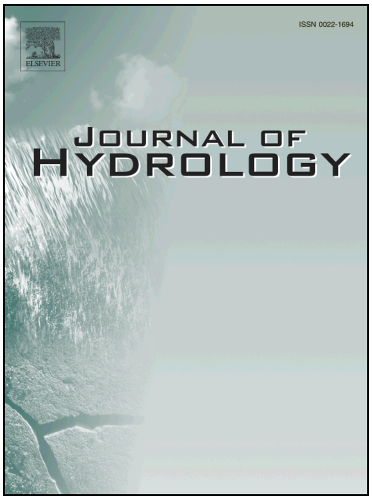

Research papers

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Effect of *Eucalyptus* plantations, geology, and precipitation variability on water resources in upland intermittent catchments

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Keywords:
plantation forestry, land-use change, groundwater, evapotranspiration, intermittent catchments, Australia

Highlights:

- Water balances of pastures and *Eucalyptus* plantations were studied
- Contrasting land use differences had no clear effect on annual streamflow
- Groundwater storage declined in plantation catchments
- Groundwater changes had minimal effect on intermittent streamflow
- Pasture actual evapotranspiration was higher than predicted by global relationships

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Abbreviations: ET_a Actual evapotranspiration, ET_0 Potential evapotranspiration, P precipitation, Q_{sw} streamflow, Q_{gw} groundwater outflow, ΔS_{gw} change in groundwater storage, ΔS_{vz} change in vadose-zone moisture storage, GF Gatum Farm, GP Gatum Plantation, MF Mirranatwa Farm, MP Mirranatwa Plantation, DFN Digby Farm North, DFS Digby Farm South, DP Digby Plantation

Abstract

Land-use change and climate variability have the potential to alter river flow and groundwater resources dramatically, especially by modifying actual evapotranspiration. Seven catchments with intermittent flow dominated by either winter-active perennial pastures (4 catchments) or *Eucalyptus globulus* plantations (3 catchments), located in 3 geologic settings of southeastern Australia, were studied for over 6 years to determine the primary controls on water resources. Groundwater levels in the pasture sites were stable through the 2011-2016 study period, while levels in the plantations declined in the same period. Streamflow occurred mainly during winter. Annual streamflow showed no difference clearly attributable to pasture versus plantation land use. The presence of grass buffers along streams enhances groundwater recharge and saturation-dependent overland flow, reducing the impacts of the plantations on streamflow. Site water balances indicated that the average annual actual evapotranspiration was 87-93% of precipitation for pasture catchments and 102-108% of precipitation for plantation catchments. Actual evapotranspiration greater than precipitation at the plantations was attributed to uptake of groundwater by the root system in parts of the catchments. Thus, change to groundwater storage is a critical component in the water balance. Actual evapotranspiration from pasture catchments was higher than previously estimated from global pasture and cropping data, instead matching global precipitation versus actual evapotranspiration curves for treed catchments.

1. Introduction

Anthropogenic land-use changes, including deforestation, afforestation, and agricultural practices, are known to alter streamflow (Q_{sw}), groundwater recharge, and other components of the hydrologic cycle (Andréassian, 2004; Beck et al., 2013; Bosch and Hewlett, 1982; Campbell and Barber, 2008; Colville and Holmes, 1972; Van Lill et al., 1980).

The negative impacts of these shifts in land use include decreased water supply and degraded water quality at local and regional scales (Dean et al., 2014; Dean et al., 2015). The majority of previous investigations have indicated that an increase in tree cover typically affects the catchment water budget by increasing actual evapotranspiration (ET_a), decreasing streamflow, and decreasing groundwater recharge, but there is high variability globally and within specific regions (Brown et al., 2005; McVicar et al., 2007; Scott et al., 2000; van Dijk and Keenan, 2007; Zhang et al., 2001). The difficulty in controlling or even characterizing variables, such as geologic setting (including bedrock geology, unconsolidated sediments/soils, and topography) at the catchment scale, means generalization of findings to other locations is problematic. The interrelationships between variables controlling the water balance, such as precipitation (P), vegetation growth, and ET_a is a challenge to predicting land-use change impacts and development of water management policies.

Table 1 summarizes some of the key findings from existing studies on the effect of afforestation and deforestation on water resources, including previous work at our sites and this study for completeness. A wide variability of responses to land uses is seen in global studies. In southeastern Australia, catchment studies were mainly carried out in the high-rainfall native *Eucalyptus* forests with a limited number of studies of *Pinus* plantations (Bren and Hopmans, 2007; Bren et al., 2010; Bren, 1997; Bren and Lane, 2014; Burch et al., 1987; Cornish and Vertessy, 2001) and few catchment-scale studies on *Eucalyptus* plantations. Plot-scale studies of

ET_a in southeastern Australia did not include direct measurement of groundwater or streamflow, so they may not apply to catchment scales (Benyon et al., 2007; Benyon and Doody, 2004; Benyon et al., 2009; Benyon et al., 2006).

Only a few catchment studies include monitoring of the groundwater system (Almeida et al., 2016; Istanbulluoglu et al., 2012a; Rodríguez-Suárez et al., 2011; Silveira et al., 2016). Therefore, the relationships between precipitation and both ET_a and streamflow typically do not account for the effects of groundwater recharge on the water balance. When groundwater is considered, the catchments are usually assumed closed with respect to groundwater flow (i.e., the groundwater divide at the top of the catchment corresponds to the surface-water divide and groundwater discharges to streams within the catchments as baseflow). Soil-water storage is typically assumed to respond rapidly to changes in vegetation and reach a near steady state, but saturated groundwater storage is not usually addressed.

Few studies have taken place in intermittent catchments, although several workers have noted a change from perennial to intermittent flow with afforestation (Brown et al., 2013; Brown et al., 2005; Scott and Lesch, 1997; Scott and Prinsloo, 2008; Scott et al., 2000; Zhang et al., 2012). Uptake of groundwater by deep-rooted vegetation, such as plantation trees, can alter the catchment water balance by increasing ET_a (Benyon et al., 2007; Benyon, 2002; Benyon and Doody, 2004; Benyon et al., 2009; Benyon et al., 2006). Streamflow and groundwater flow are expected to be affected by a number of factors related to intermittent flow. The limited connection between groundwater and surface water in intermittent streams decreases baseflow compared to perennial systems (Istanbulluoglu et al., 2012b). There is likely to be a greater lag in establishment of valley-bottom saturation and saturation-dependent overland flow in intermittent catchments and the extent of area contributing to saturation-dependent flow is likely to be smaller. This suggests that the streamflow may be sensitive to changes in the groundwater system induced by land-use change.

This study investigates the interrelated effects of land use, geologic settings, and precipitation variability on the water yield of small, intermittent, upland catchments in Victoria, Australia. Hardwood *Eucalyptus globulus* (blue gum) plantation was the dominant land use within one catchment at each setting, and winter-active native perennial pasture was the dominant land use at the other catchments.

<Table 1 here please >

The primary research questions were:

1. What are the differences between plantations and pastures in terms of groundwater resources and how important is it to factor groundwater into water-balance changes?
2. What are the effects of contrasting land uses on streamflow and ET_a? Do the water dynamics in our research catchments support the water-budget relationships derived from other global studies and, particularly, studies in southeastern Australia?
3. How does the geologic setting affect the water balance and relate to the water resource effects of plantations?

These objectives provide the structural sub-headings used in the following Methods, Results and Discussion sections. The Discussion section additionally addresses the implications of the research to water and land-use management policy.

2. *Study Area*

2.1. Site description

The study area is located in the Hopkins and Crawford River catchments of the Glenelg River basin in southwestern Victoria, Australia (Figure 1). The study includes seven catchments in three areas, named according to the closest adjacent townships: Gatum Farm (GF) and Gatum Plantation (GP), Mirranatwa Farm (MF) and Mirranatwa Plantation (MP), and Digby Farm North (DFN), Digby Farm South (DFS), and Digby Plantation (DP).

< Figure 1 here please >

The farm catchments are predominantly sheep and cattle grazing of winter-active perennial grasses with minor cropping and small treed areas. The plantation catchments include varying amounts of pasture and unplanted grassland areas along the valley bottoms. GP was planted in 2005, with a stand density of ~800 trees/ha (Adelana et al., 2015) that decreased to ~730 in 2015. Mean diameter at breast height over bark at the end of 2016 was 23.8 cm with a mean tree height of ~20 m. At MP, planted in 2008, surveys taken between 2011 and 2015 saw the mean height of trees increase from 8.9 to 13.7 m, with the mean diameter at breast height over bark growing from 9.6 to 14.3 cm; the number of trees per hectare declined from 1,139 to 889 [*Darren*

Shelden, Macquarie Forestry, pers. comm.]. The plantation at DP was planted in 2001 at a stocking density of ~700 to 800 trees/ha and was harvested between late 2015 and early 2016 [*Adrian Marty, Elders Forestry*, pers. comm.]. The DP catchment includes ~55 ha of native *Eucalyptus* forest that was not harvested.

2.2. Geologic setting and topography

The catchment designations, geology, and physical characteristics are listed in Table 2. Catchment perimeters and areas were determined using differentially corrected Global Positioning System (GPS) elevations tied to Geoscience Australia benchmarks. Elevations used the Australian Height Datum (AHD). Interpolation between measured locations was performed by hand and guided by topographic maps and field observations. Catchments were subdivided into valley bottom, mid slope, and upper slope landscape positions (see Table 2), based on subjective evaluation of the topographic maps, except at DP where only mid slope and valley bottom were used because of the low relief.

<Table 2 here please >

Calculation of height above nearest drainage (HAND) is a method to assess the hydrologic effects of topography and to classify landscapes to develop conceptual models (Gharari et al., 2011; Nobre et al., 2011; Rennó et al., 2008). The HAND analysis calculates the height difference (m) between each cell in a Digital Terrain Model (DTM) and the height of the cell where flow from that location first reaches the drainage line. We used HAND, based on a 20-m by 20-m DTM with vertical accuracy of 5 m or better (Department of Environment Land Water

& Planning, 2014) to assess the topographic differences between the monitored catchments. The low relief in some locations meant that the boundaries shown in the HAND analysis, determined from the state-wide 20-m by 20-m DTM, are less accurate than our more detailed surveyed catchment areas. The drainage-line cells were defined as those where flow accumulation is from an area ≥ 0.1 km^2. This value was chosen because it captures drainage networks in each study catchment and is similar to the drainage shown in the State of Victoria topographic layers.

