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Where to locate a tree plantation within a low rainfall catchment to minimise impacts on groundwater resources

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Abstract

Despite the fact that there are many studies that consider the impacts of plantation forestry on water resources, and others that explore the spatial heterogeneity of groundwater recharge in dry regions, there is little marriage of the two subjects in forestry management guidelines and legislation. Here we carry out an in-depth analysis of the groundwater and surface water regime in a low rainfall, high evapotranspiration paired catchment study to examine the impact of reforestation, using water table fluctuations and chloride mass balance methods to estimate groundwater recharge. Recharge estimations using the chloride mass balance method were shown to be more likely representative of groundwater recharge regimes prior to the planting of the trees, and most likely prior to widespread land clearance by European settlers. These estimations were complicated by large amounts of recharge occurring as a result of runoff and streamflow in the lower parts of the catchment. Water table fluctuation method estimations of recharge verified that groundwater recharge occurs predominantly in the lowland areas of the study catchment. This leads to the conclusion that spatial variations in recharge are important considerations for locating tree plantations with respect to conserving water resources for downstream users. For dry regions, this means planting trees in the upland parts of the catchments, as recharge is shown to occur predominantly in the lowland areas.

1 Introduction

Tree plantations are known to have the potential to negatively impact groundwater and surface water resources (e.g. Bell et al., 1990; Benyon, 2002; Bosch and Hewlett, 1982; Jobbagy and Jackson, 2004; Scanlon et al., 2007; van Dijk et al., 2007), particularly in dry regions (low rainfall and high evapotranspiration), where the high transpiration demands of the trees make them a significant user in the water balance (e.g. Benyon et al., 2006; Fekeima et al., 2010; Jackson et al., 2005; Schofield, 1992). Groundwater

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recharge and discharge in dry regions are also affected by a variety of other factors that cause substantial spatial variability, in particular topography, soil characteristics and geology (e.g. Delin et al., 2000; Scanlon et al., 2002; Schilling, 2009; Webb et al., 2008; Winter, 2001). But the important conclusions made in these studies have not been brought together with the results of tree plantation studies, and directly applied to water resource management problems accompanying the establishment of tree plantations (Farley et al., 2005). In southeast Australia this issue is particularly relevant because efforts over the past few decades to reforest land that was cleared in the late 1800s by European settlers (Schofield, 1992), are causing difficulties for land managers trying to define sustainable action plans for surface water and groundwater (Dalhaus et al., 2008; Jackson et al., 2005; Nicholson et al., 2006).

The earliest work on defining groundwater systems (Chamberlin, 1885; King, 1899), which forms the basis of our modern conceptualisation of groundwater recharge and discharge (Domenico and Schwartz, 1998; Drever, 1997; Toth, 1963), shows topography to be a major control; groundwater is predominantly recharged at topographic highs, and discharges at topographic lows where the upward hydraulic gradient prevents recharge from occurring (Fig. 1; Domenico and Schwartz, 1998; Schilling, 2009).

However, in arid and semi-arid regions, recharge during rainfall events often occurs predominantly in local depressions and along ephemeral streams, due to the focussing of overland flow in these areas, encouraging infiltration; the presence of preferential pathways in these areas, along which infiltrating water may more readily reach the water table may also be a factor (Delin et al., 2000; Scanlon et al., 2002; Schilling, 2009; Winter, 2001). In these groundwater systems, recharge occurs to a large extent in topographic lows (diverging from the early conceptual models such as Fig. 1), because water tables under ephemeral streams are generally below the stream bed (except during extended rainfall events), and therefore upwards groundwater gradients do not occur most of the time.

Vegetation can also play a significant role in reducing recharge by intercepting rainfall and evaporating it from leaf surfaces and by transpiration (Scanlon et al., 2002;

Winter, 2001). Altering land cover can therefore affect recharge patterns; for example, the replacement of native forest vegetation by pasture and crops, which use less water, has led to increased recharge, rising water tables and ultimately water and land salinisation in southeast Australia (Allison et al., 1990; Bennetts et al., 2007). In contrast, afforestation of cleared farmland is likely to decrease recharge (Benyon et al., 2006). In particular, the evergreen Eucalyptus tree plantations commonly planted in southeast Australia take up and transpire significantly more water than pasture, their canopy intercepts more rainfall and allows it to evaporate, and their roots reach greater depths than grasses, meaning they can extract and transpire water from a larger volume of the soil column (Bosch and Hewlett, 1982; Feikema et al., 2010; Hibbert, 1967). This recharge reduction is the reason why some studies have suggested using targeted tree plantations to reduce recharge in areas where there are high rates of saline groundwater discharge (e.g. Bennetts et al., 2007). Tree plantations also sequester carbon dioxide, prompting ongoing debate over the trade-off between increased water use by trees versus their increased carbon sequestration potential (Farley et al., 2005).

Despite the evidence that recharge is often concentrated in topographic lows, the authors have observed that many groundwater management strategies in southeast Australia still operate on the assumption that recharge occurs primarily in the upper parts of catchments, particularly along the ridgelines. Current regulations for tree plantations in Australia focus on the percentage of a given catchment that can be forested, rather than what areas should be planted to maintain or intercept groundwater recharge, depending on the management application.

Here we present the findings from a paired catchment study in southwest Victoria, Australia, where one catchment is planted with a tree plantation, and the adjacent catchment is covered with pasture. This approach largely removes the variables of climate, topography, soil and geology, with the only major difference between the two catchments being vegetation cover. Groundwater recharge patterns and conceptual models of groundwater flow are used to assess the impact of a *Eucalyptus globulus* plantation on the hydrologic and hydrogeologic regime, and this understanding is then used to determine the best areas to site tree plantations within dry region catchments.

2 Background

This study is part of a multi-site, paired-catchment investigation into the impacts of land use and climate change on the quality and quantity of groundwater and surface water resources in western Victoria, Australia (Dresel et al., 2012; Dean et al., 2014; Adelana et al., 2014).

2.1 Site description

The study area consists of a pair of small, adjacent catchments at Mirranatwa in south-western Victoria, one covered predominantly in a recently planted (July 2008) *Eucalyptus globulus* (Blue Gum) plantation (0.8 km^2), the other a farm, mostly pasture for sheep grazing (0.4 km^2; Fig. 2).

Both catchments are underlain by the same weathered/fractured aquifer, the Devonian Dwyer Granite (390–395 Ma; Hergt et al., 2007; VandenBerg 2009). The upper ~ 20 m of the granite is well-weathered, porous and permeable saprolite; below this is relatively fresh, fractured bedrock. The fractured granite aquifer extends no deeper than 150 m, as below this depth the fracture conductivity is negligible due to the high lithostatic pressure (Boutt et al., 2010; Cook, 2003; Dept. Sustainability and Environment, 2012). The granite saprolite is generally thicker beneath the lower parts of the catchment than along the ridges, and is overlain by up to 7 m of alluvial/colluvial material along and adjacent to drainage lines. This alluvium/colluvium is clay-rich and impermeable in places, causing temporally variable artesian behavior in some of the bores along the drainage lines in both catchments. The topography of the site (hills in the middle of a broad valley, Fig. 2) means both catchments are local ground water systems, and there are no regional groundwater inputs. There is 50 m of relief in the plantation

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catchment, and 30 m in the farm catchment; both catchments have reasonably steep hills separated by a marked break in slope from the more or less flat topography along the drainage lines (Fig. 2).

The climate is Mediterranean, maritime/temperate (Cfb in the Köppen classification); the average annual rainfall for the area is 672 mm ($\pm 125\,\sigma$), while pan evaporation is around 1350 mm annually, exceeding rainfall for the majority of the year, excepting the winter months of May to September (data from Bureau of Meteorology, Hamilton, Australia). Runoff ratios for the farm and plantation catchments are 3.4 % and 4.3 % respectively (based on the stream hydrograph records).

