Identifying groundwater dependent ecosystems
A guide for land and water managers

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Key points

Groundwater dependent ecosystems (GDEs) are important elements in the landscape that require access to groundwater to maintain their health and vigour. They are important because of their conservation, biodiversity, ecological, social and economic value.

There are two threats to GDEs—outright loss of habitat and outright loss of groundwater resources.

The presence of a GDE can be logically inferred from a set of observations or experimentally shown using a range of techniques. If groundwater is found to be within the rooting depth of the vegetation we may reasonably conclude that the vegetation is using that groundwater.

If diurnal changes in groundwater depth are observed, this is strong evidence of groundwater uptake by vegetation.

Although rain is the most common source of water for plants, there is a class of vegetation that routinely uses groundwater to support growth and photosynthesis. This class is said to be groundwater dependent because the absence of groundwater has a negative impact on the growth and health of the vegetation. Prolonged absence of groundwater from sites that formerly had groundwater available leads to plant death and a change in ecosystem composition—and hence ecosystem structure and function.

Thus, groundwater dependent ecosystems are ecosystems whose current composition, structure and function are reliant on a supply of groundwater. This reliance might be expressed every day of the year, or only for a few months every few years, but the reliance becomes apparent when the supply of groundwater is removed for a sufficient length of time that changes in plant function (typically rates of water use decline first) are observable.

There are many types of GDEs, but they can all be classed into one of two types. The first class of GDE relies on the surface expression of groundwater. Swamps, wetlands and rivers are ecosystems that rely on the discharge of groundwater to the surface, either into a river or into a swamp or wetland. Rivers and streams that flow all year (perennially flowing) are generally groundwater dependent because a significant proportion of their daily flow is derived from groundwater discharging into the river course. When groundwater availability declines, river flow is reduced and swamps and wetlands may become dry, temporarily or permanently.

The second class of GDEs rely on the availability of groundwater below the surface but within the rooting depth of the vegetation. These terrestrial ecosystems include riparian forests all across Australia, Banksia woodlands of Western Australia, eucalypts on the floodplains of the Murray River and plantation forests in South Australia, Victoria and New South Wales. They all require a supply of groundwater within the root zone.

GDEs are important for a host of reasons. Some have obvious and immediate commercial value (for example, plantations). Some have tourism value. Tourists like to see rivers flowing and healthy. Riparian forests provide pathways for the movement of animals across fragmented landscapes. The dewatering of landscapes by trees can stop the development of dryland salinity, while their ability to hold onto soil and capture run-off is important in maintaining land and water quality. Therefore, preserving our GDEs is valuable at many levels.

Introduction

What are groundwater dependent ecosystems and why do we care about them?

All vegetation requires water to grow. Even desert cacti need occasional rainfall to sustain them. For most plants, rainfall is the dominant and often the only source of water available, although the water present in fog and mist can supply a small fraction of the water needs for some plants in some locations. Water is required by plants to keep leaves turgid, to drive growth and to provide a medium for all the biochemical reactions that take place in cells. In addition, a large amount of water is lost from leaves as transpiration when stomata open to allow carbon dioxide in for photosynthesis. Without photosynthesis [and therefore without the water that is transpired during the day] plant growth ceases, crops produce no yield and life grinds to a halt.

Drilling to access the water table is a dirty business
Threats to groundwater dependent ecosystems

There are two principal threats to GDEs. The first arises from the development of land for commercial purposes. The construction of towns and suburbs often results in the removal of riparian forests while the drainage of wetlands and swamps for grazing or construction use represents a significant threat to these GDEs. These threats arise from changes in land-use and result from active decisions to remove these types of vegetation from a site. In contrast, the most poorly understood threat to GDEs generally arises as an unintended consequence of groundwater pumping/extraction. When groundwater is extracted at a rate that exceeds the rate of recharge the water table drops. This will reduce the flow of groundwater into nearby rivers, wetlands and swamps, thereby causing these systems to become water stressed. It can also take the water table to depths that exceed the maximum rooting depth of the vegetation and therefore the vegetation becomes water stressed.

