graphical representation of river or stream discharge or of groundwater-level fluctuations in a well. Source: Australian and New Zealand Guidelines for Fresh and Marine Water Quality (2000) *http://www.mincos.gov.au/__data/assets/pdf_file/0016/316123/wqg-apps.pdf.*

hyporheic zone	The saturated interstitial areas beneath the streambed and into the stream banks that contain some proportion of channel water or that have been altered by channel water infiltration. Source: White DS 1993, 'Perspectives on defining and delineating hyporheic zones', *Journal of the North American Benthological Society* 12:61–69.
hypothesis	Statements or theories that can be subjected to statistical evaluation when monitoring data has been obtained to determine whether they can be accepted (or rejected). Source: Australian and New Zealand Guidelines for Fresh and Marine Water Quality (2000) *http://www.mincos.gov.au/__data/assets/pdf_file/0016/316123/wqg-apps.pdf.*
interflow	The runoff infiltrating into the surface soil and moving toward streams as shallow, perched ground water above the main ground-water level. Source: USGS Definition of Terms *http://pubs.usgs.gov/ha/ha747/pdf/definition.pdf.*
introduced tracer	Dyes or conservative tracer that may be added to streams or aquifers to identify the occurrence and flux of discharging groundwater to river and wetland systems.
isotope	A particular atom of an element that has the same number of electrons and protons as the other atoms of that element, but a different number of neutrons; that is, the atomic numbers are the same but the atomic weights differ. Isotopes have essentially the same chemical properties as other atoms of the same element. Source: National Water Commission Water Dictionary *http://dictionary.nwc.gov.au/water_dictionary/pdf/WaterDictionary.pdf*
karst	A terrain characterised by sinkholes, caves and springs developed most commonly in carbonate rocks where significant dissolution of the rock has occurred due to flowing water Source: Jennings 1985; Culver et al. 1995; Fetter 2001 as referenced in M Tomlinson and A Boulton 2008, *Subsurface groundwater dependent acosystems: a review of biodiversity, ecological processes and ecosystem services*, National Water Commission Waterlines Occasional Paper No. 8, October 2008 *http://www.nwc.gov.au/resources/documents/Waterlines__subsurface_full_version.pdf.*

kriging	An interpolation technique in which the surrounding measured values are weighted to derive a predicted value for an unmeasured location. Weights are based on the distance between the measured points, the prediction locations, and the overall spatial arrangement among the measured points. Source: ESRI *http://support.esri.com/en/knowledgebase/GISDictionary/term/kriging*
laser scintillometer	Measurement system for the determination of the turbulent fluxes of heat and momentum based on optical scintillation measurements.
leaf area index (LAI)	The ratio between the total upper leaf surface area of vegetation and the surface area of ground over which the vegetation grows.
leaf water potential (LWP)	Measure of the water pressure of a leaf and hence the plant. A plant that is fully hydrated may exhibit a water potential close to zero.
losing stream	A stream from which water is lost to the surrounding and underlying substrate via infiltration through the streambed.
macrophyte	A member of the macroscopic plant life of an area, especially of a body of water; large aquatic plant. Source: Australian and New Zealand Guidelines for Fresh and Marine Water Quality (2000) *http://www.mincos.gov.au/__data/assets/pdf_file/0016/316123/wqg-apps.pdf*
major ions	Constituents commonly present in concentrations exceeding 1.0 milligram per litre. For dissolved cations this includes calcium, magnesium, sodium, and potassium; the most prevalent anions include sulphate, chloride, fluoride, nitrate, and those contributing to alkalinity, most generally assumed to be bicarbonate and carbonate.
matric potential	A variable describing how strongly the water within a soil matrix is bound to the soil by capillary and other forces. Source: National Water Commission Water Dictionary *http://dictionary.nwc.gov.au/water_dictionary/pdf/WaterDictionary.pdf*
model, conceptual	Documentation of a conceptual understanding of the location of GDEs and interaction between ecosystems and groundwater.
model, analytical / numerical	Simulates groundwater flow indirectly by means of governing equations considered representative of the physical process occurring in the system, in addition to equations describing heads or flow along the model boundaries. Mathematical models can be solved analytically or numerically.