Vegetation of the area prior to European settlement was mostly open eucalypt woodland (Department of Sustainability and Environment, Victoria). Following European settlement there was extensive land clearance, and the catchments were entirely converted to pasture by 1869 (White et al., 2003). 60 % of the northern catchment was subsequently converted to an *E. globulus* plantation in July 2008 (Fig. 2). Prior to the planting of the eucalypts, the eucalypt plantation catchment (Euc – Table 1) was used for grazing, and was virtually identical to the pasture grazing catchment (Pas – Table 1) immediately to the south. During the planting of the trees the eucalypt catchment was ripped to an average depth of 800 mm and mounded to an average height of 300 mm. The tree density is 1010 stems per ha (2.2 m between trees along a row, and 4.5 m between rows), and fertilizer was applied following ripping and mounding at 60 kg per ha (McEwens Contracting, personal communication, 2011). The tree rows run east-west in the main north-eastern part of the catchment, and north-south to the west of H Addinsalls Road (Fig. 3).

The pasture catchment has 13 bores drilled to different depths, and the eucalypt catchment has 10 bores; (the bores may be considered to be piezometers – each is screened towards the bottom of the casing over a two metre interval; Table 1). A groundwater logger was installed in every bore in the eucalypt catchment in August 2009, measuring at a minimum four hour time interval, and eight bores in the pasture catchment have loggers measuring at the same frequency. Seven bores in the eucalypt catchment and two bores in the pasture catchment were drilled for this project in late 2009; the other bores were installed in the late 1980s in the pasture catchment, and the mid-1990s in the eucalypt catchment. There is a v-notch weir at the end of each catchment on both streams, with one bore immediately adjacent to the eucalypt catchment weir and two next to the pasture catchment weir (Fig. 2). The bores adjacent to the weirs have Campbell CS450-L pressure transducers (accuracy ±0.01 m) measuring water level and electrical conductivity (EC) at 30 min intervals, while the other bores have Schlumberger Mini Diver loggers (accuracy ±0.025 m) measuring only water level. At the weirs the surface water level was measured using a standard V-notch construction, and EC was recorded using a logger in the weir pool (Dresel et al., 2012). Prior to installation of groundwater loggers in the older bores, groundwater levels were generally measured manually every month.

There are two small dams in each catchment, ranging in size from 10 m^2 to 50 m^2; they are not large enough to significantly impact the hydrology of the site (Fig. 2). The roads at the site are single lane and unsealed, and although they are less permeable than the normal ground surface and therefore promote runoff, their very small area means that they have negligible impact on the site hydrology.

3 Methods

Groundwater levels, surface water flow and rainfall data were collected from August 2009 for this study, with some older data available from the Department of Environment and Primary Industries, Victoria, archives. Groundwater recharge values and hydrographs are based on the groundwater logger data collected in this study from August 2009 to February 2013. The long-term groundwater levels are from manual measurements going back as far as 1986 in some cases. The chloride mass balance method for estimating recharge is carried out using a range of rainfall chemistry (discussed further in Sect. 3.5.2), and groundwater and surface chemistry is available from sampling campaigns in August 2010 to August 2011 (Dean et al., 2014).

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3.1 Rainfall and streamflow

Daily rainfall measurements were available from a Bureau of Meteorology station (089019) approximately two kilometres south of the study site. To determine rainfall patterns, cumulative deviation from the monthly mean (CDM) values were calculated alongside daily values (Sect. 4.1), whereby the difference between a given monthly rainfall total and the average for that month (calculated from the entire station's data record of 1901 to 2012), was cumulatively summed from one month to the next (modified from Craddock, 1979). The CDM values represent the longer term rainfall patterns, with a sustained negative trend for drought periods and positive values indicating wetter than usual periods, and match well with the longer term hydrographs (Sect. 4.1).

Streamflow was measured at 30 min intervals at V-notch weirs at both catchment outlets and summed to annual totals and a total for the complete study period, 2009–2013. To allow comparison between catchments, volumes were converted to depth equivalents (mm) by dividing by the respective catchment area. Streamflow is derived predominantly from direct runoff, as the proportion of groundwater input into the stream is small (Sect. 4.2).

3.2 Grain size analysis

The grain size of the saprolite was used to estimate the average specific yield value for this aquifer over the whole study site, as the geology of the two catchments is very similar (see Sect. 2.1). During drilling of four bores on the eucalypt catchment, samples of the regolith were taken at one metre intervals to a depth of 10 m, or until bedrock was encountered. Samples were sieved using a two-millimetre sieve and the material that passed through was then analysed using a Malvern Mastersizer 2000.

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3.3 Groundwater composition

All 23 groundwater bores across the entire site were sampled once each over a period of a year, August 2010 to August 2011. Seasonal variability in groundwater composition is considered negligible due to the age of the groundwater at the study site, and repeat sampling produced virtually identical field parameters (Dean et al., 2014). Subsamples for Cl^- were filtered with 0.45 µm filter paper and were analysed using Ion Chromatography. Groundwater sampling, Cl^- analyses and calculations of average rainfall Cl^- concentrations are described in more detail in Dean et al. (2014).

3.4 ^{14}C analysis and tritium analysis

Dating of the groundwater was carried out to determine the time period over which recharge has occurred. Groundwater samples from all the bores at the study site were radiocarbon dated; there is no indication that the radiocarbon ages have been compromised by "dead" carbon in the regolith. In addition, seven bores in the eucalypt catchment and 11 bores in the pasture catchment (including the shallowest and deepest bores and a range in between), were dated using tritium (Table 1). The methodologies for both are described in detail in Dean et al. (2014). The dating results showed that the groundwater in both catchments was almost all recharged before the July 2008 establishment of the eucalypt plantation, so the groundwater composition is unrelated to the recent change in land use (Dean et al., 2014).

3.5 Radon (^{222}Rn)

Radon surveys were carried out on groundwater and surface water samples in both catchments to ascertain whether there is a significant contribution of groundwater to surface water flow. The ^{222}Rn content of surface water and groundwater was measured using the gas-extraction for H_2O accessory of the Durridge RAD-7 radon detector. The RAD-7 is an alpha particle detector that measures the decay of the radon daughters,

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^{214}Po and ^{218}Po. Samples from weirs and nearby bores, as well as upslope dams representative of disconnected surface water bodies (Fig. 2), were collected in 250 ml vials and aerated for five minutes to degas the radon into the air circulation within the instrument, which takes four measurements (five min each), and then gives the mean ^{222}Rn concentration in Bq / L (Durridge Co. Inc., 2010).

3.6 Groundwater recharge

To ensure robust estimates of groundwater recharge, two different, well established methods were used, namely the water table fluctuation method and chloride mass balance method. While both methods are in widespread use, they have known deficiencies, which are discussed below.

3.6.1 Water table fluctuations

The water table fluctuation (WTF) method for measuring groundwater recharge was first applied in the 1920s (Healy and Cook, 2002; Meinzer, 1923) and has since been refined (e.g. Jie et al., 2011; Scanlon et al., 2005; Sophocleus, 1991). The principle of this method is that rises in the groundwater hydrograph of an unconfined aquifer provide an estimate of recharge to the water table, calculated from:

$$R = S_y \frac{\Delta h}{\Delta t} \quad (1)$$

where recharge (R) is the product of the specific yield of the aquifer (S_y) and the change in hydrograph height (Δh) over a given time interval (Δt). This method assumes that recharge occurs vertically from piston flow and that water discharges continuously from the aquifer, causing a drop in the water table when recharge is not occurring. Therefore the change in hydrograph height from which recharge is calculated is the sum of the rise in the hydrograph, together with the decline in the hydrograph that would have occurred in the absence of recharge over the same time period (Healy and Cook, 2002;

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Jie et al., 2011). Several techniques have been developed to estimate the hydrograph decline: the graphical approach – where the exponential decay curve of the hydrograph is manually extended to coincide with the peak of the next recharge event (Delin et al., 2007), the master recession curve approach – where regression functions are assigned to simulate the potential hydrograph decline for each data time-step (Heppner et al., 2007), and the RISE approach – where the assumption is made that in the absence of recharge, no decline in the water table occurs (Jie et al., 2011; Rutledge, 1998).