The HAND map for each study catchment and histograms of the distribution show similarity in topography and stream drainage for catchments within each geologic setting (Figure 2). The Mirranatwa catchments are the steepest. At the Gatum sites, GP has the drainage extending somewhat farther up the catchment, but the differences are considered unlikely to have a major effect on the flow dynamics. The relatively flat topography at the Digby sites means that large areas of each catchment are near stream level. The central part of DFS is dominated by an ellipsoidal area at stream level. A smaller area with elevations near the stream is also seen in the center of the DFN catchment. The central part of the DP catchment shows drainage on the HAND map, but was a closed depression until a drain to the north was constructed. We interpret these features as being dolines in the underlying Port Campbell Limestone, indicating potential recharge areas.

< Figure 2 here please >

Soil development contrasts between locations. The Gatum site is dominated by yellow and brown mottled Chromosol soil developed over saprolitic Gatum Ignimbrite rhyolite of the Lower

Devonian Rockland Volcanics (Baxter and Robinson, 2001). The Mirranatwa site has yellow and brown Solodic soil over weathered granitic Devonian Victoria Valley Batholith (Sibley, 1967). The soil type at the Digby sites is variable with DP generally being sandier; Baxter and Robinson (2001) described it as a black Vertisol developed on late Miocene-Pliocene marine Loxton clay and sands that overlie late Oligocene to late Miocene Heytesbury Group Port Campbell Limestone. Depth to limestone is ~8 m at DFS and DFN, while ~60 m at DP (Perveen, 2016).

2.3. Climate

Annual historic precipitation from Bureau of Meteorology (BOM) sites near the study areas are listed in Table 2, together with measurements from this study. Precipitation during the study was greatest in the Digby catchments and lowest at Mirranatwa. The study catchments were established in 2009-2010 at the end of the ‘Millennium Drought,’ the worst drought on record for southeastern Australia, with approximately 8 years of below long-term average precipitation (van Dijk et al., 2013; Yang et al., 2017). The drought broke in 2010 with high precipitation; widespread flooding continued through the 2011 summer. Precipitation is winter dominated and annual precipitation in the region is highly variable. Using data in the period 1984-2017 (Hamilton Airport, BOM station 090173), February is the hottest month, having a mean monthly maximum temperature of 26.8 °C (daily maximum temperature range 13.8-44.5 °C) and mean monthly minimum temperature of 11.3 °C (daily minimum temperature range 2.1-24.7 °C). July is the coldest month with mean monthly maximum temperature of 12.1 °C (daily maximum temperature range 6.2-18.7 °C) and mean monthly minimum temperature of 4.4 °C (daily minimum temperature range -2.8-11.3 °C).

3. *Data collection and analysis*

3.1. Precipitation

Precipitation was recorded at 10-minute intervals using tipping-bucket rain gauges at Gatum, Mirranatwa, Digby farm, and Digby plantation. Measurements were summed to 30-min and daily values (mm d^{-1}). Daily precipitation data were supplemented with data from nearby BOM stations (see Figure 1) to infill missing or suspect data when the onsite gauges clogged or data loggers failed. This affected a maximum of 5.4% of the data at the DP catchment, largely as the result of a logger failure in 2011. Correlation of daily data between our gauges and the BOM stations was satisfactory (r^2 = 0.78-0.95), with the exception of the Gatum sites (r^2 = 0.44). Only one daily measurement at Gatum was replaced with BOM data, so the poor correlation has little effect.

3.2. Groundwater analysis

Groundwater levels were measured in wells installed for this study and some pre-existing wells. Locations are shown in Figure 2 and construction details are given in the Supplementary Data. The locations and surface elevation were measured with differentially corrected, survey-grade GPS. Groundwater levels were measured from 2009 or early 2010 through December 2016 and were presented as either depth below ground surface (m) or elevation above Australian Height Datum (m AHD). Water-level measurements were logged at 4-hr intervals with Campbell, Diver, Instrumentation Northwest, or Troll data loggers. Measurements were barometrically compensated and corrected to periodic manual measurements. Visual trend assessment was used to exclude suspect data. Data that result from data logger failure and where the water levels recovered slowly after purging for sampling were excluded.

Changes in groundwater level were used to calculate changes in annual groundwater storage, ΔS_{gw} ($m^3\ y^{-1}$– converted to mm y^{-1}), beneath the catchments. ΔS_{gw} was calculated by multiplying the average decline for wells at each landscape position by area and the specific yield (unitless), estimated from sediment grain size (Adelana et al., 2015; Dean et al., 2015; Perveen, 2016). ΔS_{gw} and other water volumes used in the water balance (Section 3.4) were converted to mm by dividing by the catchment area, applying unit conversion factors, and summing over the time of interest (e.g., daily or annual values).

Groundwater outflow from the catchments, Q_{gw} ($m^3\ d^{-1}$, converted to mm d^{-1}), was calculated from Darcy's Law for one-dimensional flow,

$$Q_{gw} = -K\ i\ A \tag{1}$$

where K (m d^{-1}) is the average hydraulic conductivity of the aquifer estimated from sediment grainsize, i (unitless) is the hydraulic gradient calculated from a planar fit to average January (summer) groundwater levels in 3 widely spaced wells in each catchment, and A (m^2) is the cross-sectional area of groundwater outflow. The aquifer depth used to calculate A was estimated from geologic maps and site drilling data. A width equal to the catchment width approximately perpendicular to the flow direction was selected as an upper bound to A, such that ET_a calculated from the water balance (Section 3.4) could be considered as a lower estimate.

3.3. Streamflow analysis

Streamflow (Q_{sw}) was measured at flow-control weirs at the outlet of each catchment. Measurements were initiated in 2010, and this study considers the full calendar years 2011-2016. Flow data were divided by the respective catchment area and summed over time periods of interest to be expressed as equivalent water depth (in mm time^{-1}). Intense rain periods caused flow to overtop some of the weirs, leading to an underestimation of total flow. This particularly affected the flow measured at the GP catchment, where the maximum flow rate measurable at the weir was 4.5 mm d^{-1} because of the logistics of installation. The events where the streams overtopped the weirs were generally infrequent and short-lived, with the exception of the GP catchment in 2016, when flood debris blocked the weir causing slow drainage. Pipe erosion and/or tunnelling by *Cherax destructor* (common yabby) caused leakage under the MP weir in the period February 2011 to May 2011. Accordingly, the flow at this site for that time period may be underestimated. This predominantly affects the estimation of the timing of flow in 2011 rather than the total flow because the weir was repaired prior to the onset of the wet winter season. Some of the series had gaps in the data: 12 d were missing at GF, 18 d at MF, 5 d at DF, and 122 d at DP. The days missing at DP were between March and July 2012 and in January 2013. We believe that most of the flows were recorded because these periods commonly do not show large flows.

Streamflow for the different catchments was summarized to daily, quarterly, and yearly values. Flow duration curves from 30-minute flow data are presented for the combined 2011-2016 periods.

3.4. Water balance and evapotranspiration

Annual actual evapotranspiration (ET_a) was calculated from the annual catchment water balance as:

$$ET_a = P - Q_{sw} - Q_{gw} - \Delta S_{gw} - \Delta S_{vz} \qquad (2)$$

where P is precipitation, Q_{sw} is streamflow, Q_{gw} is groundwater outflow, ΔS_{gw} is change in groundwater storage (change in water volume below the water table), and ΔS_{vz} is change in vadose-zone moisture storage (change in water storage between the water table and the ground surface – the unsaturated zone and the capillary fringe). Units for the components of equation (2) are mm time^{-1}, totalled over the measurement period of interest.

P and Q_{sw} were measured; Q_{gw} and ΔS_{gw} were determined as discussed in Section 3.2. ΔS_{vz} is assumed to be ~0 at the annual and longer timescales, although water content possibly decreased as the roots extended into the deeper vadose zone during plantation establishment. If the last three terms in equation (2) are neglected, as a first approximation, Q_{sw} approaches 0 at low P and approaches P-ET_0 at high P, where ET_0 is the potential evapotranspiration (McGuire and Bren, 2013; Zhang et al., 2001). This suggests that a plot of annual Q_{sw} versus P may fit a power function of the form:

$$Q_{sw} = a\,P^b \qquad (3)$$

where a is expected to be a small positive number, because $Q_{sw} << P$ at low values of P, and b is positive. The parameters a and b are fit to the data by ordinary least squares. Equation (3) is equivalent to the Midgely & Pitman curves described in Greenwood et al. (2014), neglecting the linear form used above a critical threshold of P.

The role of vegetation type on ET_a and catchment water balance from our study was compared to that from world-wide catchment experiments reviewed by Zhang et al. (1999; 2001), who developed a relationship between long-term average annual ET_a and annual precipitation for forest and grass catchments, referred to as the "Zhang Curves":

$$ET_a = \left[f \frac{1+2\times\frac{1410}{P}}{1+2\times\frac{1410}{P}+\frac{P}{1410}} + (1-f)\frac{1+0.5\times\frac{1100}{P}}{1+0.5\times\frac{1100}{P}+\frac{P}{1100}} \right] P \tag{4}$$

where P is the annual precipitation and f is the fraction of forest cover. The values 1410 and 1100 in equation (4) relate to the potential evapotranspiration for treed and un-treed catchments, respectively. At low values of annual precipitation, ET_a increases linearly with precipitation and approaches a constant value equal to potential evapotranspiration at high annual precipitation.

4. Methods

4.1. Effects on the groundwater system

Groundwater level measurements were used to determine groundwater flow directions at the study sites and calculate streamflow for incorporation into the water balance. The spatial and temporal variation in depth to the water table across the catchments shows the degree of groundwater-stream connectivity. Seasonal groundwater recharge is indicated by the degree of water-table fluctuation (Dean et al., 2015). ΔS_{gw} indicates the change in the groundwater system resulting from plantation establishment and is included in the water balance.

4.2. Effects on streamflow and ET_a

The effect of contrasting land uses (i.e., pasture versus plantation) on streamflow was evaluated by determining changes in flow at the catchment outlets on time scales that vary from the 30 min data collection interval to average annual values over the 2011-2016 study period. The measurements were used to determine the variability in quarterly and annual streamflow within catchments and fit to descriptive precipitation-streamflow curves (see equation 3). Flow-duration curves for the catchments compare the relative contributions of peak flow and delayed flow for the catchments and compare the duration of flow between catchments. Water-balance ET_a was compared between catchments and to that calculated in other studies.

