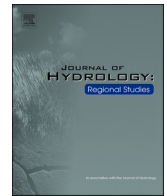




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The influence of different tree species and age on the surface water balance of a small commercial forestry catchment

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ABSTRACT

Acacia mearnsii and *Eucalyptus dunnii* plantations play an important role in the South African economy as a source for a variety of wood products. However, these species are commonly associated with high evapotranspiration (ET) which may cause streamflow reduction, affecting downstream water users who are reliant on the stream for survival. The potential future increase in exotic plantations worldwide necessitates understanding the impact of these different species on the water balance, hence the streamflow. At the Two Streams research catchment in South Africa, intense hydrological observations (streamflow, ET and weather) have been conducted on *A. mearnsii* for almost two decades. In 2018, the catchment was clear-felled with subsequent replanting of *E. dunnii* and hydrological measurements continued. This provided an opportunity to present observations of the surface water balance of the catchment. However, gaps in the data at various times prevented a compilation of a continuous hydrological record. Therefore, three window periods, with complete records of streamflow, ET and precipitation, and with similar weather conditions, were compared. Only the interception loss (I_i) was estimated using the Von Hoyningen-Huene method. First window, *A. mearnsii* trees were three years old (A_{mea3}), second window, *A. mearnsii* trees were seven years old (A_{mea7}) and the third window, *E. dunnii* trees were three years old (E_{dun3}). Results indicated a negative catchment surface water balance for all window periods. During the A_{mea7} window period, the I_i was highest compared to the young crops, which reduced effective precipitation, in turn contributing to the lowest measured streamflow. The negative surface water balance and high ET, suggests that trees were accessing water not quantified in the surface water balance. Crops of all three window periods were found to have the potential to significantly reduce the streamflow, which may in turn affect downstream water users. Further research using isotopes to trace the sources of water used by trees in the system is suggested.

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1. Introduction

In many parts of the world, exotic forest plantations including *Eucalyptus* and *Acacia mearnsii* are a major supplier of industrial roundwood, with fast growth rates and short rotations (Morris et al., 2022). Planted commercial forests only constitute 8 % of the global forest area, however, supply 46 % of industrial roundwood (Payn et al., 2015). A well-managed commercial forest plantation can improve soil infiltration rates (van Dijk and Keenan, 2007), significantly reduce soil erosion due to forest litter at the soil surface, minimise soil evaporation (Wichert et al., 2018) and mitigate air pollution and climate change (Ferreto et al., 2021). Further benefits of commercial forestry include contribution to socio-economy through employment and agricultural gross domestic product.

Despite the crucial role played by *Eucalyptus* and *A. mearnsii* in different parts of the world (including South Africa), research have indicated that evapotranspiration (ET) by both species is significantly higher than indigenous forest stands and grasslands (Dye et al., 2001; Dye and Jarmain, 2004; Albaugh et al., 2013; Almeida et al., 2016; Reichert et al., 2017). In South Africa, *Eucalyptus* and *A. mearnsii* species are largely confined in high rainfall areas, which were previously covered by low water using grasslands and Fynbos, adjacent to catchments that are critically important sources of water for rivers (Dye, 2013). This has resulted in a significant reduction of streamflow, hence affecting downstream water demands by the environment, industry, agriculture and human settlements (Dye, 2013; Farley et al., 2005; Jackson et al., 2005).

In addition, commercial forest plantations, especially the genetically improved *Eucalyptus* hybrids have a deep taproot (Dye, 1996), providing the capability to access groundwater reserves during the dry season (van Dijk and Keenan, 2007). This usually results in perennial streamflow reduction and lowering of the groundwater table (Scott and Prinsloo, 2008; Lu et al., 2018). A study by Scott and Lesch (1997) in the Mokobulaan experimental catchment in South Africa reported that afforestation with *Eucalyptus* and pines significantly reduced the streamflow (Q) after three and four years of planting, respectively. A complete cessation of Q was observed at year nine for *Eucalyptus*, and year twelve for pines, with full perennial Q returning five years after clear-felling. A study by Dye and Jarmain (2004) on the implications of removing invading *A. mearnsii* on the Q indicated that the Q increased after removal of invading *A. mearnsii*, attributed to high water use by this species resulting to streamflow reduction.

The Two Streams research catchment (in Mistley Canema, KwaZulu-Natal, South Africa) is one of the few catchments in South Africa where detailed hydrological observations have been conducted (Dye and Jarmain, 2004; Clulow et al., 2011; Everson et al., 2014) on *A. mearnsii* for extended periods. Results indicated that *A. mearnsii* ET exceeded precipitation in the first 6 years of growth by as much as 46 %, and there was sufficient evidence suggesting that trees can access deep underground water reserves using their deep taproots. In February 2018, after a 12-year rotation, the *A. mearnsii* trees were harvested and *E. dunnii* was planted in March 2018. The hydrological measurements resumed in September 2019. This presented a unique opportunity to quantify the catchment surface water balance for *A. mearnsii* (at two different stages of growth) and *E. dunnii* (in the early stages of growth) in the same study site and catchment. However, the various components of the water balance were incomplete at various times, due to research funding constraints at times as well as various equipment failures, and compiling a continuous surface water balance record was not possible. Therefore, annual measurement window periods were identified in the dataset when, 1) measurement records were complete, and 2) climatic conditions were representative of the long-term mean of Mistley Canema. The aim of this study was therefore to compare the surface water-balance for young *A. mearnsii* (~three years old), matured *A. mearnsii* (~seven years old) and young *E. dunnii* (~three years old). Since the hydrological data for measurement windows were conducted on the same study site and for similar climatic