It proved difficult to apply the graphical and master recession curve methods in the present study because they require the recession limbs to be exponential, and the recession limbs in the Mirranatwa hydrographs were often steep and straight (Fig. 4); this issue has been highlighted elsewhere (Cuthbert, 2014). In addition, because the streams in both study catchments are ephemeral, groundwater discharge as baseflow occurs only occasionally; the majority of groundwater discharge occurs at the bottom of the catchments and downstream of the catchment boundaries. As a result the RISE approach was adopted, i.e. the decay curve of the hydrograph was ignored, removing problems arising from irregular groundwater discharge. Applying the RISE approach means that the values calculated in this study potentially underestimate actual recharge, but when compared with the graphical approach carried out for a subsample of the same data, leads to very similar values.

Raw bore hydrograph data collected using data loggers at the site contain small fluctuations due to the impact of barometric pressure on the water column in the bore (Fig. 4a; Rasmussen and Crawford, 1997). The fluctuations in the water level and the barometric pressure are normally inversely correlated (Butler et al., 2011), and can be readily corrected (Rasmussen and Crawford, 1997; Toll and Rasmussen, 2007). At the study site these fluctuations are clearly correlated with barometric fluctuations (Fig. 4a), but are positively correlated, and as a result normal barometric compensation techniques could not be applied. Instead a 15-day moving average was used to remove the small fluctuations but retain the overall response to rainfall (Fig. 4b). The 15-day timestep is a narrow enough time period to incorporate recharge events and reflect the general trend of the hydrograph, but removes the small barometrically forced fluctuations that bear no relationship to rainfall (Fig. 4). Recharge was then calculated using Eq. (1), where Δh was taken as the sum of the increases in groundwater level over the timestep, and then summed for the entire length of the record. When there was a drop in groundwater level from one timestep to the next, this was taken as zero recharge. The measurement uncertainty of the loggers (±0.025 m) was used as the threshold for recognition of recharge for each 15-day timestep. The RISE method was also used to calculate recharge for the longer-term hydrographs (generally monthly measurements taken prior to logger installation).

A specific yield value of 0.095 ± 0.014 was calculated for the saprolite aquifer from the average grain size (clay to coarse sand; Table 2) of all the bore samples analysed (see Sect. 3.3), using a general relationship between specific yield and grain size from Tables 1 and 2 in Healy and Cook (2002). The estimation of specific yield is a potential source of considerable error in recharge calculations, as it can vary spatially and temporally (Healy and Cook, 2002). However, the specific yield value calculated here is comparable to other values from weathered granites in the region (0.043 – Hekmeijer and Hocking, 2001; 0.075 – Edwards, 2006). When calculating recharge, this specific yield was applied only to bores that are unconfined and screened within the saprolite, and is assumed to be representative for the whole site because of the relatively uniform nature of the soils (Table 2).

3.6.2 Chloride mass balance

The chloride (Cl^-) mass balance (CMB) method for calculating recharge is based on the relationship between Cl^- in groundwater and in precipitation, assuming that all Cl^- in the groundwater is derived from rainfall and remains in solution within the groundwater system, that direct recharge (R, in mm) occurs via piston flow, and that runoff is

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negligible:

$$R = P\frac{C_p}{C_{gw}} \quad (2)$$

where P is the amount of rainfall (mm), C_p is the concentration of Cl^- in P, and C_{gw} is the concentration of Cl^- in groundwater (Allison and Hughes, 1978; Scanlon et al., 2002). R was calculated at all bores using the groundwater Cl^- content (Table 1), and rainfall Cl^- content was the median value from three different sampling periods at nearby sites (Fig. 2): 1954–1955 at Cavendish (Hutton and Leslie, 1958), 2003–2004 at Hamilton (Bormann, 2004), and 2007–2010 at Horsham (Nation, 2009). These three sampling periods include a wet period (1954–1955) and two dry periods (2003–2004 and 2007–2009). The median rainfall Cl^- is $4.3 \pm 0.9\,mg\,L^{-1}$, and the annual rainfall is 672 ± 25 mm (1σ); the uncertainties associated with each value were used to estimate the overall uncertainty in the recharge values calculated. R is strongly governed by C_p in this equation, so it is important to take the variability in C_p, due to wet and dry climatic conditions, into account.

4 Results and discussion

4.1 Conceptual models of groundwater recharge

The groundwater hydrographs vary significantly across the study site (Fig. 5). Hydrographs from the upper parts of the catchment show a limited response to rainfall patterns during the period when detailed groundwater logger data is available (Fig. 5), and also over the longer term monitoring period of the older bores (Fig. 6). In contrast, bores on or close to a drainage line show a much greater sensitivity to sustained rainfall and streamflow events (Fig. 7). This is not due to differences in soil type and grain size, as these are more or less consistent across the catchments. Instead the steeper slopes

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in the upland areas direct runoff downslope to the lowland areas, which are therefore saturated for longer with a greater volume of water. In addition, the lower slopes cause the runoff to slow and increase infiltration into the soil.

Although this pattern is evident in the long-term water level data as well (Fig. 6), some bore hydrographs do not conform to this model. Euc84 and Euc85 (lowland bores), show very similar recharge patterns to Euc83 (an upland bore) because recharge at Euc84 and Euc85 is restricted by a localised confining layer (both bores frequently go artesian). The Pas74 hydrograph shows high recharge occurring despite its location upslope, where there is evidence of a secondary pathway for recharge other than infiltration, most likely through fracture flow as shown by geochemical evidence of rapid recharge along fractures (Dean et al., 2014), and the presence of significant amounts of tritium alongside a radiocarbon age of 790 years (Table 1).

Recharge in fractured rock aquifers like granite is often controlled to some extent by fracture heterogeneity (Cook, 2003), and multiple recharge pathways exist within the fracture network of the granite in the study area. This is shown by the presence of young groundwater (containing tritium, i.e. <50 years old) mixed with much older ^{14}C dates from bores in both catchments (Pas74, Pas81, Euc93 and Euc97; Table 1). However, the dominant control of recharge across both catchments is topography rather than fracture heterogeneity, as shown in the relatively flat hydrographs for most of the upland bores (Fig. 5).

4.2 The role of ephemeral streams in the conceptual model

The standard conceptual model of recharge (Fig. 1) indicates that recharge is unlikely to take place near drainage lines, because the discharge of groundwater in these areas means that water cannot infiltrate against the upward groundwater gradient, and it is commonly assumed that recharge primarily occurs in upland areas along rocky outcrops. However, in semi-arid regions focused recharge in low-lying areas has been shown to be a dominant mechanism of groundwater recharge (Scanlon et al., 2002; Schilling, 2009; Webb et al., 2008; Winter, 2001), and the groundwater hydrographs at

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the study site conform with this model (Fig. 5), as previously mentioned. The streams at the study site are ephemeral, flowing on average only 40 % of the time. When they are dry, recharge occurs readily along and near the streambeds, because upwards groundwater gradients are not present when the water table is below the base of the stream. The rapid response of groundwater to streamflow is demonstrated by bore Pas96 near the outlet of the pasture catchment (Fig. 7), and other bores in the lower parts of the catchment show a clear but not instantaneous link between recharge and runoff (Fig. 7).

The eucalypt catchment stream has more high flows than the pasture catchment (Fig. 8), and this flashier flow regime is probably caused by the orientation of the ripping and mounding of the catchment slopes during planting. The furrows, which run parallel to the slope direction over about 60 % of the planted area (Fig. 3), channel runoff rapidly down the slope towards the lower parts of the catchment.