The response of vegetation to reduced availability of groundwater

The response of vegetation to reduced availability of groundwater is incremental. A well-defined sequence of events is shown below. Initially, following a decline in groundwater availability, plants show short-term adaptive responses, the most important of which is a reduced opening of the stomata on leaves. This occurs to reduce the amount of water required by the plant canopy, but it also reduces the rate of carbon fixation and hence growth is also reduced. If the decline in availability persists, the leaf area index of the site declines as trees lose their leaves in an effort to further reduce their water use. Growth is now very much reduced. Recruitment of seedlings of the current suite of species is reduced and over time seedlings of new species are observed. Over the following decades, the overstory stand of now-dead trees is replaced with a new suite of species more suited to the more arid environment.

A schematic outline of the response of plants and communities of plants to reduced availability of groundwater.
How to identify groundwater dependent ecosystems

Ecosystems reliant on surface availability of groundwater

If it is suspected that a wetland/swamp or river is groundwater dependent, then positive answers to one or more of the following nine questions will support this:

1. Does a river flow all year, or a wetland or swamp remain wet all year despite prolonged periods of zero surface flows (that is, zero or very low rainfall)?

2. Within an estuary, does the salinity drop below that of seawater in the absence of surface water inputs (eg. tributaries or stormwater)?

3. Does the volume of flow in a stream or river increase downstream in the absence of inflow from a tributary?

4. Is groundwater discharged (eg. a spring) to the surface for significant periods of time each year? If such a resource is present, some species present are likely to be adapted to be using it.

5. Is the vegetation associated with the surface discharge of groundwater different (in terms of species composition, phenological pattern, leaf area index or vegetation structure) from vegetation nearby that is not associated with this groundwater?

6. Is the annual rate of water use by the vegetation significantly larger than annual rainfall at the site, and the site is not a run-on site? For example, low-lying paperbark (Melaleuca spp.) swamps in the NT receive surface and sub-surface (lateral) flows of water.

7. Are plant water relations (especially pre-dawn and midday water potentials and transpiration rates) indicative of less water stress (potentials closer to zero; transpiration rate larger) than vegetation located nearby but not accessing the groundwater discharged at the surface? The best time to measure this is during rainless periods.

8. Is occasional (or habitual) groundwater release at the surface associated with key developmental stages of the vegetation (such as flowering, germination, seedling establishment)?

9. Can small (typically less than 20 mm per day) fluctuations in the depth to groundwater be seen in the aquifer with a diurnal periodicity?

Affirmative answers to one or more of these questions support the inference that the system is likely to be a GDE, if we accept the view that when a resource is present, at least some species will be accessing that resource.

Ecosystems reliant on sub-surface availability of groundwater

The presence of ecosystems reliant on sub-surface presence of groundwater may be inferred from positive answers to one or more of the following questions:

1. Are roots able to reach the water table? If roots can reach a source of fresh water it is generally true that this water will be absorbed by the roots and transpired by the canopy.

2. During extended dry periods, does a significant proportion of the vegetation remain green and physiologically active? The green region might be using groundwater to maintain its physiological activity.

3. Are large changes in leaf area index apparent at some locations but not others within a small geographical range? The area not showing a large change in LAI might be accessing groundwater while the area that does show large intra-annual changes in LAI is probably not.

4. Is the vegetation associated with the surface discharge of groundwater different (in terms of species composition, phenological pattern, leaf area index or vegetation structure) from vegetation close-by but which is not associated (ie. accessing) this groundwater?

5. For sites that are not receiving significant amounts of lateral surface and sub-surface flows, is the annual rate of water use by the vegetation significantly larger than annual rainfall at the site?

6. Are plant water relations (especially pre-dawn and midday water potentials and transpiration rates) indicative of less water stress (potentials closer to zero; transpiration rate larger) than vegetation located nearby but upslope. The best time to measure this is during rainless periods.
7. Are seasonal changes in groundwater depth larger than can be accounted for by the sum of lateral flows and percolation to depth (that is, is vegetation a significant discharge path for groundwater)?

As the water table drops at a site (due to groundwater pumping or because of extraction by plant roots in the absence of rainfall plus lateral flow to nearby rivers) the water potential of leaves declines to maintain the flow of water from the soil to the leaf. Once the water potential of leaves reaches a lower limit stomata close, water use declines to almost zero and carbon uptake by leaves stops. Once stomata remain closed for too long, leaf mortality increases and eventually leaf loss occurs.