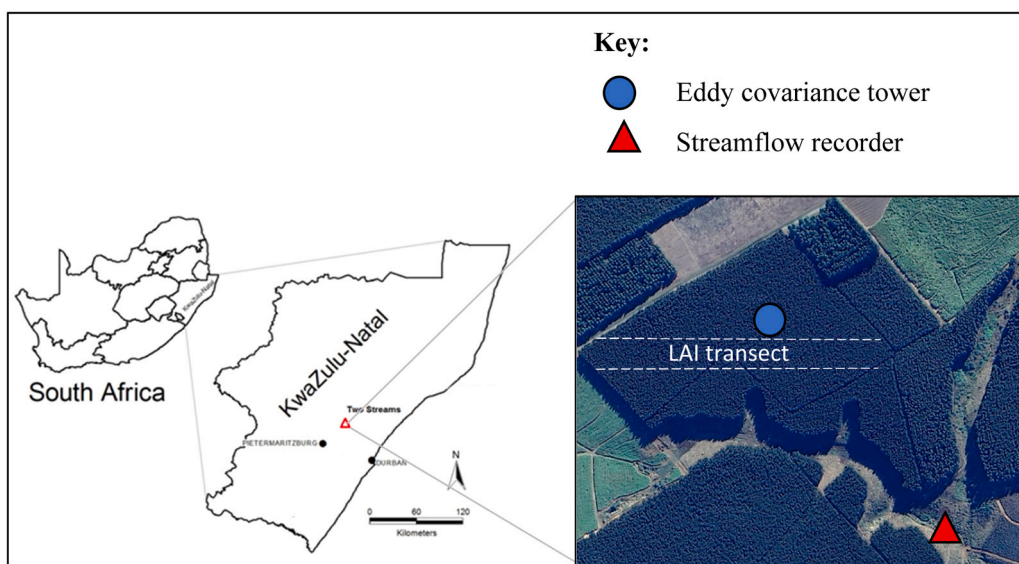


Fig. 1. Location of the study area at Two Streams Research Catchment. The Google Earth extract (extreme right) provides aerial view of the catchment with location of measurements points (© Google Maps 2023). The leaf area index (LAI) transect is indicated.

conditions, the differences in the water-balance are attributed mainly to changes in the landcover providing a unique comparison of the surface water balance for trees of different ages and species at the same site.

2. Material and methods

2.1. Description of the study site

The catchment location is at Mistley Canema (29°12'19.78"S, 30°39'3.78"E) in the Seven Oaks area, northeast of Pietermaritzburg in the KwaZulu-Natal province of South Africa (Fig. 1). The catchment is in a part of the midlands mist-belt grassland Bioregion, mostly dominated by forb-rich, tall, sour *Themeda triandra* of which few patches remain due to *Aristida junciformis* invasion (Everson et al., 2014). The catchment size is approximately one km² with hilly topography and rolling landscapes that dips towards the southeast, resulting in the northwest to southeast surface drainage. The study site weather classification according to Koppen-Geiger climate classification (Peel et al., 2007) falls within the Cwa bioclimate zone characterised by dry, cold winters and wet summer months (Table 1). *Acacia mearnsii* trees were planted in March 2006 (for a full rotation of 12 years) with hydrological monitoring including streamflow gauging (Q), ET, soil water content (SWC) and groundwater reserves conducted by Clulow et al. (2011) and Everson et al. (2014). In February 2018, the *A. mearnsii* trees were harvested. The catchment was subsequently planted to *E. dunnii* in March 2018. Hydrological processes measurements (Q, ET, SWC and depth to groundwater) resumed in September of 2019. A study by Clulow et al. (2011) and Everson et al. (2014) classified the soil profile in the catchment to be as deep as 13 m and below consists of a weathered bedrock (saprolite) and fractured basement rock under the soil profile. The soil form was classified as Hutton (Soil Classification Working Group, 1991). Both the *A. mearnsii* and *E. dunnii* crops were planted at a spacing of 2 × 3 m (1667 trees ha⁻¹).

Three hydrological years, referred to as measurement windows in this paper (a hydrological year starts on the 1st of October to the 30th of September in South Africa), with complete dataset of hydrological measurements including Q, ET, and weather data were identified for comparison. They were considered suitable as their annual precipitation and general climate was statistically similar over the window periods. The trees were between 2.7 and 3.7 years old in the first measurement period (October 2008 to September 2009, referred to as *Amea₃*). They were 6.7–7.7 years old (October 2012 to September 2013, referred to as *Amea₇*) in the second measurement period. After replanting *E. dunnii* trees in March 2018 a final measurement window from the age of 2.6–3.6 years old (October 2020 to September 2021, referred to as *Edun₃*) was compared.

2.2. Climatic conditions

An automatic weather station was installed on a flat uniform grassland area adjacent to the study site to provide supporting meteorological measurements. Measurements of air temperature (T_{air}) (HMP 60, Vaisala Inc., Helsinki, Finland), relative humidity (RH) (HMP60, Vaisala Inc., Helsinki, Finland), wind speed (WS) and direction (Model 03003, R.M. Young, Traverse City, Michigan, USA), solar radiation (I_s) (Kipp and Zonen CMP3) and gross precipitation (TE525, Texas Electronics Inc., Dallas, Tx, USA) were conducted every 30 min. The sensors were installed according to recommendations of the World Meteorological Organisation (World meteorological Organisation, 2008) with rain gauge orifice at 1.2 m and the remaining sensors at 2 m above the ground surface. The sensor outputs were recorded on a CR1000 datalogger (Campbell Scientific Inc., Logan, Utah, USA) at 30 min intervals. The datalogger was programmed to calculate the vapour pressure deficit (VPD) using T_{air} and RH measurements according to Savage et al. (1997). The reference evaporation (ET_o) was calculated using the technique described in Allen et al. (2011).