The stream in the eucalypt catchment also has more low flows than the pasture catchment (Fig. 8). Higher levels of ^{222}Rn in the surface water measured at the eucalypt catchment weir (11 Bq cm^{-3}) compared to the pasture catchment weir (1 Bq cm^{-3}) show that groundwater is discharging into the stream at the bottom of the eucalypt catchment (Figs. 8 and 9), where granite bedrock lies less than two metres below the surface, forcing groundwater towards the surface (Fig. 8). During periods of little or no rainfall, the water table remains below the surface at the downstream end of the eucalypt catchment, but when it begins to rain and the system wets up, the water table rises and groundwater begins to discharge here. Continued rain raises the water table so it connects to the stream further upstream, increasing the length of the stream that receives groundwater discharge (Fig. 8; Adelana et al., 2014). When rainfall ceases, the water table drops and progressively disconnects from the stream, starting upstream, until it is completely disconnected throughout the catchment. This means that during smaller rainfall events, when the water table remains below the land surface and does not connect to the stream, recharge occurs along the length of the stream. During

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larger rainfall events, as the water table comes to the surface, the area of potential recharge decreases.

In the pasture catchment the conceptual model is essentially the same, except that the bedrock at the bottom of the catchment is nine metres deep, keeping the water table consistently below the base of the stream (Fig. 9), and allowing recharge to readily occur here.

The groundwater hydrographs indicate that during the study period, recharge occurred mainly in the lowland areas, particularly when there was enough rainfall to generate consistent flow in the streams, while much less recharge is evident on the upper slopes. Because recharge occurs predominantly in the lowland areas, there is relatively little groundwater discharge along the streams. The ^{222}Rn data (Fig. 9) show that there is minor groundwater discharging to the surface water, particularly in the eucalypt catchment, and this is verified by the salinity of the streamflow ($7700 \pm 2300\,\mu S\,cm^{-1}$ in the eucalypt catchment and $5500 \pm 700\,\mu S\,cm^{-1}$ in the pasture catchment). Groundwater is also lost through evapotranspiration when the water table is within two metres of the ground surface (as commonly documented in southeast Australia, e.g. Bennetts et al., 2007), and a small amount flows out at the bottom of the catchment.

4.3 Groundwater recharge estimates

Recharge estimates calculated using both the WTF and CMB methods range from 0.8 ± 0.3 to $161 \pm 4\,mm\,yr^{-1}$ (Table 3), a very wide range that matches recharge calculations from similar climatic areas in Australia (5–250 $mm\,yr^{-1}$; Allison and Hughes, 1978; Cook et al., 1989), and elsewhere from drier regions around the world (0.2–35 $mm\,yr^{-1}$; Scanlon et al., 2006).

4.3.1 Water table fluctuation method

Recharge values calculated from logger data using the WTF method are relatively high for low-lying areas in both catchments ($> 40\,mm\,yr^{-1}$ for seven out of nine bores; Fig. 6;

Table 3). Only two out of seven upper slope bores show recharge of this magnitude (Pas74 and Pas78), and both show signs of preferential recharge down fractures in the granite (see Sect. 4.1; Fig. 6). The high recharge values are confirmed by calculations using only data from the longer-term hydrographs, indicating that the recharge trends have been consistent over the past 20–30 years.

Recharge values calculated using the WTF method were excluded for bores affected by confining layers (Euc84 and 85; see Sect. 4.1), and Pas95, which behaves disparately from the nested shallower bore Pas96 (Fig. 5).

4.3.2 Chloride mass balance method

Recharge values calculated from the CMB method (Eq. 2) are much lower than the WTF method values, often by an order of magnitude or more. The difference depends to some extent on the landscape position (Table 3). For example, Pas96 – Low has an R value of 1.1 ± 0.4 from the CMB method versus a WTF method value of $161 \pm 24\,\mathrm{mm\,yr^{-1}}$, while Pas82 – Up has a CMB value of $8.8 \pm 3.3\,\mathrm{mm\,yr^{-1}}$ and a WTF value of $26 \pm 4\,\mathrm{mm\,yr^{-1}}$. Likewise in the Eucalypt catchment Euc90 – Low gives a CMB value of $1.0 \pm 0.4\,\mathrm{mm\,yr^{-1}}$ and a WTF value of $74 \pm 11\,\mathrm{mm\,yr^{-1}}$, while Euc94 – Up gives CMB and WTF values of 1.0 ± 0.4 and $1.7 \pm 0.2\,\mathrm{mm\,yr^{-1}}$ respectively.

Fracture recharge results in dilute groundwater with low Cl^- concentrations and gives high CMB values, as shown in bores Pas77 – Up and Pas79 – Up with CMB values of 102 ± 38 and $76 \pm 29\,\mathrm{mm\,yr^{-1}}$ respectively. However, the remainder of the bores have CMB values between 0.5 and $9\,\mathrm{mm\,yr^{-1}}$, confirming the WTF results that rapid recharge is not a significant feature across the whole landscape.

The most likely explanation for the mismatch between the CMB and WTF results is that Eq. (2) is highly sensitive to rainfall Cl^-, so the CMB method is biased by the input Cl^- values. The bore hydrographs indicate that there is much more recharge occurring in the lowland bores than is indicated by the CMB values, due to recharge both through the stream bed and across the low gradient slopes adjacent to the streams, where runoff velocities decrease due to the reduction in slope, allowing more infiltration to

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occur. Therefore, recharge in the lowland areas is from runoff rather than rainfall, as previously discussed (e.g. for bore Pas96, rises in the hydrograph directly correspond to flow in the ephemeral stream channel; Fig. 7).

To account for this difference the CMB values were recalculated using the volume and Cl^- content of runoff in place of rainfall volume and Cl^- concentration in Eq. (2). Therefore, the episodic recharge from runoff events that generate streamflow (R_{ro}) is calculated from:

$$R_{ro} = RO\frac{C_{ro}}{C_{gw}} \tag{3}$$

where RO (mm) is the estimated amount of runoff (using streamflow as a proxy) that would reach a given bore, C_{ro} is the estimated Cl^- concentration of the runoff, and C_{gw} is the Cl^- concentration in the groundwater. RO is calculated from the average streamflow per year divided by the amount of the catchment that could theoretically provide runoff to a given bore location (i.e. a bore in the middle of the catchment is only going to receive approximately half the runoff that could potentially recharge a bore at the bottom of the catchment). C_{ro} is calculated from the average EC measured at each weir (averaged over the available data at the weirs from May 2010 to February 2013), converted to Cl^- using the EC : Cl^- ratio for the study site dataset (0.39 and 0.37 for the pasture and eucalypt catchments respectively). Equation (3) was only applied to bores in the lowland parts of the landscape where runoff and streamflow are likely to recharge the groundwater. Because of the highly variable nature of the streamflow Cl^-, the potential variation in recharge values calculated from Eq. (3) is large, and this is seen in the error values (1σ – Table 3).

The recalculated recharge values generated from Eq. (3) are much closer to the WTF recharge values, but are still generally a factor of five to 15 lower. This may reflect the fact that the groundwater across the study site is mostly thousands of years old, indicating that the CMB values are mostly representative of recharge rates under native vegetation prior to land clearance during European settlement in the late 1800s. In

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contrast, the WTF values represent recent recharge (August 2009 to February 2013), so the difference from the recalculated CMB values may be partly due to difference in vegetation (discussed further below).

4.4 Topographic controls on recharge

Recharge estimates using the WTF method (Table 3) show that within the local groundwater systems of the study catchments, variations in recharge predominantly reflect differences in topography. Dominant areas of recharge are not along the topographic highs of the catchments, as in the traditional conceptual model of recharge (Fig. 1), but are instead analogous with more arid regions, where most recharge occurs in topographic depressions (Scanlon et al., 2002).

Recharge rates increase as surface elevation decreases (Fig. 10). The steeper slopes of the upland areas promote runoff rather than infiltration, aided by low permeability silty soils (Table 2). Overland flow is focused into topographic lows and along drainage lines, where the granite is most weathered as indicated by the greater depth to bedrock here (9 m in the pasture catchment, and 30 m in the eucalypt catchment except at the very bottom of this catchment, see Sect. 4.3.2), encouraging recharge to occur, particularly through the stream bed.