4.3. Effect of geologic setting

The study catchments were set in three different geologic environments to provide understanding of the source of variability in the relationship between precipitation, streamflow, and ET_a. Our hypothesis was that lithology and topography change the relationship between precipitation, streamflow, and groundwater recharge. Steeper topography likely enhances streamflow at the expense of infiltration. Additionally, the hydrogeologic setting, including depth to groundwater, affects the ability of tree roots to reach the water table. The interpretation of these effects is necessarily qualitative, but forms the basis for conceptualizing catchment models e.g., Dean et al. (2016).

5. *Results*

5.1. Effects on the groundwater system

Representative catchment summer water-table maps for January 2014, near the middle of the study period and when influence of seasonal recharge events on individual wells is minimal, are shown in Figure 3. The water-table contours shown are consistent with intermittent catchments that are not closed with respect to groundwater flow, although the well spacing is not sufficient to completely constrain the flow directions. In particular, groundwater flow at the GP catchment is largely to the south, whereas the stream drainage is to the southwest. The southerly groundwater flow increases the cross-sectional area used to calculate Q_{gw} over that of GF. The groundwater at the DP catchment is interpreted to converge on a drainage to the east, controlled by solution-enhanced permeability within the underlying limestone. This means that the groundwater gradient in the eastern part of the site converges sharply from the north and south, but the gradient to the east is much lower. The depth to groundwater along the west-east line through the catchment is >25 m.

< Figure 3 here please >

Groundwater levels at the farm site wells were generally steady, except for seasonal fluctuations (Figure 4). The levels increased from higher precipitation and recharge in 2010, 2011, and 2016 and decreased slowly during drier years. Water-table fluctuations at the GF and MF catchments are greatest along the valley bottoms as a result of greater recharge and a shallower depth to groundwater (Dean et al., 2015).

< Figure 4 here please >

The plantation monitoring wells show declining water levels and lower seasonal fluctuation, showing that recharge is nearly absent, except near the streams and in areas lacking trees. The water-table decline in MP was slow through 2011, apparently because of the recently planted trees, but it is difficult to separate the effect of tree growth from the high precipitation in late 2010 and early 2011. In spite of the maturity in DP, the water table continued to decline, at least through 2015. In 2016, water levels increased in DP wells 5532, 5537, and 5540 because of the high precipitation combined with harvesting of the plantation trees in late 2015-early 2016. The small but continuing water-table decline at DP prior to harvesting in late 2015-2016 shows that a new steady state was not reached within the harvest cycle of 14 years.

5.2. Effects on streamflow and ET_a

Catchment flow is dynamic with sharp peaks associated with rain events (Figure 5). Flow peaks typically occur within 4 hours of precipitation peaks. Late spring through late autumn flow is only associated with large rain events; more continuous flow occurs during the winter, except in 2015, which was very dry, resulting in minimal winter flow. Annual total flow in all catchments is very low when annual precipitation is below ~400 to 600 mm y^{-1} (Table 3, Figure 6).

< Figure 5 here please >

< Figure 6 here please >

<Table 3 here please >

Annual and mean streamflow over the 6-year period was lower at the GP and DP compared to GF and both DFN and DFS; however, it was almost identical in the case of the two sites at Mirranatwa, MP and MF, (see Table 3). Flow at GP is lower than GF when precipitation is less than ~800 mm y^{-1}. Streamflow at GP in 2016, the wettest year, apparently exceeded that of GF, but this may be caused by the difficulty of measuring large flows accurately. The similarity in average streamflow for the Mirranatwa catchments is largely because of the much higher peak flow for MP offsetting MF's higher flow between intense rain events. The Mirranatwa catchments were better fit by linear regression than by power functions.

Figure 6 showed that the flow in the winter-quarter (Q3), between July and September, is linearly correlated between catchments for each geologic setting. During the other quarters, the plantation flow often plots above the Q3 trend in response to intense rain events following periods of no flow. This can be explained by a proportionally greater effect of infiltration-excess overland flow at the plantations from differences in under-story vegetation or soil hydrophobicity.

The timing of flow was highly variable from year to year (Figure 7). Winter flow was continuous in the July-September (Q3) period most years, but could start as early as April and extend as late as November, depending on the catchment and year. Flow-duration curves, constructed from the 30-min measurements (Figure 8), show that the period of catchment flow ranged from 18% of the time at DFS to a maximum of 45% at GF; 75% of the flow volume occurred in less than 10% of the time period for every catchment.

< Figure 7 here please >

< Figure 8 here please >

The flow-duration curves have high slope at the high-flow periods and become steep again when the catchments cease flowing. The latter, sudden drop in flow, likely results from nonlinearity in the drainage (Chapman, 1999). The shallow slope in the center of the flow-duration curves is commonly attributed to groundwater baseflow, although other delayed flow, such as drainage of surface-water storage or perched flow, may also contribute. The curves show higher delayed flow at farm catchments than at plantations.

The flow duration does not appear to be affected by the declining groundwater levels in the plantations (see Table 3). The most likely explanation is that the annual flow duration is controlled by the extent of water storage along the valley bottom rather than groundwater baseflow. This storage may be in near-stream soils or farm dams, possibly supplemented by flow in perched aquifers. Water levels measured in some of the wells that were installed at GF and MF during early 1990s are still much deeper than the depths before the ‘Millennium Drought’. Thus, connectivity between the groundwater and surface water in the pastures may still be affected by the drought.

ET_a in the water balance (see equation 2) makes up 87% to 108% of the precipitation (Table 4). All plantation catchments had higher calculated ET_a than the farm catchments in comparable geologic settings. However, this did not directly translate to a reduction in streamflow because of differences in ΔS_{gw} and Q_{gw}. The calculated ET_a for the plantations was greater than 100% because of a loss of groundwater from storage in the plantation catchments. The importance of ΔS_{gw} in evaluating ET_a and catchment baseflow has previously been noted (Istanbulluoglu et al., 2012b). Groundwater storage loss within the plantation catchments cannot be explained by baseflow to the streams or Q_{gw} because ΔS_{gw} is greater than $Q_{sw} + Q_{gw}$, even though our calculation was designed to place an upper bound on Q_{gw}. Thus, the ΔS_{gw} is best explained by direct uptake of groundwater by the trees. This uptake is greatest in the mid-slope position. Higher in the catchment, the water table appears to be too deep for access by the tree roots. Lower in the catchment, much of the land is not treed, and the water table is affected by focused recharge in the valley bottom. It appears that higher salinity in the valley bottom is detrimental to growth and limits the groundwater uptake (Dean et al., 2016), although some *Eucalyptus* species are known to tolerate saline groundwater (Benyon et al., 1999; Feikema et al., 2010).

Plantation water balance ET_a, higher than that calculated from the Zhang curves, is largely explained by inclusion of groundwater components of the water balance (Table 4). The difference in ET_a calculated for plantation versus farm catchments ranges from 14% for Gatum and Mirranatwa to 21% for Digby (DFN versus DP). The difference calculated from the Zhang curve ranges from 16% to 17% at Gatum and Mirranatwa to 25% at Digby. However, if ET_a is calculated from only P-Q_{sw}, as used for the Zhang data, the difference in ET_a between farm and plantation catchments at Gatum and Mirranatwa is < 2%. P-Q_{sw} is still 19% higher at DP than at DFN because of the low streamflow from the DP's central depression.

<Table 4 here please >

5.3. Effect of geologic setting

The subsurface limestone karst at the Digby sites had a large effect on the groundwater and surface-water systems. Other sites illustrate features related to groundwater-flow direction, artesian conditions, and perched flow.

The runoff at Digby is largely controlled by flow in the underlying karstic limestone, although the water table is in the upper clays and sands. The relationship between annual precipitation and streamflow at the Digby farm sites is highly variable. Years with precipitation between 700 and 800 mm y^{-1} have streamflow varying by more than three times (see Figure 6). The variability is controlled by both the timing of precipitation within the year and the continued effects from previous years' precipitation level. The flow-duration curve at DFS is much shorter than at DFN, but the shape during high-flow periods is nearly identical (see Figure 8). Thus, peak overland flow is largely unaffected by the geologic differences.

The annual flow at DP is considerably lower than at the Digby farm catchments during wet years in spite of slightly higher precipitation (Figure 6). DP flow tends to be less continuous than DFN but more continuous than DFS most years (Figure 7). The deep water table in the center of the DP catchment means that there is no groundwater connectivity to produce saturation-dependent overland flow. The surface depression holds runoff to drain slowly, extending the flow duration curve (Figure 8). The doline may focus recharge to the aquifer, mitigating the effect of the plantation ET_a on the water budget.

The geologic setting has more subtle effects at the Mirranatwa sites. The aquifer at the MP weir is strongly artesian with head above the land surface. The water level contours in Figure 3 suggest that this is largely due to pressure induced by the granite at higher elevation to the northwest (not shown) and the potential for preferential fracture flow (Dean et al., 2014). The upward gradient near the MP stream prolongs saturation of the sediments contributing to the longer but lower flow duration curve at MP compared to MF (Figure 8) This interpretation is supported by radon measurements (Dean et al., 2015). The head in well 2292, near the MP weir, remains artesian but is declining so the conditions contributing to the extended flow duration may not persist as the plantation matures (Figure 4). This suggests the curve may reach a tipping point where the aquifer cannot support streamflow through baseflow or saturation-dependant overland flow. Alternatively, the artesian head might mitigate impacts on flow duration through the entire growth and harvest cycle.

It is unclear how the local geology relates to the extremely large streamflow response to high precipitation at GP in 2016. The rapid response to precipitation events and the observed debris near the weir indicate enhanced overland flow. This suggests waterlogging is induced by lateral flow within the soil B horizon and within the kaolinized pallid zone on top of the weathered ignimbrites as observed at GF by Brouwer and Fitzpatrick (2002).

6. *Discussion*

6.1. Groundwater-flow direction and level trends

The plantation catchment groundwater levels declined markedly in most monitoring wells away from the stream lines, whereas the levels did not change significantly in the farm catchment monitoring wells. In addition, the seasonal fluctuation was higher in farm wells. The decreased seasonality and declining water levels in the plantations are consistent with a decrease in groundwater recharge as a result of increased ET_a by the trees. This decrease in groundwater recharge is in agreement with previous research (Amdan et al., 2013; Fan et al., 2014; Rodríguez-Suárez et al., 2011), although no decrease was seen by Silveira et al. (2016). The change in ΔS_{gw} is seldom included in catchment water-balance calculations. However, it can be significant where the catchments are not closed to groundwater; i.e., where groundwater is not discharged as baseflow that is incorporated into streamflow.