The monthly effective precipitation (P_{eff}) was calculated using:

$$P_{eff} = P_g - I_l \quad (1)$$

where P_g is the gross precipitation (mm) and I_l is the plant canopy interception loss (mm). The negative P_{eff} values were rounded off to 0 mm.

Table 1

The general characteristics of the Two Streams Research catchment (South African taxonomic system).

Characteristics	Our study site
Minimum MAT (°C)	4.5
Maximum MAT (°C)	31.7
MAP (mm)	778
Climate	Warm subtropical
Altitude (meters above sea level)	1060 – 1110
Soil bulk density (g. cm ³)	1.25
Soil texture	Sandy clay
Lithology	Shale

^aSoil Classification Working Group, (1991)

2.3. Streamflow measurements

The Q was measured from a 457.2 mm 90° V-notch using a CS450 pressure transducer (Campbell Scientific Inc., Logan, Utah, USA) with data recorded in a CR200X datalogger (Campbell Scientific) for all three measurement periods. The CS450 pressure inducer sensor consists of a piezoresistive sensor housed in a water resistance stainless steel package to enhance reliability (Campbell Scientific, 2010). The sensor provides accurate measurements of water pressure and level that are fully temperature compensated. The water level measurements from the CS450 sensor were calibrated by directly measuring the water level from the V-notch using a measuring tape.

2.4. Evapotranspiration

All data for the first two window periods were sourced from the Centre for Water Resources Research (CWRR) at the University of KwaZulu-Natal in Pietermaritzburg (details of measurement techniques and equipment used can be found in Clulow et al. (2011) and Everson et al. (2014). For $Edun_3$, the ET was measured using an eddy covariance system (EC) to derive sensible heat flux (H), using a three-dimensional sonic anemometer (CSAT3, Campbell Scientific Inc., Logan, Utah, USA) and measurements of net radiation (R_n) and ground heat flux (G) were conducted simultaneously on the study site. The R_n was measured using a net radiometer (NRLite, Kipp and Zonen, Delft, Netherlands) attached to the lattice mast (24 m in height) on a horizontal boom 2.5 m away from the lattice mast at a height of 18.5 m. The sonic anemometer was mounted on the lattice mast at a height of 18 m. The G was measured using two HFPO1-L soil heat flux plates and parallel TCAV-L averaging thermocouples (Campbell Scientific Inc., Logan, Utah, USA). The soil heat flux plates and thermocouples were buried in the middle of the compartment (approximately 2 m away from the EC system) at a depth of 0.08 m and 0.02 m below the soil surface, respectively, to estimate the heat stored in the soil.

The EC is a technique based on estimation of eddy fluxes. The H used in estimation is expressed as:

$$H = \overline{\rho_a c_p w' T_{air}'} \quad (2)$$

where, ρ_a is the density of dry air (kg m^{-3}), c_p is the specific heat capacity for air at constant pressure ($\text{J kg}^{-1} \text{K}^{-1}$), w' is the vertical wind speed (m s^{-1}) and T_{air} is the air temperature ($^\circ\text{C}$). The w' and T_{air} are measured using the sonic anemometer and the primes denote fluctuation from a temporal average and the overbar represents a time average. The averaging period of the instantaneous fluctuations of w' and T_{air} should be long enough (30–60 min) to capture all the eddies that contribute to the flux and fulfil the assumption of stationarity (Meyers and Baldocchi, 2005). The zero plain displacement and roughness layer were determined to be at 12.0 m and 24.0 m, respectively. Therefore, the sonic anemometer height was 18 m above tree canopy. The energy balance (LE) was calculated as a residual term using the simplified energy balance equation:

$$R_n = G + H + LE \quad (3)$$

where, R_n is the net irradiance, H is the sensible heat flux, LE is the latent heat flux (equivalent to ET by conversion, Savage et al. (2004)) and G is the ground heat flux. The EC data was processed using the Eddy Pro® 7 software (Licor Inc., Lincoln, Nebraska, USA) for spikes in the data, sonic temperature corrections, co-ordinate rotation and planar fit. In addition to these processing steps, the 30-min flux data were screened using the following criteria 1) data obtained when the sensor malfunctions were removed from the analysed dataset 2) data on rainy days were excluded due to the negative impact of precipitation on turbulent fluxes as reported by Zhang et al. (2017) 3) incomplete 30-min data were removed, when the missing ratio was greater than 5 % in the 30-min raw data 4) night-time data ($R_n < 0$) was removed from the analysis due to potentially large nocturnal influences at night-time (Blanken et al., 1998; Wilson et al., 2001).

2.5. The leaf area index

The leaf area index (LAI) measurements were conducted monthly on $Amear_3$, $Amear_7$ and $Edun_3$ measurement periods using a LAI-2200 Plant Canopy Analyzer (Licor Inc., Lincoln, Nebraska, USA). Measurements were conducted on a transect that was identified in the middle of the study site for each measurement window to avoid the impact of edge effect on LAI measurements (Woodgate et al., 2015). The transect was 250 m in length and measurements were conducted every 5 m, producing a total 50 LAI measurements, which were thereafter averaged to a single LAI measurement per month.

2.6. Canopy interception loss

The Von Hoyningen-Huene is a simplistic method of modelling the interception loss (I_i) in agricultural crops and is incorporated as part of the Agricultural Catchments Research Unit model, commonly known as ACRU model. The Von Hoyningen-Huene approach was designed for calculating precipitation interception loss (I_i) in agricultural crops, however, Schulze (1995) found that the approach performed very well in estimating I_i in commercial forest plantations (*P. patula*). The I_i in this study was calculated using the Von Hoyningen-Huene equation (Von-Hoyningen-Huene, 1983):

$$I_i = 0.30 + 0.27P_g + 0.13LAI - 0.013P_gLAI - 0.007LAI^2 \quad (4)$$

where, P_g is the gross precipitation (mm) measured using the automatic raingauge and the LAI is the leaf area index. The Von Hoyningen-Huene equation has been found to be only stable for P_g daily precipitation amounts of less than 18 mm, above which it is assumed that no I_l occurs (Schulze, 1995). In this study, I_l was calculated monthly using Von Hoyningen-Huene equation and monthly values were summed up to annual total I_l for each measurement period.