4.5 Vegetation controls on recharge

The bore hydrographs in the eucalypt catchment show a clear overall declining trend during the study period, evident even in artesian bores (Euc84 and Euc85), and regardless of landscape position (Fig. 5). This decline is not evident in hydrographs from the pasture catchment (Fig. 5), where the water table has increased by 0.5–1 m during the whole study period as a result of consecutive wet summers of 2010/11 and 2011/12 (Fig. 10).

In the plantation catchment the water level has decreased by up to 3 m over the same time period, and this is attributed to greater water use by eucalypts, as has been demonstrated elsewhere (e.g. Bosch and Hewlett, 1982; Adelana et al., 2014). The water table decline is less in the upland areas (Fig. 10), probably because recharge rates here are lower, so that the decrease in recharge due to tree water use has had relatively little impact. Furthermore, in the upland areas the water table is too deep for the vegetation to access the groundwater directly; Benyon et al. (2006), in a study in the same region of southeastern Australia, found that deep-rooted eucalypts can only access groundwater up to a depth of six to eight metres. In the lowland areas the trees are able to reach the groundwater (Fig. 11), and this, combined with the interception of potential recharge in the soil zone by the growing plantation, is causing the observed decline in groundwater level in the plantation catchment, as there is no corresponding drop in the pasture catchment (Figs. 6 and 11). Although tree roots can provide preferential pathways for infiltration of rainfall to the water table (Burgess et al., 2001), any effect of this is masked by the overall downward trend in the eucalypt catchment hydrographs.

The areas immediately adjacent to the drainage lines in the plantation catchment are covered in grass and therefore there is less direct interception of potential recharge, but in fact these areas show the biggest decline in groundwater level (Fig. 10), because this is where the highest rates of recharge are occurring, and the nearby trees can therefore have the greatest impact, especially if they can access the groundwater.

4.6 Management of tree plantations and recharge

Afforestation of farmland was widespread in southeast South Australia and southwest Victoria (known as the Green Triangle) from the 1980s through to the 2000s, with plantation area expanding by 5–14 % to 30 000 ha in Victoria alone (Adelana et al., 2014; Benyon et al., 2006; Ierodiaconou et al., 2005). However, the subsequent development of tree plantations in the region has been hindered by a poor timber market (HVP Plantations, personal communication, 2013), and concerns that plantations use more groundwater and surface water than other landuses like farming. As a result, tree plantations in the state of South Australia must now be licenced as groundwater users

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(Govt. of South Australia, 2009), while it is hoped that the potential reduction in water availability resulting from reforestation will be offset by the beneficial gains of the carbon sequestration within the new trees (Schrobback et al., 2011).

A reduction of groundwater recharge by plantations, as documented in this study, lowers the water table and can reduce stream flow. If this is the object of the reforestation, for example to reduce saline groundwater discharge, then this landuse change may well serve its purpose (Bennetts et al., 2007). However, since the recent drought in southeast Australia over the late 1990s and 2000s, there is much concern that trees may be a significant user of local and regional water resources, reducing groundwater recharge, discharge and surface water availability (Jackson et al., 2005).

In order to reduce the impact on water availability, current regulation of tree plantations in southeast Australia focuses on the percentage of a catchment that may be planted, but the present study shows that the location of the plantation is significant also. If the aim is to reduce the impact of plantations on groundwater recharge, tree planting should be avoided in the dominant zone of recharge, i.e. the topographically low areas and along the drainage lines. Instead trees should be planted on the upper slopes where the water tables are deeper and the trees are less likely to access the groundwater and transpire it directly. This is supported by the smaller water table decline seen in the upland areas of the eucalypt catchment at the study site. At present, tree plantations in Victoria cannot extend within 20 m of drainage lines, due to the erosion that can occur when the crop is removed (Dept. of Environment and Primary Industries, Victoria); the suggested management change would expand the currently restricted area along the drainage lines based on the topography of the site.

This management strategy for tree plantations will be applicable to other low-rainfall areas, and should be considered for tree plantations in similar climatic areas worldwide.

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5 Conclusions

While the importance of topography and ephemeral streams to focused recharge in dry regions around the world has been known for some time, the implications of this aspect of the groundwater resource literature have not been incorporated into plantation management guidelines and legislation. In this study it is shown that the majority of modern recharge at the study site (10 % of rainfall in the lowland areas versus 3 % in the upland areas), calculated from the water table fluctuation method, occurs in the lower parts of both the pasture and the eucalypts catchments. While overall the tree plantation in this study caused a drawdown in groundwater levels, compared to a slight rise in groundwater levels in the pasture catchment, this was spatially variable due to the topography confining most recharge to the lower parts of the catchment. This leads to the conclusion that in order to reduce the potential effect of higher evapotranspiration from tree plantations on groundwater levels in dry regions, the trees should be planted in the upland areas of the catchments, because groundwater recharge rates in these areas are low enough that any further reduction will have minimal impact.

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Table 1. Groundwater characteristics and bore construction.

Bore ID	Earliest data from bore	Screen depth (m below surface)	Surface elevation (m AHD)	Radiocarbon age (yr BP)	1σ– error	Activity of ^{3}H (Bq kg^{-1})	1σ– error	Logger	Groundwater Cl^- (mg L^{-1})
Pasture Catchment									
Pas72 – Low	31/08/1986	9.4–11.6	259.55	1665	±30	BD		N	3292
Pas73 – Low	31/08/1986	4–6.1	259.54	2055	±30			N	3110
Pas75 – Low	31/08/1986	12–13.6	263.93	935	±35			Y	2231
Pas76 – Low	31/08/1986	2.2–4.2	263.98	575	±30	BD		Y	1595
Pas95 – Low	26/08/2009	22.8–24.8	254.13	3540	±30	BD		Y (weir)	2732
Pas96 – Low	26/08/2009	5–7.55	254.18	345	±25	0.133	±0.011	Y (weir)	2553
Pas74 – Up	31/08/1986	6.2–8.5	268.62	790	±30	0.053	±0.005	Y	306
Pas77 – Up	31/08/1986	17.7–19.7*	271.11	Modern		0.339	±0.015	N	28
Pas78 – Up	31/08/1986	17.3–19.4	277.45	650	±90	BD		Y	1185
Pas79 – Up	31/08/1986	23.65–25.65*	283.23	Modern		0.304	±0.014	N	38
Pas80 – Up	31/08/1986	23.3–24.4	288.23	115	±30	0.148	±0.01	Y	2290
Pas81 – Up	31/08/1986	7.1–8.9	272.12	690	±100	0.094	±0.007	N	668
Pas82 – Up	31/08/1986	23.2–24.8	283.54	430	±30	0.072	±0.006	Y	329
Eucalypt catchment									
Euc84 – Low	12/11/1996	5.6–7.5	268.67	785	±30			Y	3909
Euc85 – Low	12/11/1996	7.9–10	268.66	**		BD		Y	3537
Euc89 – Low	30/10/2009	26–28	261.80	7330	±50			Y	2833
Euc90 – Low	30/10/2009	13–15	261.93	6980	±45			Y	2788
Euc92 – Low	30/10/2009	26.2–29.2	255.43	20770	±90	BD		Y (weir)	1490
Euc93 – Low	2/03/2010	11–14	263.31	725	±30	0.087	±0.007	Y	1357
Euc83 – Up	12/11/1996	14.8–16.7	274.21	685	±30	BD		Y	2064
Euc91 – Up	30/10/2009	33.9–35.9	280.02	415	±30	0.047	±0.005	Y	1114
Euc94 – Up	30/10/2009	28–30	286.05	2060	±30	BD		Y	2891
Euc97 – Up	30/10/2009	43.1–45.1; 57.6–59.6	291.74	5655	±35	0.0354	±0.005	Y	3494

BD denotes below detectable; * assumed screen depths; ** CO_2 concentration too low for analysis.

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Table 2. Median grain size compositions for sampled profiles used to estimate a range of values for S_y in Eq. (1).