A simple case study illustrates this point. In the Howard River of the Northern Territory, the rainless dry season lasts from May to October inclusive. During this time, the water table drops by 6–12 m (1–2 m per month) because of (a) lateral flow of groundwater into the Howard River; (b) uptake by deep rooted evergreen trees; (c) cessation of rain for the 6 month dry season. Because of this drop in the water availability of the upper soil profile, pre-dawn leaf water potential declines by between 0.5 MPa and 1.5 MPa. Therefore pre-dawn water potential is a fast, accurate, and simple measure of reduced soil water availability, including a decline arising from a drop in the water table. It can also be used to compare an ecosystem that is thought to be groundwater dependent with an adjacent ecosystem that is known not to be groundwater dependent. We must choose an adjacent ecosystem so that the rainfall, temperature regime and humidity experienced by the two systems are matched.

Thus, in a dry spell if we compare the pre-dawn water potential of a groundwater dependent ecosystem that has groundwater available, and an adjacent ecosystem that does not access groundwater, we would expect to see a lower water potential in the latter site because of the absence of the water supplied by the aquifer.

Another case study illustrates this point. Alongside the Daly River in the NT is a complex riparian forest. Trees close to the river’s edge are close to groundwater but trees located up to 80 m away from the river can be up to 10–12 m above the water table. Measurements of pre-dawn water potential along this transect show that on the same day pre-dawn water potential declined as depth to the water table increased.

A range of simple tools to measure plant function and groundwater dependency

Leaf water potential

As soil water availability declines, leaves must reduce their water potential further below zero (water potential is either zero or has a negative value). As water potential of leaves get lower and lower (for example, dropping from -0.5 MPa to -1.5 MPa) the plant is becoming more and more water stressed and growth rates decline. There is a limit to how low leaf water potential can decline, but this is site and species specific.
Measurements of leaf water potential are rapid, require only one piece of equipment (a leaf pressure chamber) and the equipment is readily portable to most sites. A full description on the method is given in Eamus et al. 2006. Most universities and environmental consulting companies are able to make these measurements.

Using stable isotopes and profiles of soil water potential

Trees and shrubs mostly access water from the upper unsaturated soil profile. However, for groundwater dependent ecosystems, roots also extract water from the capillary zone above the water table.

Stable isotopes are isotopes of an element that do not radioactively decay and are therefore stable over time. Two important stable isotopes for ecohydrology are those of oxygen and hydrogen. The most abundant form of oxygen is O\textsuperscript{16}. This is a stable isotope and accounts for about 99.76% of all oxygen. O\textsuperscript{18} is also a stable isotope of oxygen and this accounts for about 0.2% of all oxygen. For hydrogen, H\textsuperscript{1} accounts for about 99.985% of all hydrogen and this is stable, as is deuterium (H\textsuperscript{2}) which accounts for about 0.015%.

Water consists of two atoms of water and one atom of oxygen (H\textsubscript{2}O). The ratio of H\textsuperscript{2} to H\textsuperscript{1} or the ratio O\textsuperscript{18} to O\textsuperscript{16} is variable in different bodies of water. Because the molecular weight of each of these molecules is slightly different, we can quantify the amount of H\textsubscript{2}O\textsuperscript{16} and H\textsubscript{2}O\textsuperscript{18} or H\textsuperscript{1}H\textsuperscript{2}O\textsuperscript{16} in soil water, xylem sap and the water table and compare them and therefore answer whether the trees are accessing water from the water table. If they are not, then the xylem water and upper soil water isotope composition will match.

As depth to water table increases, pre-dawn water potential declines. (Data modified from O’Grady et al 2006).
In many cases, water is absorbed from more than one source. Whilst this makes interpretation more difficult, a linear mixing model of water can be applied to determine the relative contribution of the two sources of water used by the tree. A simple case study can be used to illustrate the application of this technique. At a site in a tropical remnant woodland in Queensland, O’Grady and co-workers compared the H$_2$O$^{16}$ and H$_2$O$^{18}$ ratios of soil water in the upper two metres with the ratios observed in groundwater at a depth of 10 m and in the water of the xylem of tree branches. They found that the groundwater had an O$^{18}$ composition of about -3.5 $\delta$oo (parts per thousand), the upper soil profile had an O$^{18}$ composition of about -2.2 $\delta$oo and the water in the xylem of *Corymbia clarksoniana* had an O$^{18}$ composition of about -4.0 $\delta$oo. Therefore they concluded that *C. clarksoniana* was using groundwater. In contrast, *Eucalyptus platypylla* growing at a nearby site, had an O$^{18}$ composition of about -3.75 $\delta$oo which was close to that of the upper soil profile (about -3.5 $\delta$oo) and very different from that of the groundwater (about -4.8 $\delta$oo).