2.6.1. Potential errors in estimating interception loss

Estimating I_l using the Von Hoyningen-Huene method has been shown to be relatively accurate in commercial forest plantations, such as in *Pinus patula* (Schulze, 1995). However, there are potential errors that may influence the accuracy of this method. One such error arises from exclusion of litter interception and evaporation loss in the I_l calculation. Forest litter has been shown to contribute a smaller, yet important role in interception losses (Bulcock and Jewitt, 2012). Studies (Helvey and Patric, 1986; Bulcock and Jewitt, 2012) have shown that litter interception is influenced mostly by water holding capacity and initial storage capacity of the litter, but also by the evaporative demand following the rainfall event. For example, a throughfall that reaches the dry litter gradually increases the water content of litter to field capacity and then to saturation. In our study, all studied crops were at canopy closure stage and the LAI was generally high (ranging from 2.45 to 4.11), suggesting that evaporative demands were very low and forest litter was relatively wet, therefore very low litter interception occurred. As a result, litter interception and litter evaporation losses in our study were deemed negligible. Another potential error was introduced by the assumption of the model that rainfall events greater than 18 mm does not cause interception losses. It was noted by Toucher et al. (2020) that the Von Hoyningen-Huene method underestimates the I_l of *Eucalyptus grandis* compared to a variable storage Gash model in 5838 quinararies. This underestimation was attributed to the Von Hoyningen-Huene model not being stable for gross precipitation greater than 18 mm. During the period of our study, majority of rainfall events were less than 18 mm, suggesting that our study results were less likely affected by this possible error.

2.7. Surface water balance

The monthly catchment surface water balance for $Amear_3$, $Amear_7$ and $Edun_3$ was calculated based on P_g precipitation, ET, I_l and Q using:

$$\pm\Delta S = \text{water inflow} - \text{water outflow} \tag{5}$$

where, $\pm\Delta S$ is the change in the catchment water storage, *water inflow* is water recharging the catchment and *water outflow* is the total

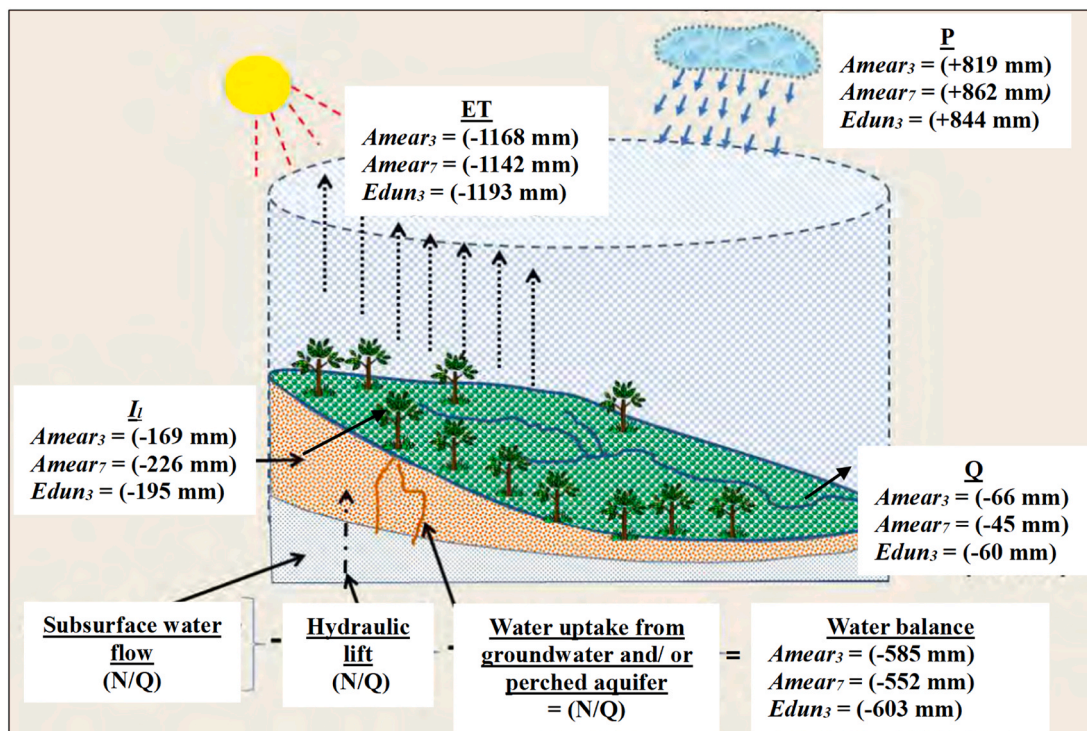


Fig. 2. A schematic presentation of annual water balance components, where P is the precipitation, ET is the evapotranspiration, I_l the interception loss and Q is the total annual streamflow, of the three-year-old *Acacia mearnsii* ($Amear_3$), seven-year-old *Acacia mearnsii* ($Amear_7$) and three-year-old *Eucalyptus dunnii* ($Edun_3$) at the Two Streams research catchment. The water balance components: subsurface flow, hydraulic lift and root uptake from groundwater and perched aquifer were not quantified (denoted as NQ).

water loss from the catchment. Eq. 5 was further expressed using the measured variables in the surface water balance as follows:

$$\pm \Delta \text{Swater storage} = P_g - ET - I_l - Q \tag{6}$$

where, P_g is gross precipitation (mm, water inflow), ET is the evapotranspiration (mm, water outflow), I_l is the interception loss (mm, water outflow) and Q is the total direct runoff (mm, water outflow which includes the baseflow). A positive value (positive surface water balance) in ΔS indicates an increase in water availability to the soil, whereas a negative value (negative surface water balance) indicates a loss in the soil water storage. It is important to note that other components potentially contributing to the total water balance of our catchment which includes, the root uptake from groundwater, the hydraulic lift, water uptake from perched aquifer and subsurface water movement from adjacent unplanted areas were not incorporated, as they were not measured (Fig. 2). Conducting such measurements is very challenging and require financial resources of which were very limited in our study.