The un-treed buffer left along drainage lines in the plantations results in recharge on the lower slopes similar to that in the pasture catchments. Runoff concentrates the recharge in the lower landscape (Dean et al., 2015). Flow in perched water tables can also concentrate recharge in the lower landscape.

Water levels at or near the surface in valley bottom monitoring wells suggest hydraulic connection between groundwater and surface water causing saturation-dependent overland flow during and shortly after winter P. Saturation-dependent overland flow will promote high streamflow during rain events.

6.2. Streamflow and ET_a

Most previous research has concluded that streamflow declines with afforestation as a result of greater ET_a (see Table 1). However, large variability in the precipitation-streamflow relationship has been noted and the findings of decreased streamflow are not universal. We did not see an indication of decreased streamflow in the plantation catchments. This is in contrast to the work of Silveira et al. (2016), where streamflow increased with afforestation but no effect on recharge was seen. Our results support previous findings that ET_a is increased where groundwater is accessible to the tree roots and suggest that the depths where this occurs may be greater than indicated by plot studies (Benyon, 2002; Benyon and Doody, 2004; Benyon et al., 2009; Benyon et al., 2006).

The higher ET_a for our pasture catchments compared to the Zhang et al. (1999) un-treed catchment curve is in agreement with their pasture and crop data from Australia (Figure 9). This high ET_a for the pasture was not expected and means that afforestation only has a small effect on the water balance unless plantation ET_a is supplemented by groundwater uptake. Conversely, Dye (2013) noted that the extremely low water use of the native fynbos in South Africa exaggerates the difference in water use between fynbos and *Pinus* plantations, suggesting caution is needed in applying results between landscapes with different pre-existing vegetation. The cause of the high pasture ET_a for the Australian setting is unknown.

< Figure 9 here please >

A relative increase in plantation streamflow compared to pasture flow was attributed to overland flow in three specific situations in our study. To our knowledge, this has not been observed in previous catchment investigations. The first is the annual flow in the GP catchment in 2016, which was close to that in GF. This suggests that during periods of intense rainfall, the increased ET_a of trees has little effect on runoff. This contrasts with the Zhang curve model, where Q_{sw} for treed catchments is predicted to remain below that of un-treed catchments. Trees likely increase leaf and litter interception, and drier soil may delay the start of infiltration-dependent overland flow. But once the system is wet, there will be no further effect on runoff. Thus, the precipitation-streamflow relationship will depend not only on the amount of precipitation but on the intensity. The second case is the relatively higher plantation response to intense summer rains. This is consistent with soil hydrophobicity seen in *Eucalyptus* plantations and forests. Dry hydrophobic soils will enhance runoff and will become less hydrophobic in wetter seasons (Burch et al., 1987; Burch et al., 1989; Doerr et al., 2003; Doerr et al., 2000; Ferreira et al., 2000). Infiltration tests at the Gatum site showed higher infiltration for the farm pasture than for the plantation (Reynolds, 2010). This makes little difference in annual streamflow but may be important ecologically in helping the persistence in remnant surface-water pools in intermittent/ephemeral streams. The final situation is the greater runoff that may be induced by deep ripping of soil during plantation establishment, as described by Dean et al. (2016). This suggests that design changes might be useful in improving catchment water management; e.g., by channelling runoff downslope for greater water yield or, conversely, by delaying runoff to decrease peak flows.

6.3. Effect of geologic setting

Differences in geologic setting alter the groundwater recharge, affect connectivity between groundwater and surface water, and increase the variability in catchment flow in response to precipitation. The water-table decline noted in our plantation catchments implies that flow duration in these intermittent catchments may ultimately become shorter, although the variability in precipitation dominates the inter-annual flow variability. Thus, the impacts may be different in regions with more consistent precipitation and for plantations with longer harvest cycles. The nonlinearity in precipitation versus annual flow complicates inter-catchment comparison and indicates that extrapolation of flow relationships, such as those used in paired-catchment studies, may not be appropriate because the nonlinear relationship cannot always be predicted from a limited measurement period.

Land-use impacts of plantation development have been studied in the South Australia karst, where the impact of direct uptake of groundwater was documented (Colville and Holmes, 1972; Holmes and Colville, 1970). Our study shows the influence of subsurface limestone, even when covered by other sedimentary formations. The karst topography controls the depth to groundwater and ability for direct groundwater use by trees, the development of saturation-dependent overland flow, and may induce focused recharge along streams and in depressions. Karst areas may need special consideration because their precipitation-streamflow relationship is highly variable and dependent on local conditions.

6.4. Policy implications

The State of Victoria has developed strategies to manage the water-resource impacts of land-use change, but these have not yet been enacted (Department of Sustainability and Environment, 2011a; Department of Sustainability and Environment, 2011b). The policy recognizes potential streamflow and groundwater impacts, but much of the focus has been on streamflow. South Australian policy, in contrast, has focused more on groundwater use by plantations. New plantations in southeastern South Australia may be licensed to use groundwater users because of the shallow water table and minimal surface-water use (Greenwood, 2013). Our investigation indicates that groundwater use by plantations in Victoria is significant, in keeping with previous work (Benyon and Doody, 2004), while the maximum depth to groundwater for uptake by trees has not been established. The larger ET_a in the plantation catchments, however, was not seen to have a major effect on the streamflow because baseflow is already minimal as a result of the seasonal nature of the precipitation and only seasonal connectivity between groundwater and surface water. Thus, we suggest that policy development in Victoria should increase focus on areas where the groundwater resource is of significant importance. This is particularly true in freshwater aquifer recharge areas, as recharge will be reduced by the increased ET_a of plantations.

The variability of pasture and plantation streamflow in different geologic settings presents a challenge in developing water management policy. The site-specific nature of the land-use impacts suggests that flexibility may be possible within management areas if the industry can show that a proposed plantation development is unlikely to have major impact.

The high pasture water use, calculated from water balance for our study and others in Australia, shows that the baseline pasture water use has not always been properly considered in evaluating the effects of afforestation. The discrepancy from global curves indicates that those curves are not appropriate for evaluating the effects of land-use changes in Australia.

7. Conclusion

Our investigation demonstrated a large effect of plantations on the groundwater system with a major reduction in groundwater recharge and a loss of groundwater storage, but there was no clear effect on streamflow. Consideration of groundwater levels and flow directions indicated that the intermittent stream catchments were not closed to groundwater flow and that baseflow to streams was small. Thus the change in ΔS_{gw} , must be considered in the water balance calculation of ET_a. The reduced recharge and uptake of groundwater by tree roots led to a loss of groundwater storage. However, apportioning groundwater flux within the catchment between baseflow, streamflow, and uptake by deep-rooted vegetation remains challenging.

Most global studies have shown high ET_a in forests and plantations and, thus, increased water use caused by plantation establishment. This study does not contradict the high ET_a in plantation systems, but, instead, indicates that ET_a for pastures in the 500 to 1000 mm y^{-1} annual precipitation region of southeast Australia is higher than for pastures in equivalent P regions elsewhere in the world. The explanation for the high pasture ET_a in southeastern Australia has not been established.

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Tables

Table 1 Selected studies of land-use change effects on water resources

Table 2 Catchment characteristics

Table 3 Annual streamflow and precipitation for study catchments

Table 4 Summary of average annual water balance 2011-2016 for study catchments and annual ET_a as percentage of annual precipitation. Water balance ET_a determined by difference from other components (equation 2).

Figures

Figures 2-4, Figure 7, and Figure 9 in color

Figure 1 Location of the Glenelg River Basin and the seven study catchments.

Figure 2 Height above nearest drainage (HAND) and monitoring-well locations. The color scheme is based on deciles of the statewide values and emphasizes the near-zero values.

Figure 3 January 2014 water-table levels and land cover.

Figure 4 Depth to water table from ground surface for wells in farms (on the left) and plantations (on the right).

Figure 5 Daily streamflow and precipitation for study catchments

Figure 6 Annual streamflow against annual precipitation and quarterly (q) streamflow comparison in the period 2011-2016

Figure 7. Days with flow in the different study catchments in different years.

Figure 8 Flow-duration curves for study catchments, 2011-2016, and annual streamflow-duration relationship between farm and plantation catchments. Flow is expressed in mm d^{-1} over 30-min periods.

Figure 9 Comparison of average annual ET_a versus average annual precipitation for the study catchments to Australian data and model curves from Zhang et al. (1999)

Table 1 Selected studies of land-use change effects on water resources

Study	Location	Flow regime	Groundwater measurement	Land use	Key results
Reviews					
Hibbert (1967), Bosch and Hewlett (1982), Zhang et al. (1999; 2001)	Global	Not specified	No	Variable	Evaluation of catchment flow versus P. Development of ET_a versus P curves
Scott et al. (2000)	South Africa	Not specified	No	*Eucalyptus, Pinus* plantation afforestation and deforestation	Wide variety in amount of flow reduction as a result of plantation growth. Peak reductions tend to occur early in rotation, then reduction diminishes.
Brown et al. (2005)	Global	Perennial to intermittent with afforestation; intermittent to perennial with deforestation	No	*Eucalyptus, Pinus* plantation afforestation, regrowth, deforestation	Good agreement seen between paired catchment and water-balance approaches. Takes more than 5 y to reach equilibrium after land-use change. Largest flow-volume changes occur in wet periods, but winter-dominant and snow-affected catchments show larger proportional change in summer months.
McVicar et al. (2007)	Loess Plateau, China	Perennial	No	*Pinus, Populus* Afforestation	Provides review of land-use change research on Loess Plateau. Afforestation reduces streamflow by up to 78%. Zhang curves used to develop decision-support tool for revegetation.
van Dijk and Keenan (2007)	Global	Decline from near perennial to intermittent with afforestation	No	*Pinus* plantation afforestation	Runoff generation from clearing is substantially less than predicted. Difference from experimental studies was attributed to scale effects
Dye (2013)	South Africa	Not specified	No	*Eucalyptus* plantation afforestation	The native vegetation that was replaced had very low water use. Young trees have lower water use efficiency
Global Studies					
Scott and Lesch (1997), Scott et al. (2000), Scott and Prinsloo (2008)	South Africa	Perennial		*Eucalyptus Pinus* plantation afforestation of scrubland and forest; harvest	Streamflow decreased or ceased after planting in several catchments and resumed several years after harvest, but there was large variability in response.
Rodríguez-Suárez et al. (2011)	Spain		Yes	*Eucalyptus* plantation afforestation of pasture and cropland	Dry-season water table declined; streamflow reduction increased as plantation matured.
Almeida et al. (2016)	Brazil		Yes	*Eucalyptus* plantation deforestation	Pasture had higher discharge; harvest increased plantation discharge, but P increased during the study period
Silveira et al. (2016)	Uruguay		Yes	Natural grassland pasture to *Eucalyptus* plantation	Plantation growth increased stream flow but no conclusive effect on groundwater recharge.
Brown et al. (2013)	Australia, South Africa, New Zealand		No	*Eucalyptus Pinus* plantation afforestation, deforestation	Low flows proportionately more effected than high flows but total volume change mainly associated with high flows.
Australian Studies					
Holmes and Colville (1970)	South Australia		Yes	Grassland comparison to *Pinus* plantation	Winter and spring ET_a of up to 2.2 times greater under forests
Colville and Holmes (1972)	South Australia	Intermittent	Yes	Grassland comparison to *Pinus* plantation	Recharge from plantation ~ 50% that of pasture. Karst flow system complicates interpretation of groundwater flow