Confirmation of the stable isotope interpretation can be obtained by examining the pattern of soil water potential through the soil profile down to the water table. For example, in the figure below we see that the top 0.25 m of the soil profile is very wet—there has just been a rain event at the site. Similarly, at depths of 4.5 m or more, the soil profile is wet (water potential close to zero) as no roots are present here. But in between these regions there is a dry region (water extracting most of their water. potentials lower than -1.0 MPa). The dry regions represent the depth from which roots are extracting most of their water.

A significant decline in the water potential of soil such as that observed between 0.8 and 2m depth indicates that significant water uptake by vegetation is occurring from these depths.
To measure the isotope composition of water requires use of a mass spectrometer to accurately measure the ratios of H\textsubscript{2}/H\textsubscript{1} and O\textsuperscript{18}/O\textsuperscript{16} in the water taken from the tree, the soil, the river and the groundwater samples. The cost of measuring 50 samples would be in the order of $2500 in 2008 prices. Many universities and environmental consulting companies provide this service to land and water managers. To measure soil water potential, a filter paper method can be applied (see Greacen et al. 1989).

**Soil sampling to the water table to establish root depth**

An unequivocal observation that can be made with respect to groundwater dependency is the presence of roots within the capillary fringe of an aquifer. For some soils where the water table is relatively shallow, percussion coring to the depth of the water table can be used followed by close examination of the core for roots. Alternatively, use of a medium-to-large back-hoe to excavate to the required depth, with examination of the soil extracted or examination of the soil cross section of the excavated hole can then be used to ascertain the presence/absence of roots.

**Using leaf area index—on ground measurements and remotely sensed data**

The leaf area index (LAI) of a site is the ratio of the total leaf area of a canopy to the ground area covered by the canopy. The most accurate method of measurement requires the canopy to be cut and the total leaf area in the canopy to be measured after removing all the leaves from the plants. A leaf area meter is used to measure leaf area. This approach is time consuming, expensive, dangerous and destructive and can only be done once at a given plot. It is therefore impractical.

An alternative method uses a commercial LAI meter. Measurements must be made beneath a canopy and above the canopy (or in a very large clearing within the forest) simultaneously and the sun must not be present within the field of view of the sensor. Therefore measurements are usually made at dawn or dusk or in a completely overcast [cloudy] sky. This makes the collection of many measurements within a forest problematic. The sensor is also expensive.

A newer, faster and cheaper method is now available that requires only a standard digital camera, a tripod and access to some specialised software. This method requires upward facing pictures to be taken from the camera attached to the tripod. Typically 50–100 pictures can be taken in a single morning, but again the sun should not appear in the picture. Using analyses detailed in MacFarlane et al. it is possible to calculate the LAI of the site. Why is this useful? For two reasons. First, a comparison of the LAI of two adjacent sites during a prolonged dry spell can tell us if one site is losing leaf area faster than another. Sites with access to groundwater are expected to lose LAI more slowly than sites unable to access groundwater. Second, a far larger LAI on one site adjacent to a second site usually arises because of a larger annual water supply at the site with a larger LAI. If it can be established that there is no significant surface nor sub-surface lateral flow to the site with a larger LAI, the presence of the larger LAI is usually a strong indication of groundwater supply.

It is now possible to measure LAI using remotely sensed [satellite based] data. One instrument that is widely available is MODIS (or Moderate Resolution Imaging Spectroradiometer). This is an instrument aboard the TERRA and AQUA satellites which orbit around the Earth from the north pole to the south pole (TERRA) or from the south pole to the north pole (AQUA). Terra MODIS and Aqua MODIS view the Earth’s surface every one to two days, acquiring data about the earth’s surface in 36 spectral bands. These data are used to calculate LAI of sites all around the world, including Australia. More importantly, historical data going back a decade or more can be obtained and therefore the changes in LAI of patches of vegetation during wet and dry periods can be compared.

Sites accessing groundwater are expected to maintain a larger leaf area index and maintain this leaf area index for longer into a drought, than adjacent sites that do not access groundwater.

**Spatial resolution** (the smallest patch of vegetation the sensors can see) is 250 m x 250 m.

**Depth to groundwater**

If rooting depth is known at a site (through measurement or knowledge of published...
measurements of root depth of similar species) and it can be shown that the groundwater or its associated capillary fringe is within this depth, it is reasonable to conclude that the roots will be using groundwater.