2.8. Statistical analysis

The statistical analysis was performed using the R statistical computing software (R Development Core team, 2008). An analysis of variance (ANOVA) was used to assess the differences in hydrological parameters (Q , ET , I_l and climatic variables) between $Amear_3$, $Amear_7$ and $Edun_3$. Variables were transformed as appropriate to meet the assumption of normality. Where the overall F-statistic was significant ($p < 0.05$), treatment means were compared using Fischer’s Least Significant Difference at the 5 % level of significance ($LSD_{5\%}$).

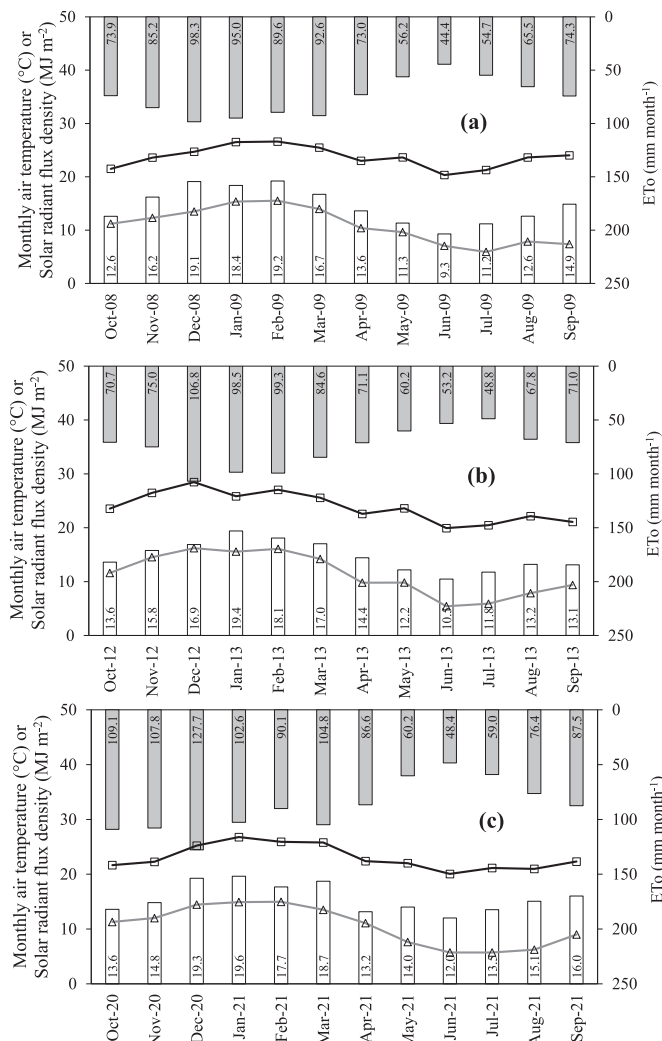


Fig. 3. Monthly values of mean daily radiant flux density ($MJ m^{-2}$), maximum (T-Max) and minimum (T-Min) air temperatures ($^{\circ}C$) and corresponding monthly reference evaporation (ET_o , $mm month^{-1}$) measured at Two Streams Research Catchment in (a) 2008/ 09 ($Amear_3$), (b) 2012/ 13 ($Amear_7$) and (c) 2020/ 21 ($Edun_3$) hydrological years.

3. Results

3.1. Weather conditions

The weather for three measurement periods reflected typical warm temperate climatic conditions with warm wet summers and cool dry winters (Fig. 3). The daily I_s over all window periods was lowest in June (mean range: 3.1–11.7 MJ m⁻² day⁻¹) but more consistent, whereas December and January experienced higher and more variable I_s (reaching a peak of 30 MJ m⁻² day⁻¹). These conditions were consistent with clear winter days and a wetter summer season with thunderstorms at times. The maximum T_{air} (range: 34.1–38.2 °C) was measured in January for all measurements periods, while the lowest measured T_{air} was between 0 and -1 °C in June. The total measured gross annual precipitation in 2008/ 09, 2012/ 13 and 2020/ 21 was 819 mm, 862 mm and 844 mm, respectively, which mostly (70 %) occurred during summer from September to April of each measurement period. The VPD was low in the summer season and increased during the winter season with a mean of 0.59 kPa for $Amea_{r3}$, 0.62 kPa for $Amea_{r7}$ and 0.72 kPa for $Edun_3$. The $Edun_3$ period had 15 % greater annual ETo (1060 mm) compared to $Amea_{r3}$ (903 mm) and $Amea_{r7}$ (907 mm) (Fig. 3). The lowest measured daytime RH occurred during berg wind conditions in September (31.8 %), December (27.5 %) and October (21 %) for $Amea_{r3}$, $Amea_{r7}$ and $Edun_3$, respectively. The average wind speeds were notably high in July for $Edun_3$ (maximum 37 m s⁻¹) and in October for $Amea_{r3}$ and $Amea_{r7}$ (maximum 32 m s⁻¹).