Study	Location	Flow regime	Groundwater measurement	Land use	Key results
Bren and Turner (1985),;Bren (1997),;Bren et al. (2006),;Bren and Hopmans (2007), Hopmans and Bren (2007), Bren et al. (2010)	Victoria Australia			Native *Eucalyptus* harvest and regrowth or conversion to *Pinus* plantation	Harvesting increased water yield 300 mm y^{-1}, but the flow subsequently declined and remained lower than the control for 34 y. Conversion to plantation immediately increased the water yield up to 300 mm y^{-1} followed by decline in response, but it remained higher than the native forest in dry years. Conversion of grassland to plantation decreased flow
Burch et al. (1987)	Victoria Australia	Intermittent	No. Perched zone was monitored	Native *Eucalyptus* forest deforestation	Higher Q_{sw} in grassland attributed to lower soil hydraulic conductivity rather than ET_a differences
Cornish and Vertessy (2001)	Victoria Australia			Native *Eucalyptus* harvest, regrowth	Increased flow for 2 y after logging and then declining flow, reaching levels statistically below pre-harvest after 12 y
Webb et al. (2012)	New South Wales Australia			*Eucalyptus* harvest and regrowth	Eucalyptus forest regrowth Q_{sw} may follow curves where water use initially increases but then decreases to levels below pre-harvest flow as seen in *Eucalyptus regnans* forest.
Benyon (2002), Benyon and Doody (2004), Benyon et al. (2006), Benyon et al. (2007), Benyon et al. (2009)	Victoria and South Australia	Not specified	No	*Eucalyptus* plantation afforestation	Plot scale studies. ET for *Eucalyptus* plantations approaches P. $ET_a > P$ attributed to groundwater uptake by tree roots.
Greenwood and Cresswell (2007)	South Australia	Intermittent	No	*Pinus* plantation regeneration after fire	Plantation resulted in ~85% reduction in streamflow. Maximum impacts were detected after 5 y of regrowth.
Adelana et al. (2015)	Gatum Site Victoria Australia (site included in current study)	Intermittent		*Eucalyptus* plantation afforestation	Consistently higher streamflow seen in pasture catchment than in plantation using 2 y data. Water table rose in pasture catchment but fell in plantation.
Dean et al. (2015)	Mirranatwa Site Victoria Australia (site included in current study)	Intermittent	Yes	*Eucalyptus* plantation afforestation	Groundwater recharge occurred dominantly in valley bottoms. Groundwater levels declined in the plantation but not the pasture. Groundwater was lost from the plantation catchment dominantly by ET_a.
Dean et al. (2016)	Mirranatwa Site Victoria Australia (site included in current study)	Intermittent	Yes	*Eucalyptus* plantation afforestation	ET_a in plantation catchment was greater than P and greater than in pasture catchment, but Q_{sw} was similar over a 4 y period. Downslope orientation of plantation furrows promoted runoff.
This Study	Victoria Australia	Intermittent	Yes	*Eucalyptus* plantation afforestation	

Table 2 Catchment characteristics

Catchment	**Total area ha**	**Valley bottom ha**	**Mid slope ha**	**Upper slope ha**	**Tree cover ha, %**	**Mean annual precipitation 2011-2016 (long term mean*) mm y^{-1}**	**Average annual potential ET$_0$** mm y^{-1}**	**Geology**
Gatum Farm (GF)	151	33	50	68	5, 3%	622 (627)	1080	Weathered Devonian acid volcanics
Gatum Plantation (GP); established in 2005	338	45	99	194	230, 68%			
Mirranatwa Farm (MF)	47	8	11	28	2, 3%	595 (672)	1300	Weathered Devonian granite
Mirranatwa Plantation (MP);;established in 2008	78	10	25	43	51, 66%			
Digby Farm North (DFN)	195	50	66	79	38, 19%	702 (734)	1044	Tertiary marginal marine clays and sands over limestone
Digby Farm South (DFS)	160	59	73	28	2, 1%			
Digby Plantation (DP); established in 2001	391	274	117	-	375, 96%	771 (734)	1020	

[*] Long-term mean precipitation from nearest Bureau of Meteorology Sites: Gatum Station 089043; Mirranatwa Station 89019; Digby Station 090057. http://www.bom.gov.au/climate/data/

** Potential ET calculated using the Food and Agriculture Organization of the United Nations (FAO) Penman-Monteith formula from http://www.longpaddock.qld.gov.au/silo

Table 3 Annual streamflow and precipitation for study catchments

	Gatum					Mirranatwa					Digby							
Year	**P**	**Farm**		**Plantation**		**P**	**Farm**		**Plantation**		**Farm P**	**Farm North**		**Farm South**		**Plantation P**	**Plantation**	
	mm y^{-1}	Q_{sw} mm y^{-1}	Duration % *	Q_{sw} mm y^{-1}	Duration % *	mm y^{-1}	Q_{sw} mm y^{-1}	Duration % *	Q_{sw} mm y^{-1}	Duration % *	mm y^{-1}	Q_{sw} mm y^{-1}	Duration % *	Q_{sw} mm y^{-1}	Duration % *	mm y^{-1}	Q_{sw} mm y^{-1}	Duration % *
2011	722	54	61	25	26	734	26	42	40	50	787	141	55	121	22	978	37	53
2012	527	23	39	11	22	561	22	28	16	38	774	57	35	44	21	764	4	35
2013	574	46	40	24	17	583	22	21	18	27	765	101	37	103	20	845	13	33
2014	537	20	40	11	16	476	7	10	5	14	655	49	29	2	3	590	2	18
2015	491	8	38	2	12	397	1	3	1	3	479	11	26	2	7	557	~0	7
2016	879	159	55	189	42	819	42	36	43	37	750	156	41	124	36	890	32	40
Mean	*622*	*52*	*46*	*44*	*23*	*595*	*20*	*23*	*20*	*28*	*702*	*86*	*37*	*66*	*18*	*771*	*15*	*31*
Min	*491*	*8*	*38*	*2*	*12*	*397*	*1*	*3*	*1*	*3*	*479*	*11*	*26*	*2*	*3*	*557*	*0*	*7*
Max	*879*	*159*	*61*	*189*	*42*	*819*	*42*	*42*	*43*	*50*	*787*	*156*	*55*	*124*	*36*	*978*	*37*	*53*
S.D.	*150*	*55*	*10*	*72*	*11*	*158*	*14*	*15*	*17*	*17*	*119*	*57*	*10*	*57*	*12*	*168*	*16*	*16*

* Duration is the percent of time with measurable streamflow

Table 4 Summary of average annual water balance 2011-2016 for study catchments and annual ET_a as percentage of annual precipitation. Water balance ET_a determined by difference from other components (equation 2).

	Average Annual Water Balance, mm y^{-1} (% of P)						
	GF	**GP**	**MF**	**MP**	**DFN**	**DFS**	**DP**
P	622	622	595	595	702	702	771
Q_{sw}	52 (8)	44 (7)	20 (3)	20 (3)	86 (12)	66 (9)	15 (2)
ΔS_{gw}	23 (4)	-73 (-12)	-1 (-0.1)	-80 (-13)	-8 (1)	-3 (-0.4)	-29 (-4)
Q_{gw}	6 (0.9)	19 (3)	21 (4)	11 (2)	6 (0.9)	5 (0.7)	1 (0.2)
ET_a	541 (87)	632 (102)	555 (93)	643 (108)	617 (88)	634 (90)	783 (102)

	Water Balance ET_a, mm y^{-1} (% of P)						
Year	**GF**	**GP**	**MF**	**MP**	**DFN**	**DFS**	**DP**
2011	611 (85)	752 (104)	660 (90)	728 (99)	677 (86)	677 (86)	961 (98)
2012	533 (101)	640 (121)	523 (93)	593 (106)	750 (97)	751 (97)	837 (110)
2013	503 (88)	585 (102)	541 (93)	642 (110)	610 (80)	625 (82)	828 (98)
2014	550 (102)	612 (114)	480 (101)	568 (119)	678 (103)	686 (105)	659 (112)
2015	567 (116)	595 (121)	410 (103)	494 (125)	510 (107)	494 (103)	596 (107)
2016	481 (55)	606 (69)	716 (87)	835 (102)	478 (64)	568 (76)	821 (92)
Average	*541 (87)*	*632 (102)*	*555 (93)*	*643 (108)*	*617 (88)*	*634 (90)*	*783 (102)*
SD	*47 (21)*	*62 (20)*	*114 (6)*	*122 (10)*	*106 (16)*	*92 (12)*	*133 (8)*

	Zhang Curve ET_a, mm y^{-1} (% of P)						
Year	**GF**	**GP**	**MF**	**MP**	**DFN**	**DFS**	**DP**
2011	530 (73)	613 (85)	535 (73)	618 (84)	583 (74)	555 (71)	821 (84)
2012	429 (81)	475 (90)	449 (80)	499 (89)	576 (74)	550 (71)	679 (89)
2013	456 (79)	510 (89)	461 (79)	515 (88)	572 (75)	546 (71)	736 (87)
2014	435 (81)	483 (90)	398 (84)	434 (91)	516 (79)	496 (76)	547 (93)
2015	407 (83)	447 (91)	346 (87)	370 (93)	409 (86)	399 (83)	520 (93)
2016	595 (68)	709 (81)	572 (70)	671 (82)	565 (75)	540 (72)	765 (86)
Average	*475 (78)*	*540 (88)*	*460 (79)*	*518 (88)*	*537 (77)*	*514 (74)*	*678 (89)*
SD	*72 (6)*	*101 (4)*	*84 (6)*	*112 (4)*	*67 (4)*	*61 (5)*	*121 (4)*