The depth of groundwater relative to the land surface is determined by measuring the water level in a hole in the ground (a well). In an open well (that is, in an unlined well), the measured depth is equivalent to the actual water level of the surrounding aquifer. Groundwater level in a well can be determined by manual “dipping” with a measuring tape and a sensor that signals contact with water. Increasingly, however, electronic water level recorders are permanently deployed down the hole in association with a single channel data logger, which continuously records water levels. The temporal dynamics assessed through continuous recording can give crucial insights into water table dynamics and aquifer processes that infrequent manual sampling cannot provide.

**Diurnal changes in groundwater depth**

In many arid and semi-arid regions of Australia (and globally), evapotranspiration through plants is a major pathway for the discharge of groundwater. Measuring the depth of the water table at half-hourly intervals using data loggers and depth sensors is a cheap, simple and routine procedure and therefore using diurnal changes in groundwater depth can, in some locations, be a useful indicator of groundwater use by vegetation.

A simple case study can illustrate use of this technique. For this method to demonstrate water use by groundwater dependent vegetation, the root zone must be within the capillary zone of the aquifer. A strong relationship between net radiation and rates of decline in the water table is a strong indicator that vegetation is using groundwater, since net radiation is a principle determinant of vegetation water use. Similarly, finding maxima and minima in the depth to water table that show a 24 hour cycle is also a strong indication of vegetation discharge of groundwater.

Lautz (2008) monitored groundwater depth every 20 mins with a standard water table logger for several months in the Rocky Mountains of the United States. As is often observed, the water table was closest to the land surface around dawn because of overnight recharge in the absence of transpiration from vegetation. During the day evapotranspiration caused the water table to decline. The difference in height between these two extremes represents discharge of water through vegetation. Converting changes in water table depth to volume of water removed requires estimation of the specific yield of the aquifer sediments. Groundwater use can be quantified from:

$$E_{gw} = S_y'(24R_{gw} + s)$$

Where

- **$E_{gw}$** = groundwater evapotranspiration
- **$S_y'$** = Readily available specific yield of the aquifer
- **$R_{gw}$** = hourly rate of water table rise observed between 00:00 and 04:00h arising from groundwater influx in the absence of evapotranspiration
- **$±s$** is the 24h rise or fall in depth of the water table.

Actual evapotranspiration is taken as the difference between the actual depth of the water table observed at 00:00 each day and the depth expected if the only cause of the change in depth to water table was due to lateral groundwater flow. In the event of rainfall and subsequent recharge of the aquifer, the water table can rise and negative evapotranspiration is calculated (incorrectly). Therefore the method cannot be applied under these circumstances. The readily available specific yield is not the same as the classic hydrological specific yield of an aquifer. It is the volume of water that can readily drain from an aquifer in 24 hours, per metre of drop in water table.

Guidelines for converting classic specific yield to readily available specific yield are given in Loheide *et al* (2005).

This method cannot be applied if there are rainfall events that lead to recharge, or if pumping from groundwater wells is occurring sufficiently close to affect the measurement wells, or if there are significant changes in stream depth close by which can cause or reflect changes in groundwater flux into and out of the aquifer.
A water balance approach to determining groundwater use

For much of the Australian continent, native vegetation uses 90–98% of available rainfall (available rainfall is rain that reaches the ground; a fraction of all rainfall doesn’t reach the ground because it gets intercepted by the over and understorey canopy and leaf litter and is evaporated back to the atmosphere).

If the amount of water being used by vegetation each year can be estimated and it is found to be significantly larger than the annual available rainfall for the site, we can conclude that groundwater is being used (or the site receives significant lateral surface or sub-surface lateral flow).

The net water balance of a site can be estimated from:

\[ Q_n = P - (I + E_s + T) - (S_c - S_p) \]  \[2\]

Where \( Q_n \) = net water balance

\( P \) = gross total rainfall

\( I \) = interception loss

\( E_s \) = soil evaporation

\( T \) = transpiration

\( S_c \) = current soil water content

\( S_p \) = previous soil water content

\( I + E_s + T \) = total evapotranspiration, and

\( Q_n \) is negative if water use exceeds rainfall input and positive if there is deep drainage of water past the roots.

A stylised representation of changes in groundwater height over a 34 hour period starting at midnight. Groundwater height increases during the night and declines in the day. Based on Lautz 2008.
Tree water use can be measured using sensors embedded into the sapwood of the tree.