Bore ID	Clay (%)	Silt (%)	Fine sand (%)	Coarse sand (%)
Euc89 – Low	3	39	38	19
Euc91 – Low	3	39	40	18
Euc93 – Low	3	36	43	18
Euc94 – Up	3	35	44	18
Euc97 – Up	3	34	43	20

Table 3. Recharge (R) values using different methods for all the bores across both catchments.

Bore ID	R (mm yr^{-1}) – groundwater Cl$^-$	R (mm yr^{-1}) – groundwater Cl– with stream input correction	R (mm yr^{-1}) – water table fluctuation method	R (mm yr^{-1}) – long-term hydrograph water table fluctuation method
Pasture catchment – lowland landscape position				
Pas72 – Low*	0.9 ± 0.3	6.8 ± 4.6	L	D
Pas73 – Low*	0.9 ± 0.3	7.2 ± 4.8	L	D
Pas75 – Low	1.3 ± 0.5	3.9 ± 2.6	58 ± 9	38 ± 6
Pas76 – Low	1.8 ± 0.7	5.5 ± 3.7	77 ± 11	D
Pas95 – Low*	1.1 ± 0.4	24 ± 16	C	D
Pas96 – Low	1.1 ± 0.4	26 ± 17	161 ± 24	D
Pasture catchment – upland landscape position				
Pas78 – Up	2.5 ± 0.9	C	36 ± 5	D
Pas80 – Up	1.0 ± 0.4	C	12 ± 2	30 ± 5
Pas82 – Up	8.8 ± 3.3	C	26 ± 4	28 ± 4
Pasture catchment – possible fracture flow				
Pas74 – Up	9.4 ± 3.5	C	65 ± 10	56 ± 8
Pas77 – Up	102 ± 38	C	L	D
Pas79 – Up	76 ± 29	C	L	D
Pas81 – Up	4.3 ± 1.6	C	L	D
Eucalypt catchment – lowland landscape position				
Euc84 – Low*	0.7 ± 0.3	1.7 ± 1.3	C	C
Euc85 – Low*	0.8 ± 0.3	1.9 ± 1.4	C	C
Euc89 – Low	1.0 ± 0.4	5.7 ± 4.3	59 ± 9	D
Euc90 – Low	1.0 ± 0.4	5.8 ± 4.4	74 ± 11	D
Euc93 – Low	2.1 ± 0.8	8.0 ± 6.1	40 ± 6	D
Eucalypt catchment – upland landscape position				
Euc83 – Up	1.4 ± 0.5	C	10 ± 2	19 ± 3
Euc91 – Up	2.6 ± 1.0	C	17 ± 3	D
Euc94 – Up	1.0 ± 0.4	C	1.7 ± 0.2	D
Euc97 – Up	0.8 ± 0.3	C	26 ± 4	D
Eucalypt catchment – possible fracture flow				
Euc92 – Low*	1.9 ± 0.7	C	C	D

* Denotes confined bores; L no logger present; D no data; C indicates that this calculation was not done for that bore as it did not meet the required conditions (see Sects. 3.6.1 and 3.6.2).

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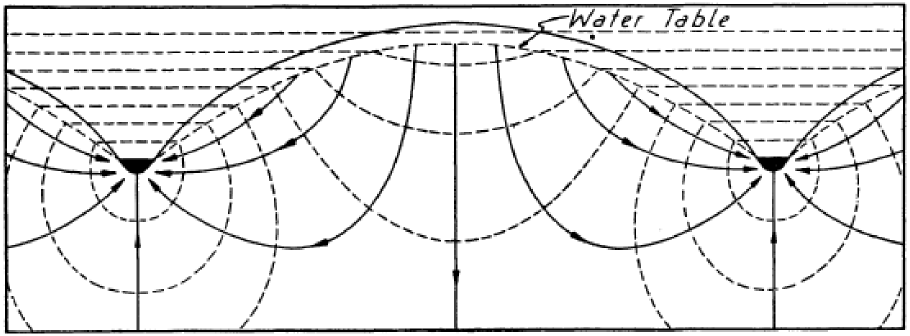

Figure 1. The control of groundwater flow based on topography assuming uniformly permeable material, reprinted from Hubbert (1940) from J. Geol. (reprint permission not yet attained).

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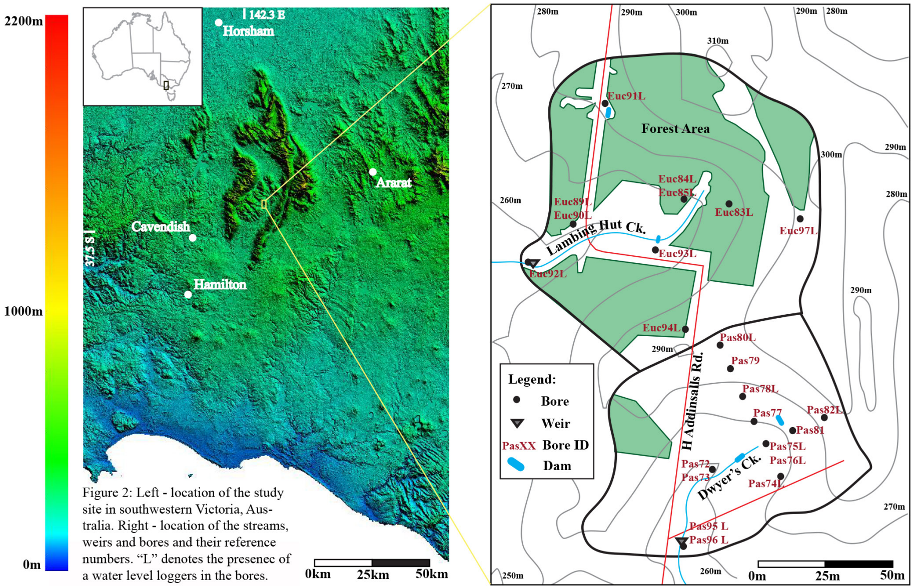

Figure 2. Left – location of the study site in southwestern Victoria, Australia. Right – location of the streams, weirs and bores and their reference numbers. "L" denotes the presence of a water level logger in a bore.

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Where to locate a tree plantation within a low rainfall catchment

J. F. Dean et al.

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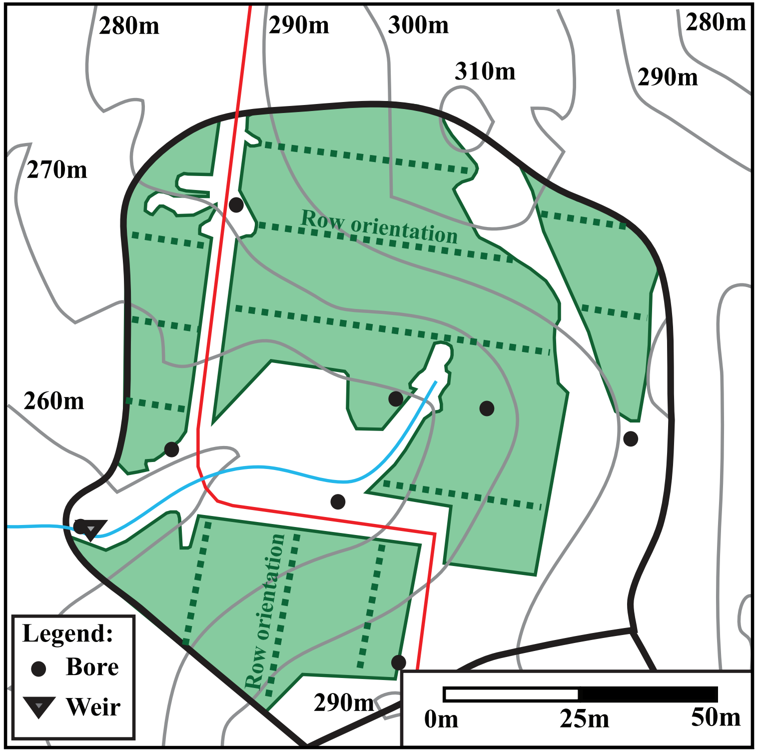

Figure 3. Orientation of the tree rows in the Eucalypt plantation.