multiple lines of evidence	Weight of the evidence based on different types of information from a variety of different sources and studies. Source: Australian and New Zealand Guidelines for Fresh and Marine Water Quality (2000) *http://www.mincos.gov.au/__data/assets/pdf_file/0016/316123/wqg-apps.pdf*
neutron probes	Neutron probes enable a rapid measurement of soil moisture to be made. The neutron probe has a radioactive source which releases neutrons. The neutrons are emitted into the soil when the probe is lowered into an aluminium tube which has been installed in the ground. Whenever a neutron collides with a hydrogen atom (part of a water molecule) it is slowed down. A detector counts the slow neutrons that have been deflected back to the instrument. A calibration equation is used to convert this number into the soil moisture content.
osmotic potential	Osmotic potential is the potential of water to move into a region by the process of osmosis, the potential of the water to travel from a hypotonic (low concentration) solution to a hypertonic (high-concentration) solution.
parameter	Statistical constants that can be summarised to show some measure of central tendency and variability such as mean, median, standard variation.
piezometer	A non-pumping well, generally of small diameter, that is used to measure the elevation of the watertable or potentiometric surface. A piezometer generally has a short well screen through which water can enter. Source: National Water Commission Water Dictionary *http://dictionary.nwc.gov.au/water_dictionary/pdf/WaterDictionary.pdf*
pH	Value that represents the acidity or alkalinity of an aqueous solution. It is defined as the negative logarithm of the hydrogen ion concentration of the solution. Source: Australian and New Zealand Guidelines for Fresh and Marine Water Quality (2000) *http://www.mincos.gov.au/__data/assets/pdf_file/0016/316123/wqg-apps.pdf*
phreatophyte	Plant that draws water from groundwater or the capillary zone to maintain vigour and function.

potentiometric surface	A surface representing the hydraulic head of ground water; represented by the watertable altitude in an unconfined aquifer or by the altitude to which water will rise in a properly constructed well in a confined aquifer. Source: USGS Definition of Terms *http://pubs.usgs.gov/ha/ha747/pdf/definition.pdf.*
radioactive isotopes	Varieties of an element possessing the same number of electrons and protons but differing numbers of neutron that emit detectable radiation by means of which they can be identified and traced.
remote sensing	Any kind of data recording by a sensor which measures energy emitted or reflected by objects located at some distance from the sensor (i.e. no direct ground contact). Can include aerial photographs, airborne digital sensors and satellite imagery.
resilience, ecosystem	The persistence of relationships within an ecosystem and a measure of the ability of the ecosystem to absorb changes in external and internal conditions and still persist. Source: modified from CS Holling 1973, 'Resilience and stability of ecological systems' *Annual Review of Ecology & Systematics* 4:1–23.
resilience building	Increasing the ability of an ecosystem to cope with stress or unexpected events, usually by manipulating the system to increase the likelihood of it persisting despite disturbance. Modified from Peterson GD 2005, 'Ecological management: control, uncertainty, and understanding' in K Cuddington and BE Beisner, *Ecological Paradigms Lost*, pp. 371–396. Elsevier, Amsterdam.
resistance, ecosystem	The ability of an ecosystem to return to an equilibrium state after a temporary disturbance. It can involve factors such as constancy (lack of change), persistence (survival times), inertia (ability to resist external perturbations), elasticity (speed with which a system returns to its original state following a perturbation), and amplitude (range over which a system is stable). Source: modified from Holling CS 1973, 'Resilience and stability of ecological systems' *Annual Review of Ecology & Systematics* 4:1–23 and Orians GH 1974, 'Diversity, stability and maturity in natural ecosystems' in WH van Dobben and RH Lowe-McConnell (eds) *Unifying Concepts in Ecology*, De W. Junk, The Hague, pp. 139–149.