Total rainfall can be obtained on site with rain gauges or estimated from the nearest meteorological station. Losses can be estimated as the difference between gross rainfall and throughfall. Throughfall is measured with collection troughs distributed across the site. Soil evaporation is measured with mini-lysimeters installed across the site and soil water content is measured at a number of depths with neutron moisture meters, gravimetrically or with soil capacitance probes or an array of frequency domain reflectometry sensors (Theta Probe, ML2-X, Delta-T devices, Cambridge).

Transpiration is the largest single mechanism by which rainwater is lost from a relatively flat site (sites with steep terrain lose a large proportion of rain through surface flow down the slope). To measure transpiration, a number of techniques can be used. Briefly,

1. Eddy covariance techniques can be used above woodlands, forests and pastures, but these are technically challenging and expensive.

2. A Bowen ratio method can be used above short crops or pastures. This is less technically challenging and cheaper, but still requires significant data processing.

3. Sapflow measurements with probes inserted into trees, with subsequent scaling using sapwood area is relatively simple if coupled to models, such as the modified Jarvis-Stewart model or the Penman-Monteith equation.

4. Remotely sensed algorithms that include MODIS data are becoming increasingly available for regional-scale estimates of evapotranspiration. However, they remain a research tool rather than a commercially available aid to management, although this will change within the next two to five years.

Two simple case studies can help illustrate these approaches.

Benyon et al. (2006) used a water balance approach [equation 1] to establish the degree to which groundwater was being used by plantations in the south-east of South Australia. Using long-term data [more than 400 days] derived from sapflow sensors, rain gauges and measurements of soil moisture, it was shown that annual tree water use greatly exceeded rainfall (by 30–300 %) and, importantly, on an annual basis there was no significant change in soil moisture content.

It was therefore concluded that groundwater was being used at these sites. It was also established that sites where the water table was more than 7.5 m deep did not use groundwater and sites with the most shallow groundwater (1–5 m) exhibited the largest calculated groundwater use.

The Benyon et al. (2006) study also illustrates the relationship between transpiration rate and groundwater supply to roots. Sites with the largest rates of transpiration were shown to be the largest users of groundwater (see graph which follows).
Most recently, Whitley et al. (2008) have used short-term data [59 days] derived from sapflow sensors, soil moisture content in the upper 50 cm of soil and meteorological data (net radiation and humidity) to derive a simple three parameter model (a modified Jarvis-Stewart model) and have produced annual rates of tree water use, which when used with rainfall data, can be used to establish a simplified water budget.

The rate of transpiration is greatest for sites with access to groundwater (open squares, dotted line). For sites with a similar range of LAI (3–4.2) the rate of transpiration was larger when groundwater was available (open squares, dotted line) than when it was not (closed diamonds, solid line). Data redrawn from Benyon et al. 2006.

It is clear that the technology and models currently available can be used to establish a simplified water budget from which valuable inferences can be made concerning groundwater access by woodland and forests.

Conclusions

An inferential approach to establishing the presence of a groundwater dependent ecosystem [frequently called a desk-top methodology by consultants] has been the most commonly applied methodology for local councils, catchment management authorities and State departments of resource management. However, it is hoped that more robust, evidence-based methodologies, such as those outlined in this document will supplant these in the near future. A more rigorous approach will be able to better quantify the location, water requirements and nature of groundwater dependency of GDEs, thereby enhancing the environmental outcomes of sustainable resource management.
Stand transpiration measured with sapflow sensors ($E_{\text{stand}}$, data points) and estimated stand transpiration from the modified Jarvis-Stewart model (JS, black line), the Penman-Monteith equation (PM, grey line), and artificial neural network (ANN, dotted line) over the sampling periods in a) January, b) February, c) July and d) September 2004.
Further reading


Glossary of terms

**Capillary fringe**—the zone of water found immediately above the water table which is held at field capacity rather than saturation.

**Groundwater dependent ecosystems**—ecosystems that require a supply of groundwater to remain healthy and viable in the landscape.

**Leaf water potential**—a concept applied to the water in soil and leaves and stems. Low (negative) values indicate water stress. Values close to zero (but still negative), indicate non-stressed conditions.

**Sapflow**—the movement of water up the sapwood of a tree.

**Specific yield**—the ratio of the volume of water in the water table that will drain freely under gravity, to the volume of the water table itself.

**Stable isotopes**—an isotope that does not decay radioactively.