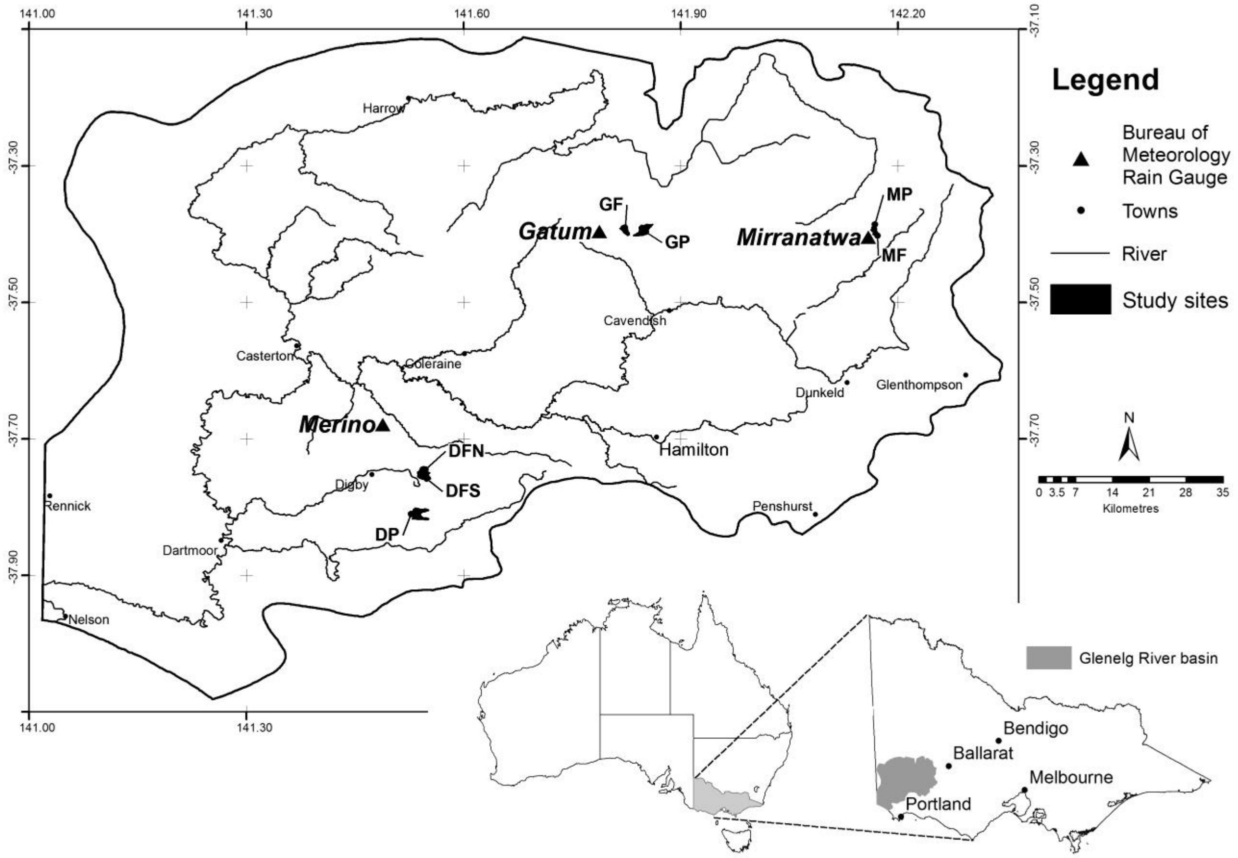

Figure 1 Location of the Glenelg River Basin and the seven study catchments. The catchments are: GF: Gatum Farm, GP: Gatum Plantation, MF: Mirranatwa Farm, MP: Mirranatwa Plantation, DFN: Digby Farm North, DFS: Digby Farm South, DP: Digby Plantation.

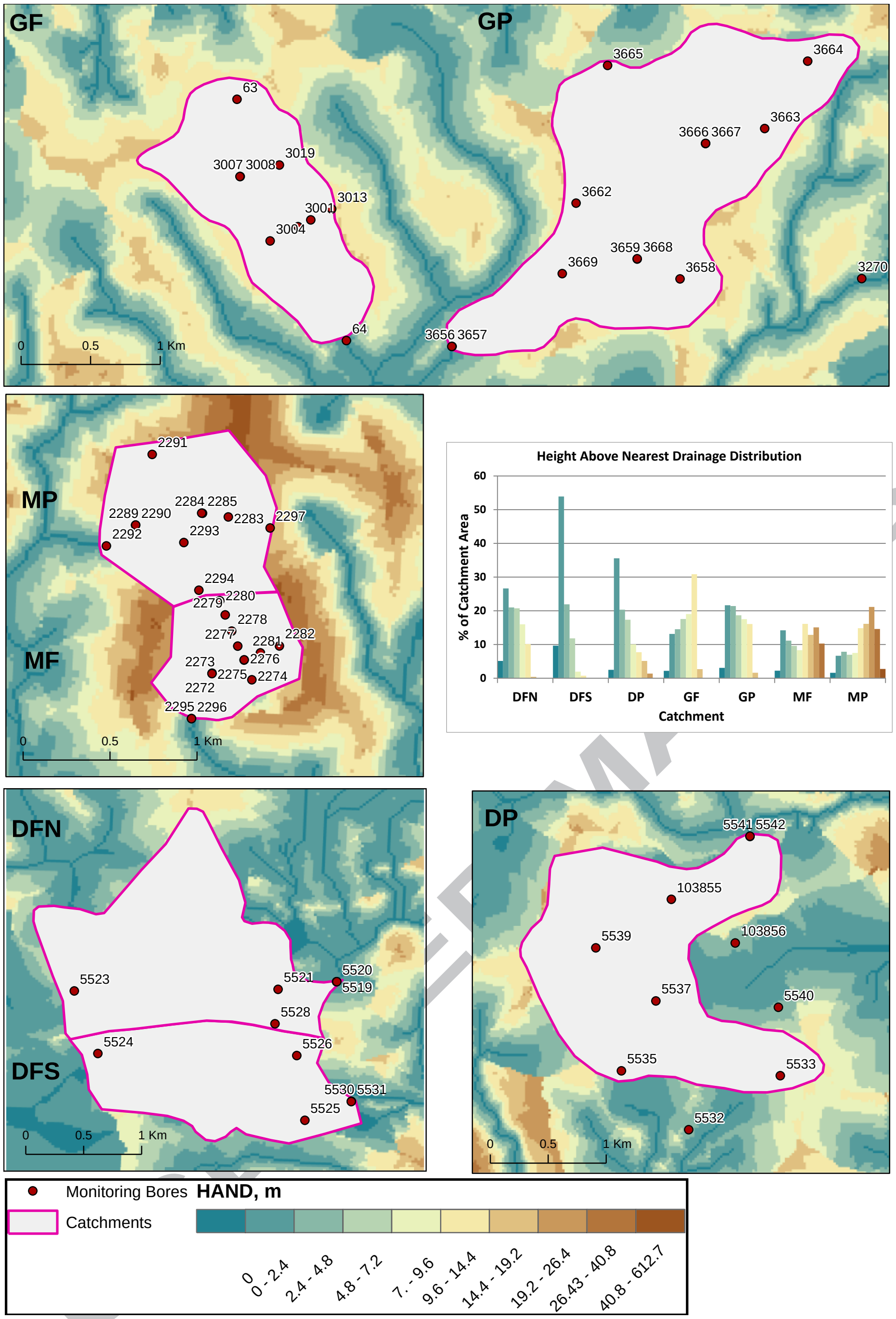

Figure 2 Height above nearest drainage (HAND) and monitoring-well locations. The color scheme is based on deciles of the statewide values and emphasizes the near-zero values.

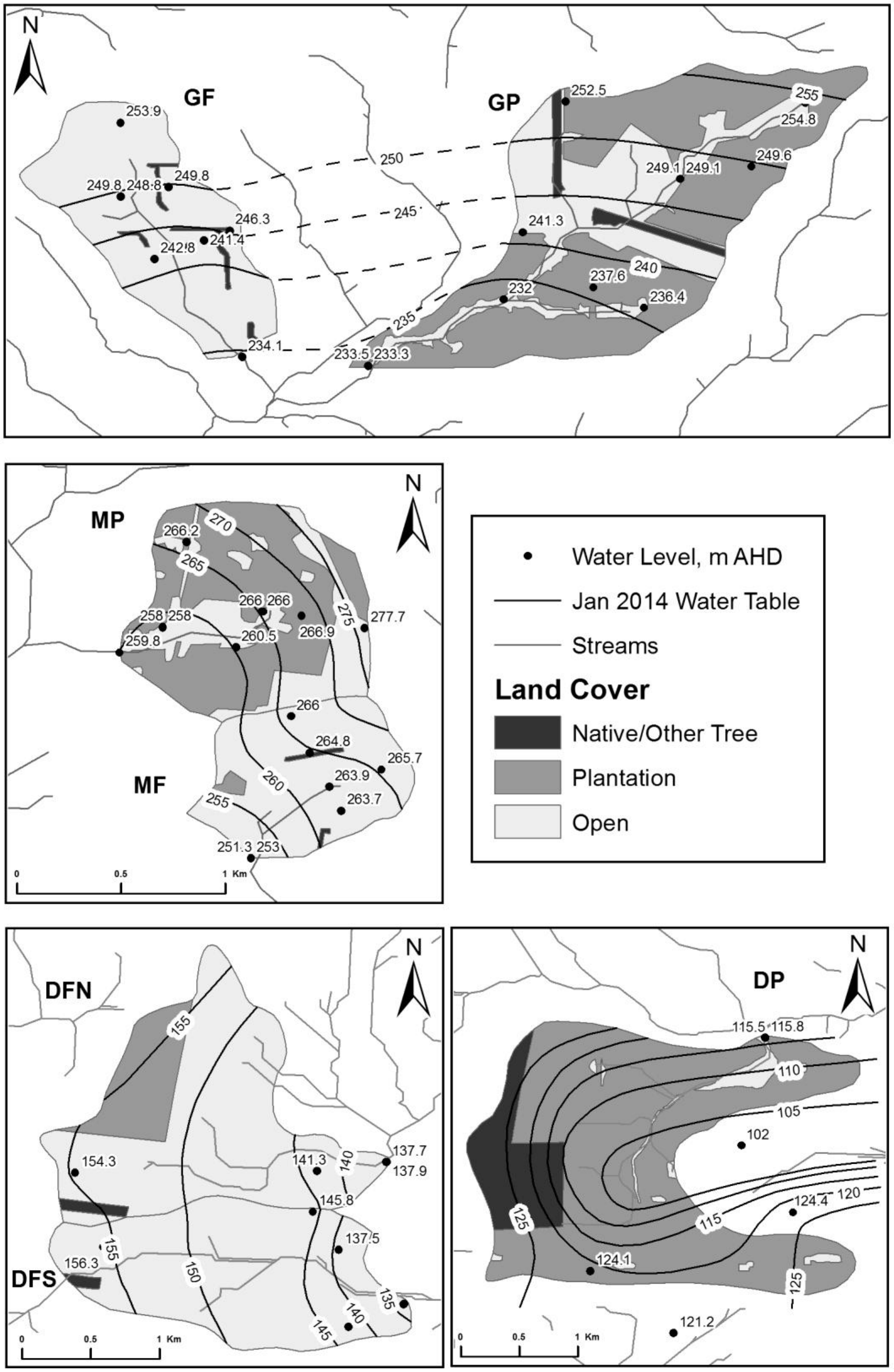

Figure 3 January 2014 water-table levels and land cover.