3.2. Effective precipitation and interception loss

The monthly effective precipitation for all measurement windows was generally higher during the wet season (October to February), ranging from 57 % to 90 % for $Amea_{r3}$, 65–88 % for $Amea_{r7}$ and 52–90 % for $Edun_3$ of gross precipitation (Table 2). During the dry season (May to August), the monthly effective rainfall was low, reaching the lowest value of zero in $Amea_{r3}$ and $Edun_3$ (May and July) while zero effective rainfall values were measured only in July for $Amea_{r7}$. The total annual effective precipitation for $Amea_{r3}$ (650 mm) and $Edun_3$ (647 mm) were significantly ($p < 0.05$) greater than $Amea_{r7}$ (617 mm).

Precipitation interception losses depended on gross precipitation and the LAI of the specific crop. The $Edun_3$ was found to have the highest LAI reaching a maximum of 4.11, compared to a peak LAI of 2.45 and 3.34 for $Amea_{r3}$ and $Amea_{r7}$, respectively. The summer monthly I_i ranged from 19.6–29.9 mm, 17.8–44.3 mm and 14.8–33.1 mm for $Amea_{r3}$, $Amea_{r7}$ and $Edun_3$ of monthly gross precipitation, respectively. The annual I_i was highest for the $Amea_{r7}$ (226 mm, 26 % of annual precipitation), followed by $Edun_3$ (195.2 mm, 23 % of annual precipitation) and finally $Amea_{r3}$ (169.1 mm, 20 % of annual precipitation), with the $Amea_{r7}$ crop statistically ($p < 0.05$) greater than the $Amea_{r3}$ and statistically similar ($p > 0.05$) to $Edun_3$. The I_i was obviously influenced by the LAI but also by the quantity of gross precipitation received per event. For example, gross precipitation events of less than 3 mm, resulted in almost 100 % interception, while high gross precipitation events (> 10 mm) resulted to less interception loss. The I_i comparison between measurement windows indicated that $Amea_{r7}$ crop I_i was 25 % and 13.2 % greater than $Amea_{r3}$ and $Edun_3$, respectively, which, was as a result of a combination of higher LAI and precipitation event characteristics.

3.3. Streamflow

The Q for all measurement periods was seasonal (Fig. 4) and did not respond significantly to effective precipitation events of less than 10 mm, 16.9 mm and 12.2 mm for $Amea_{r3}$, $Amea_{r7}$ and $Edun_3$ cropping periods, respectively, except after consecutive effective precipitation events where antecedent conditions played a role.

During summer, (November to February) Q was generally high, reaching peaks of 18.3, 8.2 and 12.2 mm month⁻¹ for $Amea_{r3}$, $Amea_{r7}$ and $Edun_3$ cropping windows, respectively. The summer water yield (expressed as a ratio of total annual streamflow to total annual effective precipitation, $Q/P_{eff} \times 100$) for $Amea_{r7}$ (mean water yield: 4.4 %) was found to be statistically lower ($p < 0.05$) than

Table 2

The monthly gross precipitation (P_g , mm), effective precipitation (P_{eff} , mm) and a ratio of P_g to P_{eff} expressed as a percentage for the Two Streams research catchment in 2008/ 09 ($Amea_{r3}$), 2012/ 13 ($Amea_{r7}$) and 2020/ 21 ($Edun_3$) hydrological years.

2008/ 09 ($Amea_{r3}$)												
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
P_g (mm)	151	121	68	130	70	95	75	3	21	2	7	79
P_{eff} (mm)	131	98	39	100	42	85	67	0	19	0	1	67
$P_{eff} / P_g \times 100$ (%)	87	81	57	77	61	90	90	0	90	0	14	85
2012/ 13 ($Amea_{r7}$)												
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
P_g (mm)	150	143	148	150	71	59	35	33	15	6	22	32
P_{eff} (mm)	124	98	115	118	46	40	24	28	6	0	12	6
$P_{eff} / P_g \times 100$ (%)	83	69	77	88	65	68	70	85	41	0	53	20
2020/ 21 ($Edun_3$)												
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
P_g (mm)	35	151	160	134	122	81	85	2	37	2	7	27
P_{eff} (mm)	18	136	136	105	89	59	68	0	24	0	1	11
$P_{eff} / P_g \times 100$ (%)	52	90	85	79	73	73	80	0	65	0	19	39