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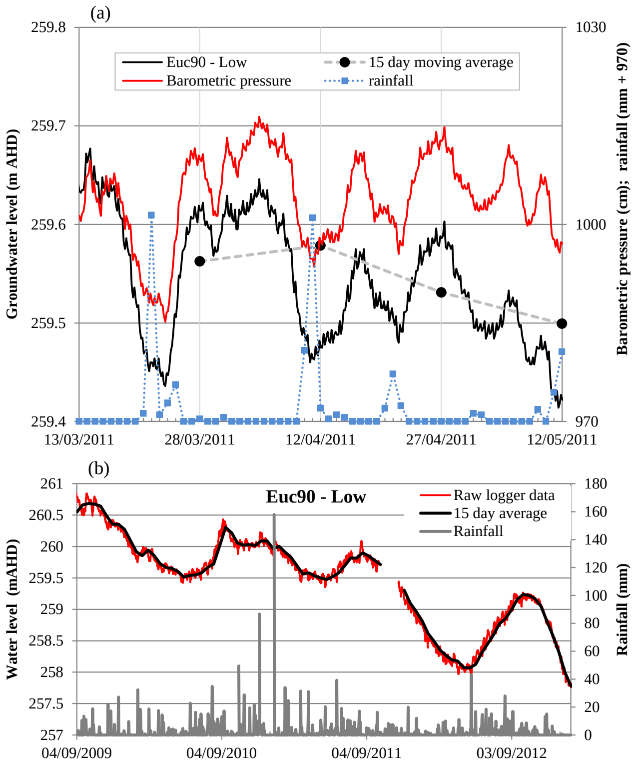

Figure 4. (a) barometric pressure, groundwater logger data, rainfall and the 15 day moving average used for the water table fluctuation method estimations of groundwater recharge. The black dots represent the average groundwater level for the preceding 15 days. **(b)** full record for the bore used in **(a)** – Euc90 – showing the complete removal of the large amount of barometric noise, but keeping the overall trend of the 15 day period.

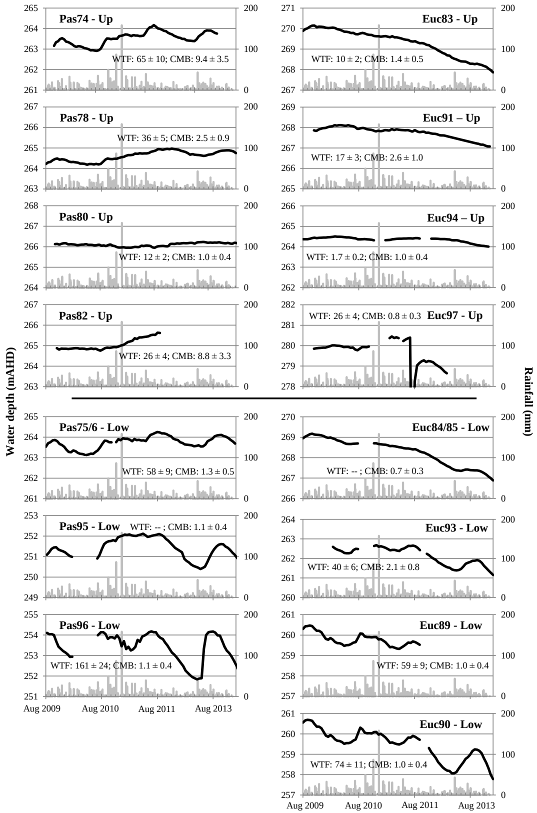

Figure 5. Bore hydrographs, rainfall and recharge estimates (in mm yr^{-1} from Table 3), for the water table fluctuation and chloride mass balance methods. Hydrographs are sorted by landscape position – lowland or upland.

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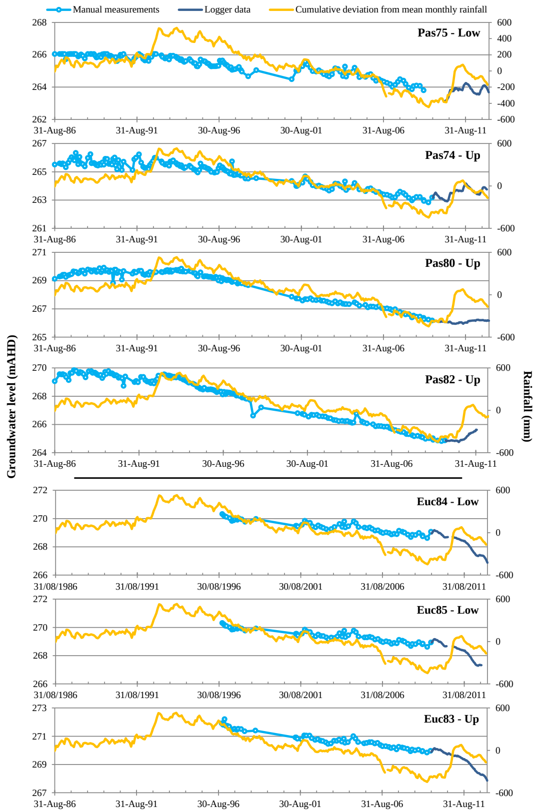

Figure 6. Long-term hydrographs for bores with available data with cumulative deviation from mean monthly rainfall to show the relationship between groundwater levels and long term rainfall patterns.

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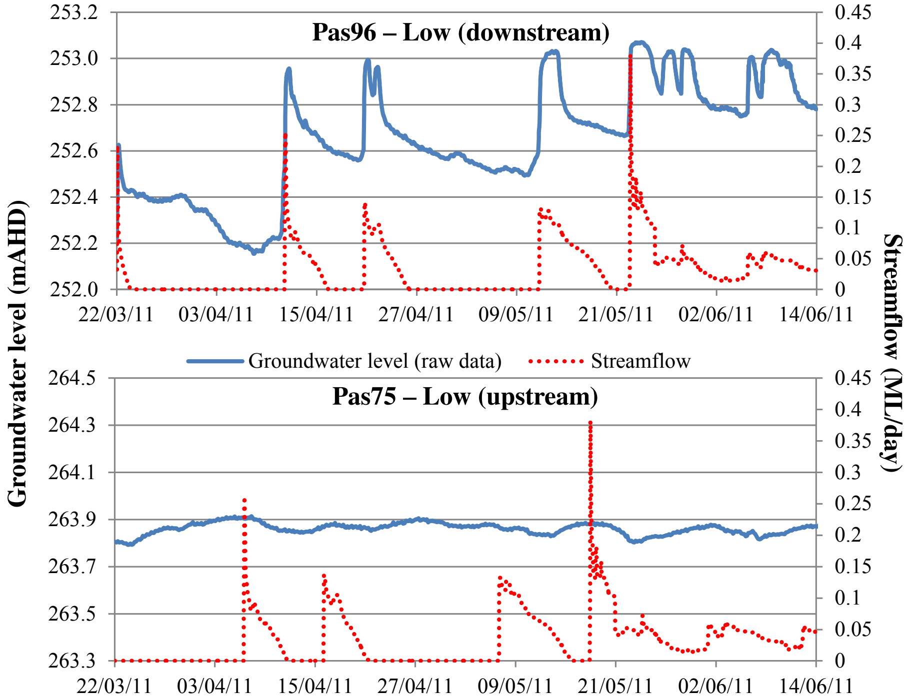

Figure 7. Stream hydrographs (Dwyer's Creek) and bore hydrographs from the bottom of the catchment (Pas96) and midway up the catchment (Pas75) showing the lessening impact of streamflow on groundwater levels as you move up the catchment.