riparian	An area or zone within or along the banks of a stream or adjacent to a watercourse or wetland; relating to a riverbank and its environment, particularly to the vegetation. Source: eWater Toolkit Glossary *http://www.toolkit.net.au/support/Glossary.aspx*
salinity	The concentration of soluble salts in a solution, soil or other medium. Source: eWater Toolkit Glossary *http://www.toolkit.net.au/support/Glossary.aspx*
sap flow techniques	A direct measurement of plant water use using heat balance, heat pulse and thermal diffusion techniques. The heat balance sensor encloses the stem, while the heat pulse and thermal diffusion sensors require probes to be inserted into the plant stems.
saturated zone	The part of the lithosphere where each void space in subsurface material is filled with water, or is saturated, under greater pressure than that of the atmosphere. Source: Poehls DJ and Smith GJ 2009, *Encyclopedic dictionary of hydrogeology*, Elsevier Inc., 517 pp.
scenario Planning	A systematic method for thinking creatively about possible futures in which uncertainty is high and controllability is low. Source: Peterson GD 2005, 'Ecological management: control, uncertainty, and understanding' in K Cuddington and BE Beisner (eds) *Ecological Paradigms Lost*, Elsevier, Amsterdam, pp 371–396.
sinkhole	See 'doline'.
slug test	A single-well test to determine the hydraulic conductivity of a formation, by which a known volume (either of water or solid) is inserted into a well and the water level response to insertion of the slug (falling head test) and removal of the slug (rising head test) is monitored. Source: Poehls DJ and Smith GJ 2009, *Encyclopedic dictionary of hydrogeology*, Elsevier Inc., 517 pp.
stomata	Pores on leaves and stems of plants that are used for gas exchange.

stratification	The formation of layers in a water body, showing differences in temperature, turbidity, pH, nutrients, salinity, dissolved oxygen and light penetration at various depths; lack of mixing within a water storage. Source: eWater Toolkit Glossary *http://www.toolkit.net.au/support/Glossary.aspx*
stressors	The physical, chemical or biological factors that can cause an adverse effect in an aquatic ecosystem as measured by the condition indicators. Source: Australian and New Zealand Guidelines for Fresh and Marine Water Quality (2000) *http://www.mincos.gov.au/__data/assets/pdf_file/0016/316123/wqg-apps.pdf*
specific yield	The amount of water that a unit volume of saturated permeable rock would yield if drained by gravity.
stable isotope	An isotope that does not undergo radioactive decay.
stygobite	Aquatic animal that completes its life cycle in groundwater. Source: Tomlinson M and Boulton A 2008, *Subsurface groundwater dependent ecosystems: a review of biodiversity, ecological processes and ecosystem services*, National Water Commission Waterlines Occasional Paper No. 8, October 2008 *http://www.nwc.gov.au/resources/documents/Waterlines__subsurface_full_version.pdf*
stygofauna	Aquatic animals found in groundwater; sometimes used as a synonym of stygobite. Source: Tomlinson M and Boulton A 2008, *Subsurface groundwater dependent ecosystems: a review of biodiversity, ecological processes and ecosystem services*, National Water Commission Waterlines Occasional Paper No. 8, October 2008 *http://www.nwc.gov.au/resources/documents/Waterlines__subsurface_full_version.pdf.*
stygophile	Animals which spend part of their life cycle in groundwater. Source: Tomlinson M and Boulton A 2008, *Subsurface groundwater dependent ecosystems: a review of biodiversity, ecological processes and ecosystem services*, National Water Commission Waterlines Occasional Paper No. 8, October 2008 *http://www.nwc.gov.au/resources/documents/Waterlines__subsurface_full_version.pdf*