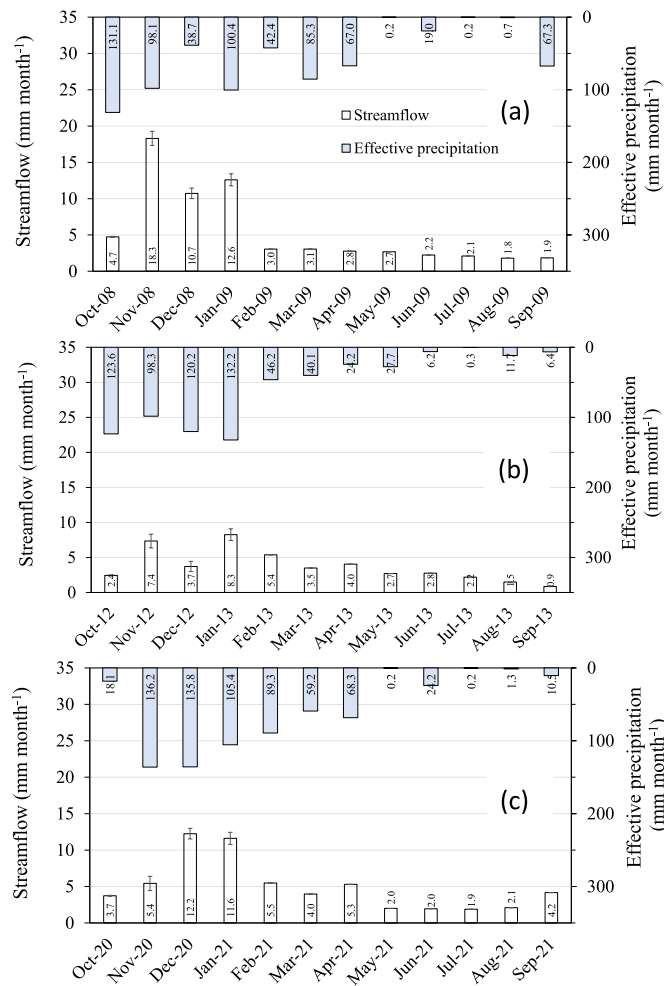


Fig. 4. The total monthly streamflow (mm month⁻¹) and corresponding total monthly gross and effective precipitation (mm month⁻¹) for hydrological years (a) 2008/ 09 (*Amea₃*), (b) 2012/ 13 (*Amea₇*) and (c) 2020/ 21 (*Edun₃*).

both the young crops (mean water yield: *Amea₃* = 9.26 % and *Edun₃* = 7.9 %), which were statistically similar ($p > 0.05$) to each other. These results suggested that when the catchment was afforested with young trees (*Amea₃* and *Edun₃*), more effective precipitation was converted to runoff, than when the catchment was planted to matured trees (Figs. 5a and 5b), which was evident in annual effective rainfall for *Amea₇* (617 mm) which was lower ($p < 0.05$) than both *Amea₃* (650 mm) and *Edun₃* (647 mm). During the dry season (May to August), the Q was low at 2.1 mm month⁻¹ for *Amea₃*, 2.2 mm month⁻¹ for *Amea₇* and 1.8 mm month⁻¹ for *Edun₃*. The water yield was high in the dry season compared to the wet season, reaching a peak of 105 % for *Amea₃*, 98 % for *Edun₃* and 44 % for *Amea₇*, which was caused by low effective precipitation in the dry season (Fig. 4b). The total annual Q for *Amea₃* (65.9 mm) and *Edun₃* (59.8 mm) was statistically similar ($p = 0.30$), while *Amea₇* (44.7 mm) was significantly ($p < 0.05$) lower than both the *Amea₃* and *Edun₃* crops.

The differences in seasonal patterns are best illustrated using the accumulated Q, gross precipitation and effective precipitation comparison (Fig. 6). The accumulated Q for the two young crop window periods (*Amea₃* = 65.9 mm and *Edun₃* = 59.8 mm) exceeded the matured crop Q (*Amea₇* = 44.7 mm) by 32 % and 25 % for *Amea₃* and *Edun₃*, respectively. The accumulated ET exceeded gross precipitation for all measurement windows by 27 %, 24.5 % and 25.1 % for *Amea₃*, *Amea₇* and *Edun₃*, respectively (Fig. 6).

3.4. Evapotranspiration

The ET for the three measurement periods was seasonal, with the ET being higher in the wet season (November to February) and lower in the dry season (June to July). In summer (November to January), mean monthly ET for *Amea₃* was statistically greater ($p < 0.05$) than the *Amea₇* and *Edun₃*, whereas during the dry season (May to July) both *Amea₇* and *Edun₃* was statistically greater ($p < 0.05$) than *Amea₃*. The annual ET followed the descending order *Edun₃* (1193 mm) > *Amea₃* (1168 mm) > *Amea₇* (1142 mm) with no statistically significant differences ($p = 0.9$).

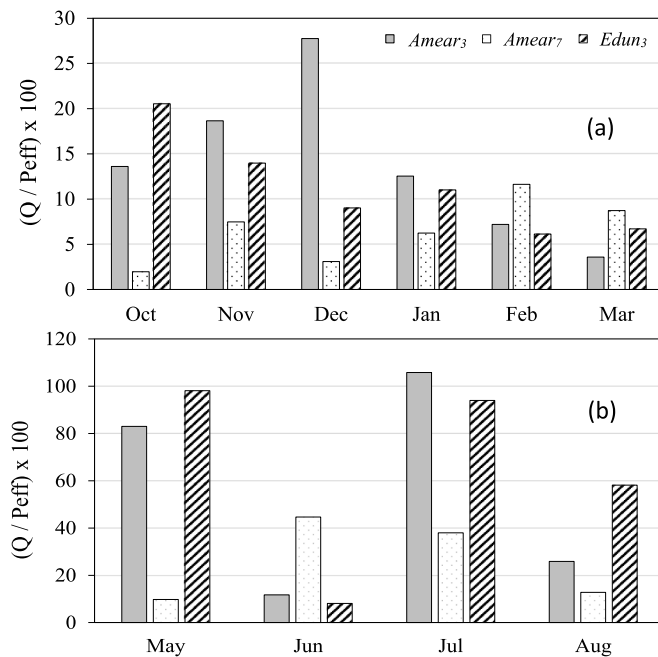


Fig. 5. A ratio of streamflow (Q) to effective precipitation (Peff) expressed as a percentage for Amear₃ (three-year-old *A. mearnsii*, in 2008/ 09 hydrological year), Amear₇ (seven-year-old *A. mearnsii*, in 2012/ 13 hydrological year) and Edun₃ (three-year-old *E. dunnii*, in 2020/ 21 hydrological year) in (a) the wet season (September to March) and (b) the dry season (May to August).