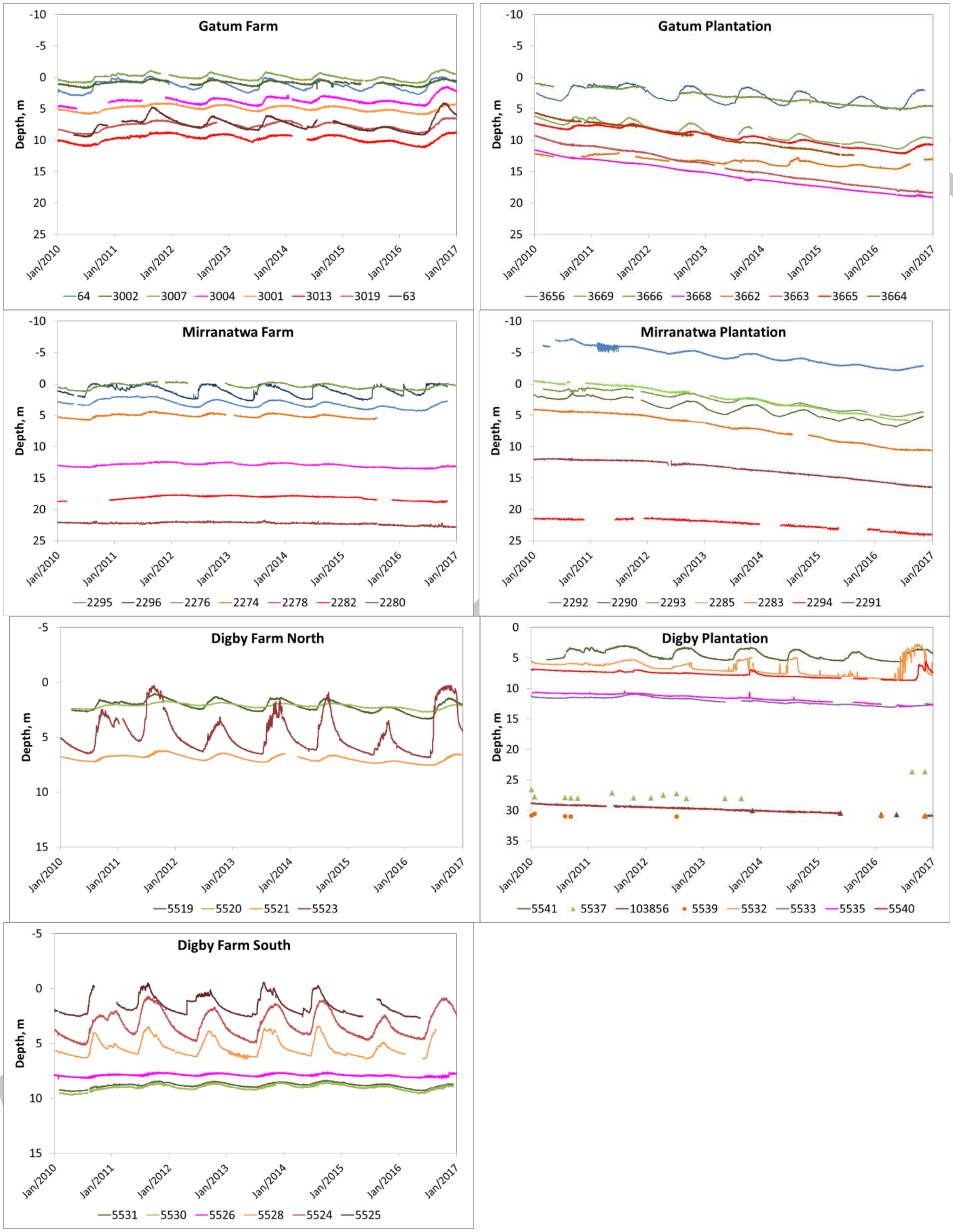

Figure 4 Depth to water table from ground surface for wells in farms (on the left) and plantations (on the right).