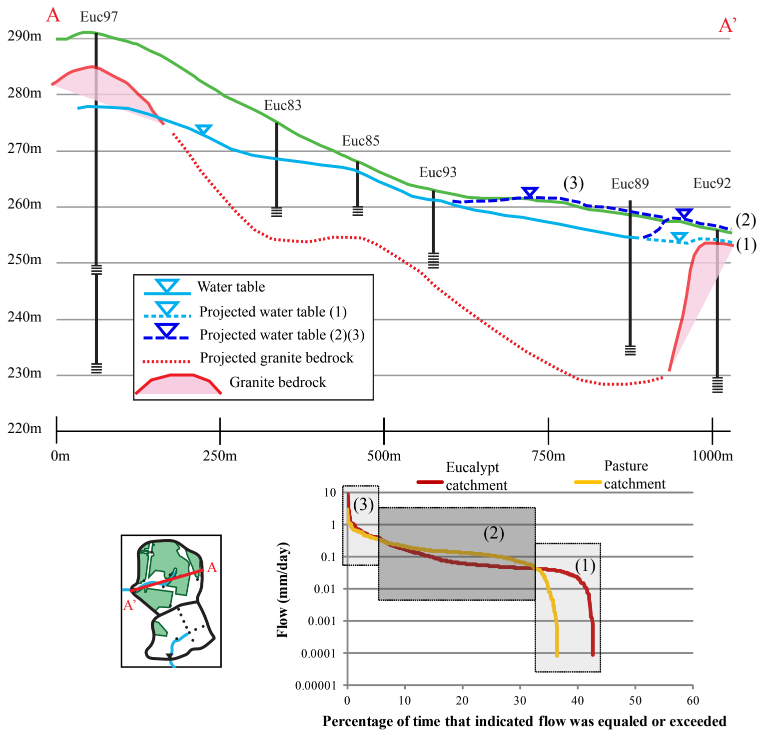

Figure 8. Long section from bores Euc97 to Euc92 demonstrating the effect of the shallow granite on the water table under different flow conditions shown in the flow duration curve below; (1) where low flows in the eucalypt catchment are sustained for longer due to some groundwater discharge compared to virtually no groundwater discharge in the pasture catchment, (2) where the water table is at the surface and runoff is transported more quickly out of the eucalypts than in the pasture, and (3) where there are some rare, very high flows, much higher than observed in the pasture catchment.

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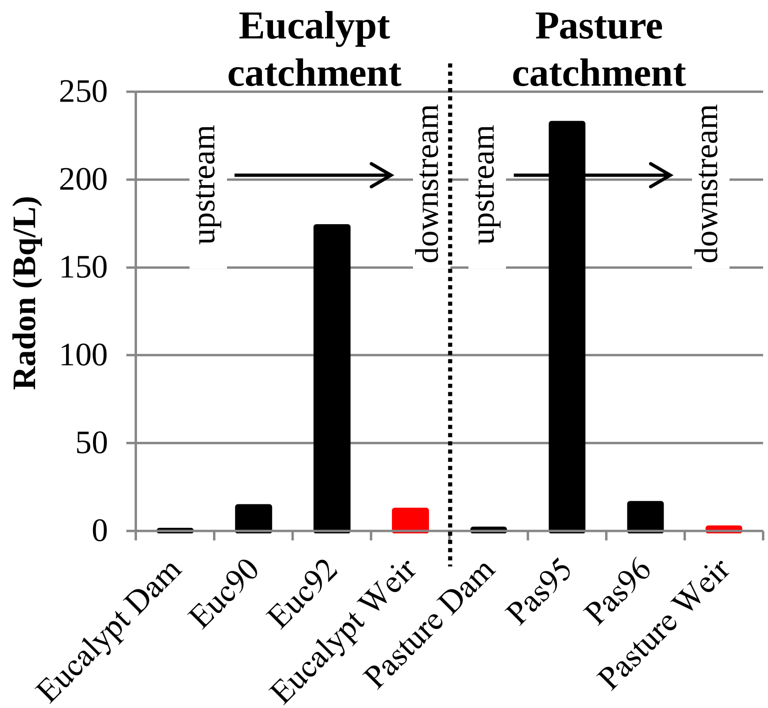

Figure 9. ^{222}Rn concentrations in the streams, measured at the weirs of both sites, and nearby bores. Surface water from further up the catchments is represented by water from dams located upslope in both catchments. The relatively high levels in the groundwater are a result of the decay of uranium present in the allanite and zircon of the granite.

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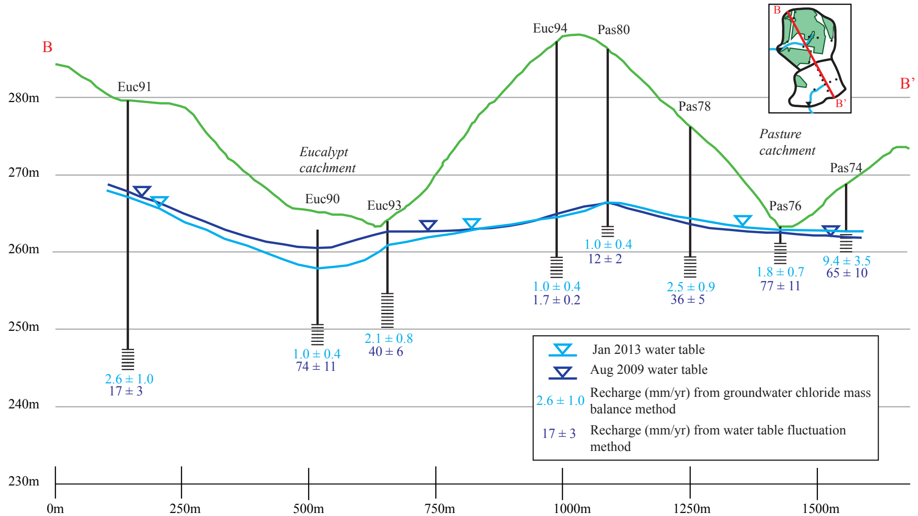

Figure 10. Cross section from bore Euc91 across both catchments to bore Pas74 showing recharge rates based on both methods used in this study, and the water table change over the course of the study period (see Fig. 1 for bore locations).

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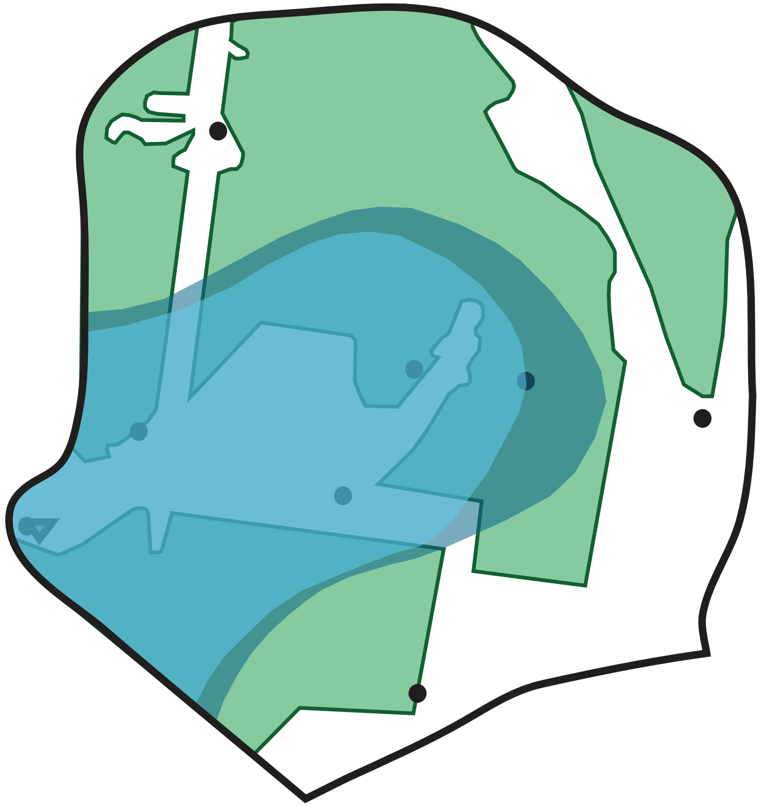

Figure 11. Area where tree roots may be able to reach groundwater between six and eight metres below the surface.

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