stygoxene	Animals which occur accidentally in groundwater but have no affinity with groundwater habitats Source: Tomlinson M and Boulton A 2008, *Subsurface groundwater dependent ecosystems: a review of biodiversity, ecological processes and ecosystem services*, National Water Commission Waterlines Occasional Paper No. 8, October 2008 *http://www.nwc.gov.au/resources/documents/Waterlines__subsurface_full_version.pdf*
taxon (taxa)	Any group of organisms considered to be sufficiently distinct from other such groups to be treated as a separate unit (e.g. species, genera, families). Source: Australian and New Zealand Guidelines for Fresh and Marine Water Quality (2000) *http://www.mincos.gov.au/__data/assets/pdf_file/0016/316123/wqg-apps.pdf.*
taxonomic (group, resolution)	An organism's location in the biological classification system used to identify and group organisms with similar physical, chemical and/or structural composition. Source: Australian and New Zealand Guidelines for Fresh and Marine Water Quality (2000) *http://www.mincos.gov.au/__data/assets/pdf_file/0016/316123/wqg-apps.pdf.*
tensiometer	An instrument designed to measure the tension or suction that plants' roots must exert to extract water from the soil. This tension is a direct measure of the availability of water to a plant. A tensiometer consists of an air tight, water filled tube with a porous ceramic tip at the bottom and either a vacuum gauge at the top or a resealable rubber bung for a portable vacuum meter.
throughfall	Precipitation that falls directly through a vegetative canopy or is intercepted by vegetation and then drips to the ground. Source: The Dictionary of Forestry, Society of American Foresters *http://dictionaryofforestry.org/dict/.*
total dissolved solids (TDS)	A measure of the inorganic salts (and organic compounds) dissolved in water. Source: Australian and New Zealand Guidelines for Fresh and Marine Water Quality (2000) *http://www.mincos.gov.au/__data/assets/pdf_file/0016/316123/wqg-apps.pdf*

transmissivity	The rate at which water moves through a unit width of aquifer or aquitard under a unit hydraulic gradient. It is the product of aquifer thickness and hydraulic conductivity.
transpiration	Evaporation loss of water from the leaves of plants through the stomata; the flow of water through plants from soil to atmosphere. Source: eWater Toolkit Glossary *http://www.toolkit.net.au/support/Glossary.aspx*
troglofauna	Terrestrial animals living in caves and other air-filled subterranean spaces. Source: Tomlinson M and Boulton A 2008, *Subsurface groundwater dependent ecosystems: a review of biodiversity, ecological processes and ecosystem services*, National Water Commission Waterlines Occasional Paper No. 8, October 2008 *http://www.nwc.gov.au/resources/documents/Waterlines__subsurface_full_version.pdf*
typology	Classification of habitats into types defined by ecological descriptors. Source: Tomlinson M and Boulton A 2008, *Subsurface groundwater dependent ecosystems: a review of biodiversity, ecological processes and ecosystem services*, National Water Commission Waterlines Occasional Paper No. 8, October 2008 *http://www.nwc.gov.au/resources/documents/Waterlines__subsurface_full_version.pdf*
unsaturated zone	The areas below the ground where void spaces are filled with a mixture of water under pressure less than atmospheric which includes water held by capillarity and air (gases) under atmospheric pressure. Source: Poehls DJ and Smith GJ 2009, *Encyclopedic dictionary of hydrogeology*, Elsevier Inc., 517 pp.
vadose zone	See ‘unsaturated zone’.
variable	A measurable or quantifiable characteristic or feature.
ventilated chamber	Measures transpiration by sampling the vapour pressure of air entering and leaving a plastic chamber enclosing a tree. The difference in vapour pressure between the two samples in used to calculate the transpiration rate.
water balance	Balance of the water resources of a region, comparing precipitation and inflow with outflow, evaporation, and changes in storage.

watertable The top of the water surface in the saturated zone of an unconfined aquifer.

Source: USGS Definition of Terms
http://pubs.usgs.gov/ha/ha747/pdf/definition.pdf