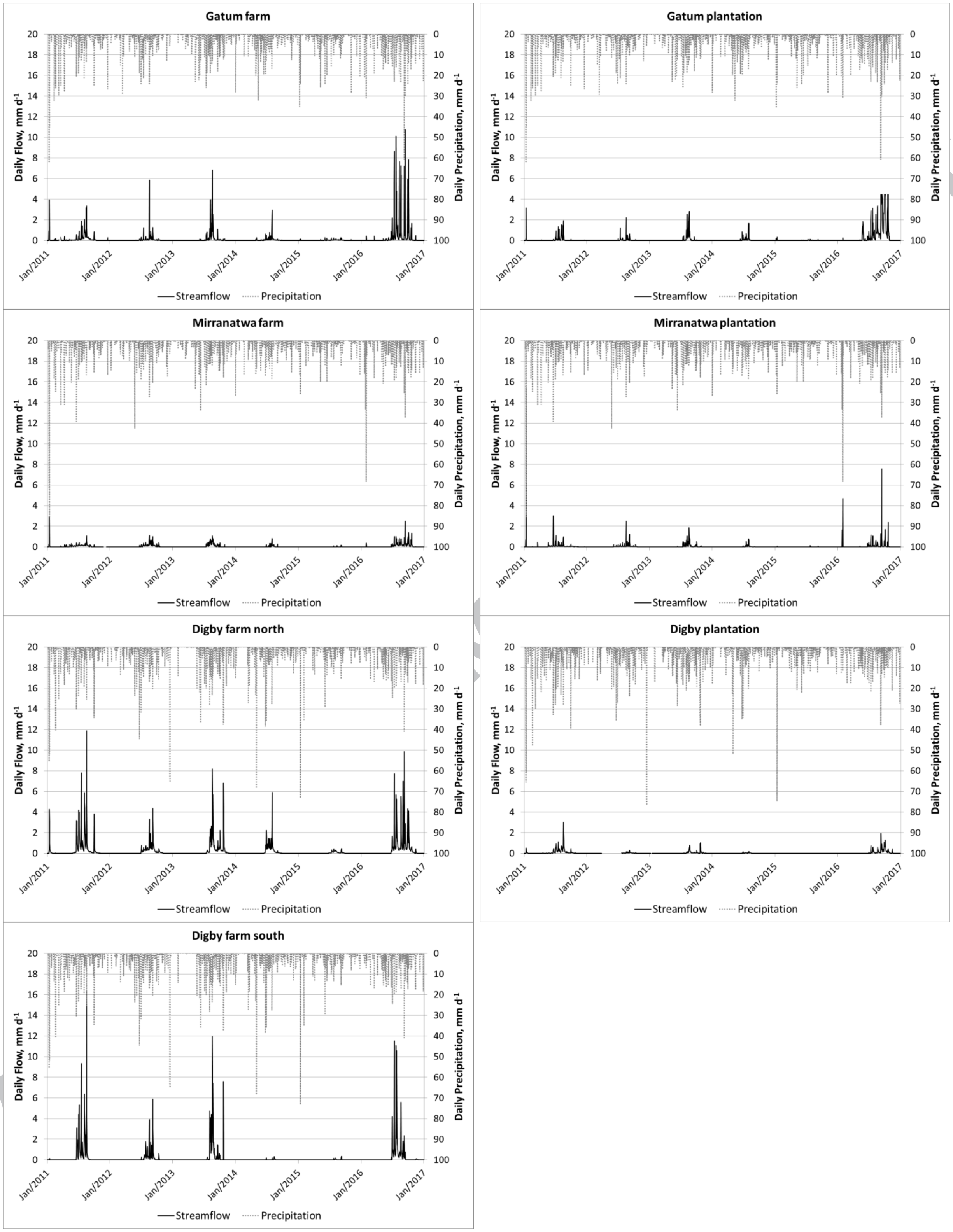

Figure 5 Daily streamflow and precipitation for study catchments

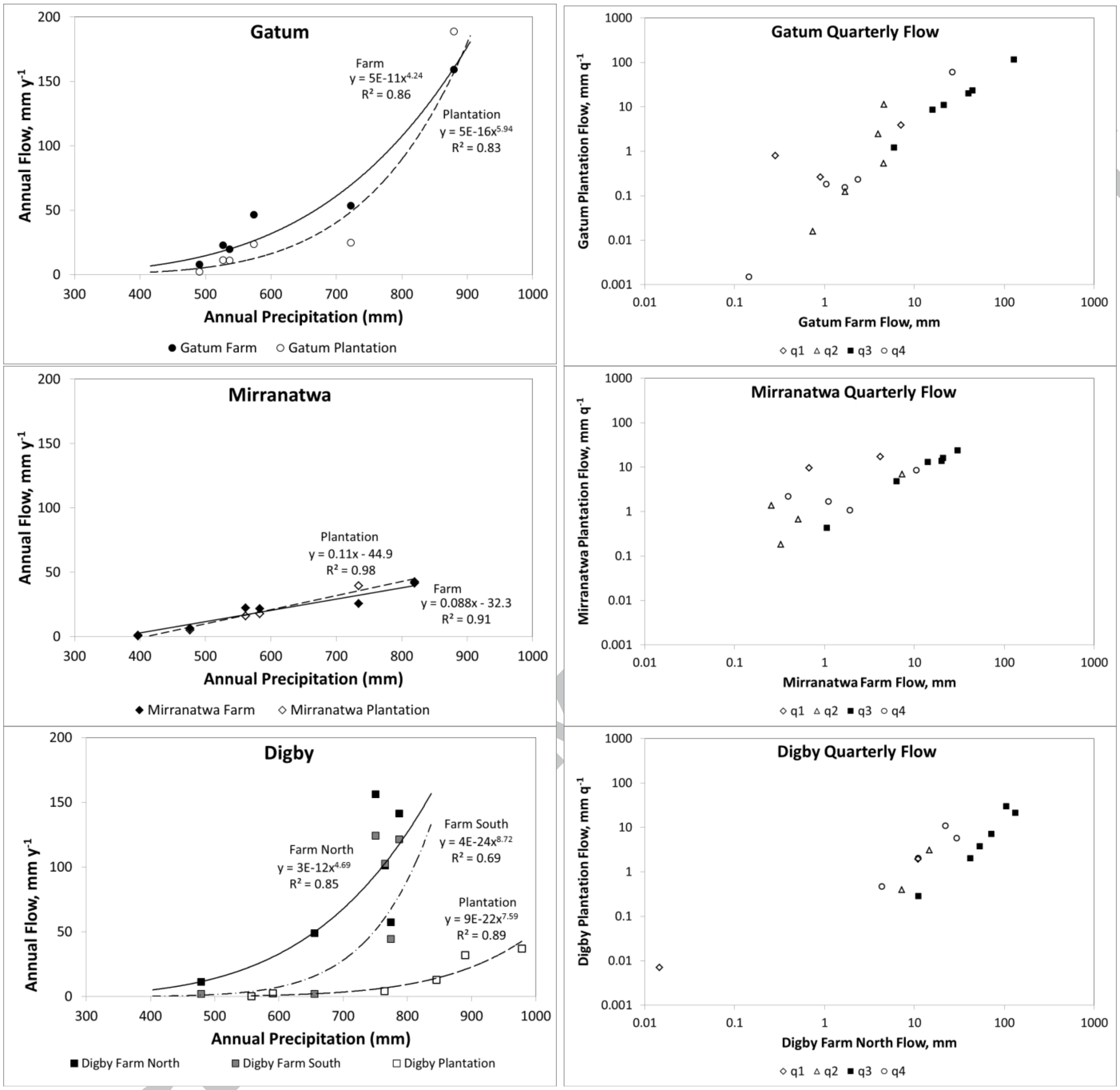

Figure 6 Annual streamflow against annual precipitation and quarterly (q) streamflow comparison in the period 2011-2016

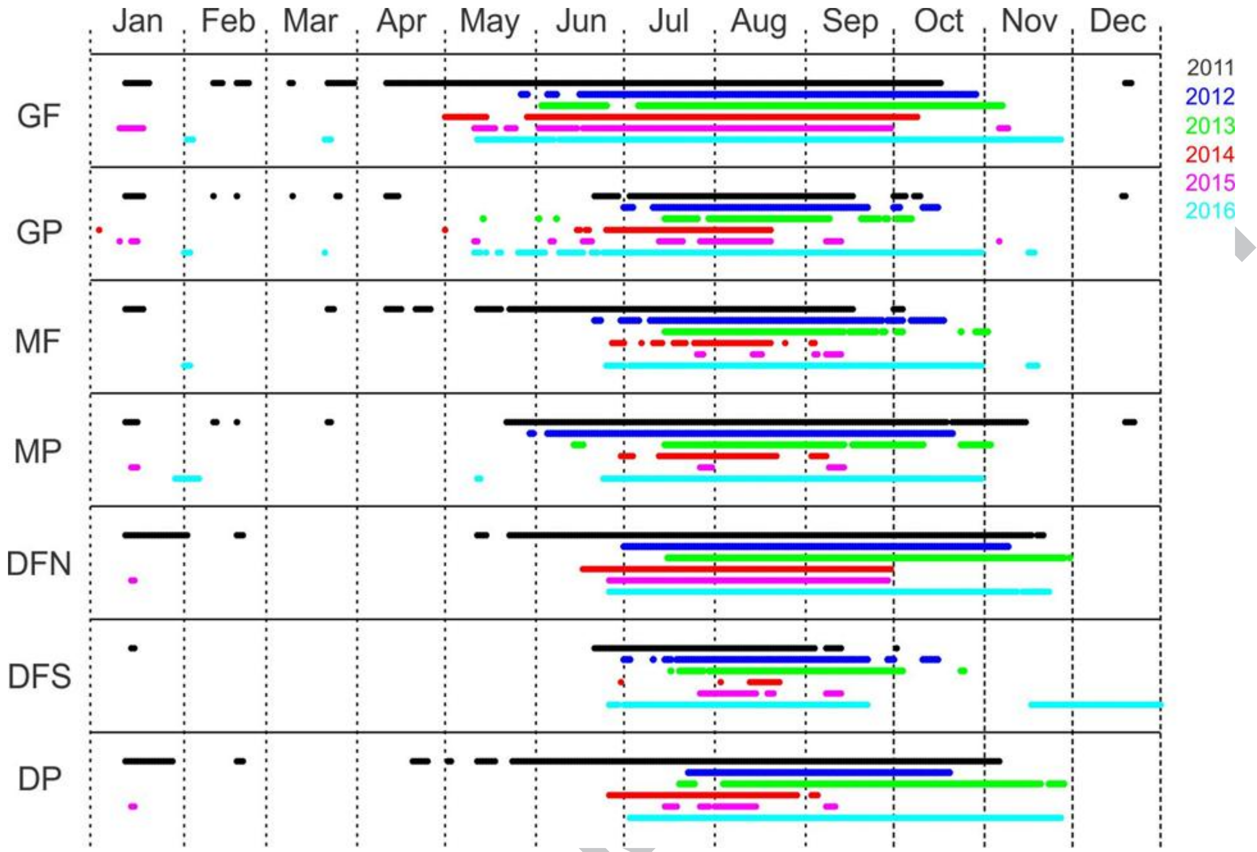

Figure 7. Days with flow in the different study catchments in different years.

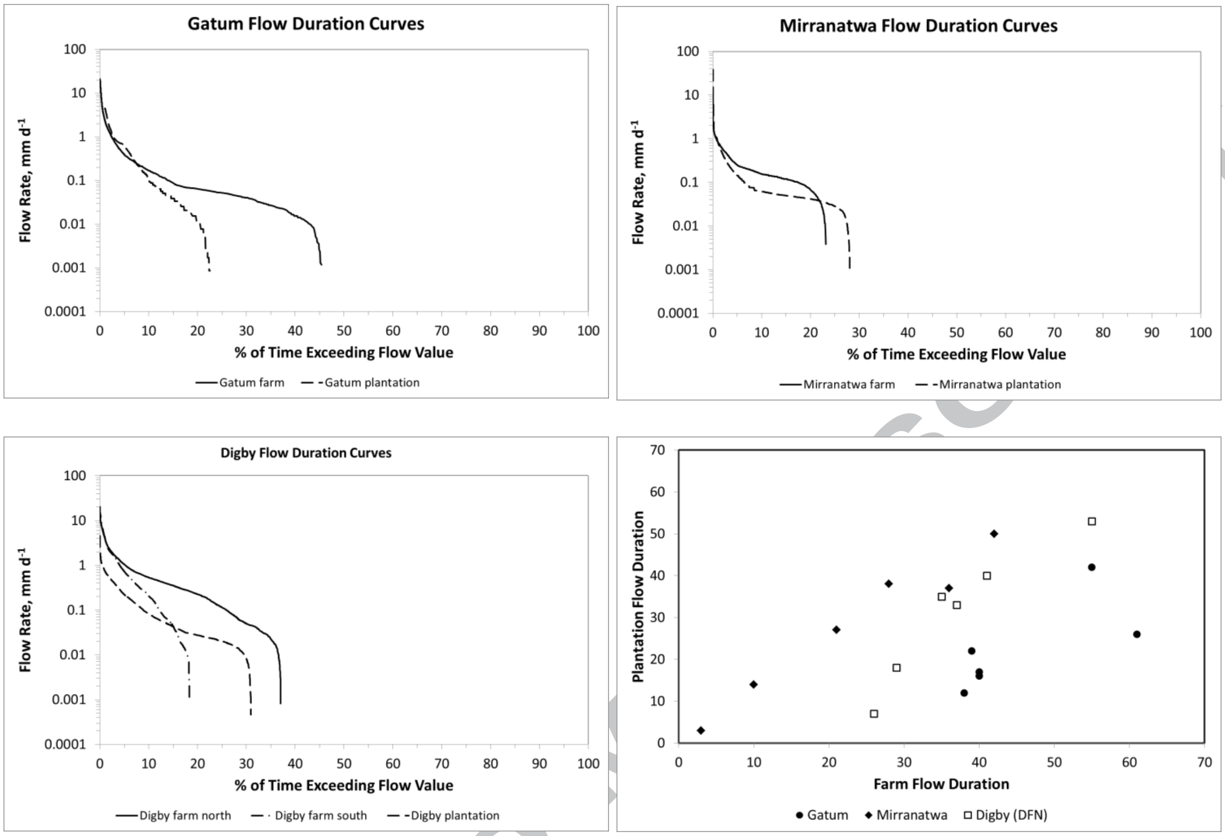

Figure 8 Flow-duration curves for study catchments, 2011-2016, and annual streamflow-duration relationship between farm and plantation catchments. Flow is expressed in mm d^{-1} over 30-min periods.

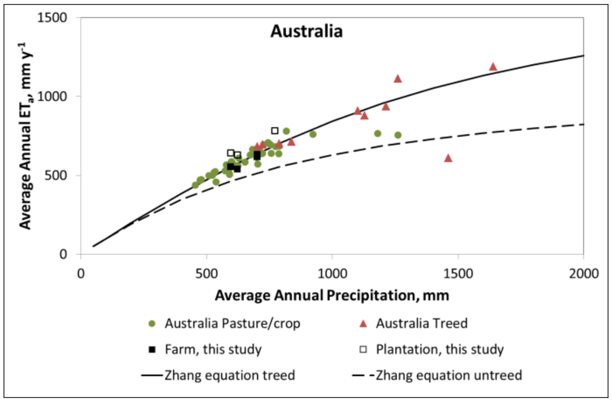

Figure 9 Comparison of average annual ET$_a$ versus average annual precipitation for the study catchments to Australian data and model curves from Zhang et al. (1999)