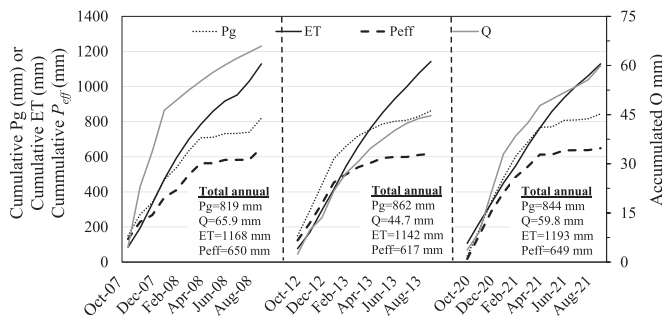


Fig. 6. Comparison between accumulated gross precipitation (Pg, mm), effective precipitation (Peff, mm), the streamflow (Q, mm) and evapotranspiration (ET, mm) of the three-year-old *Acacia mearnsii* (Amear₃, for a period Oct 2007 to Sep 2008), seven-year-old *Acacia mearnsii* (Amear₇, for a period Oct 2012 to Sep 2013) and three-year-old *Eucalyptus dunnii* (Edun₃, for a period Oct 2020 to Sep 2021). Total annual Pg, Q and ET is indicated for each hydrological year.

3.5. Surface catchment water balance

The monthly surface catchment water balance produced a negative result for all months in all three measurement periods, except for October 2008 in Amear₃, October 2012 and January 2013 in Amear₇ and November and December 2020 in Edun₃ where the catchment surface water balance was positive (Table 3). On an annual basis, ET for all measurement periods exceeded gross annual precipitation by 30 %, 25 % and 30 % for Amear₇, Edun₃ and Amear₃, respectively. The annual intercepted rainfall of 169 mm for Amear₃, 226 mm for Amear₇ and 195 mm for Edun₃ played a significant role in inducing the negative surface water balance. As a result, the Edun₃ had a greatest deficit in the surface water balance (-603 mm) followed by the Amear₃ (-585 mm) and Amear₇ (-552 mm) (Table 3).

4. Discussion

Studies that quantify the surface water balance of a catchment are not common, due to high implementation and maintenance costs associated with such studies as well as the complexity of the interactions of natural systems. The availability of historical hydrological data (ET, meteorological and Q) for *Acacia mearnsii* at different growth stages within its rotation, followed by the exchange of genus to

Table 3

The monthly surface water balance for the Two Streams research catchment for a duration 2008/ 09, 2012/ 13, and 2020/ 21 hydrological years. The negative numbers in the table indicates a water loss. P_g is the gross precipitation, I_l the interception loss and Q is the total direct runoff. Units for all terms is mm.

2008/ 09 (<i>Amear₃</i>)													
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
P_g	151	121	68	127	70	95	75	3	21	2	7	79	819
I_l	-20	-22	-29	-30	-27	-10	-8	-3	-2	-2	-6	-10	-169
ET	-86	-126	-139	-140	-121	-114	-86	-75	-59	-35	-78	-109	-1168
Q	-4	-18	-11	-13	-3	-3	-3	-3	-2	-2	-2	-2	-66
Δ catchment storage	41	-45	-111	-56	-81	-32	-22	-78	-42	-37	-79	-42	-585
2012/ 13 (<i>Amear₇</i>)													
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
P_g	150	141	148	150	71	59	35	33	15	6	22	32	862
I_l	-26	-44	-27	-18	-25	-19	-11	-5	-9	-6	-10	-26	-226
ET	-77	-90	-126	-122	-131	-112	-102	-89	-79	-70	-77	-67	-1142
Q	-2	-7	-4	-8	-5	-4	-4	-3	-3	-2	-2	-1	-45
Δ catchment storage	45	0	-9	2	-90	-76	-82	-64	-76	-72	-67	-62	-552
2020/ 21 (<i>Edun₃</i>)													
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
P_g	35	151	160	134	122	81	85	2	37	2	7	27	844
I_l	-17	-15	-24	-28	-33	-21	-17	-2	-13	-2	-6	-17	-195
ET	-108	-126	-122	-124	-107	-115	-101	-95	-77	-68	-63	-86	-1193
Q	-4	-5	-12	-12	-5	-4	-5	-2	-2	-2	-2	-4	-60
Δ catchment storage	-94	5	2	-30	-23	-59	-38	-97	-55	-70	-64	-80	-603

E. dunnii, at the same site, with ongoing hydrological measurements from the *E. dunnii*, provided a unique opportunity to compare the surface water balance of *A. mearnsii* at two different ages and between two species at the same site. The challenge with such comparisons is that there can be differences in the water balance due to difference in weather conditions. In this study, there were differences in the weather conditions across the three window periods, but generally the weather over the long-term was comparable and unlikely to confound the comparison of the surface water balance between the three measurement periods. This implies that differences in the surface water balance were predominantly due to species differences or tree age, however, lags in the water-balance and long-term differences in soil water resources may have played a role in introducing some differences.

4.1. Catchment surface water balance

The concept of water balance provides an opportunity for studying the behaviour of the catchment with an assumption that water entering the catchment is equivalent to water leaving the catchment, plus or minus any change in soil water storage (Brassington, 2006). Water inputs in a typical forestry catchment includes effective rainfall, groundwater uptake by roots, water access by roots in unsaturated zone or pocket of water lenses and tree hydraulic lift (Brooksbank et al., 2011; Ngubo et al., 2022).

The roots of commercial forest plantations have been reported to penetrate as deep into the soil as possible to access the plant available soil water, unless restricted by a hard soil layer (Kimber, 1974). Depending on characteristics of the soil, the taproot of commercial plantations have been reported to exceed equivalent tree height in order to increase chances of water uptake (Sherry, 1971). In the studied catchment, the soil profile was found to be as deep as 20 m, without any impeding soil layers (Clulow et al., 2011). A study by Everson et al. (2014) in the Two Streams catchment found tree roots up to a depth of 8 m during the deep drilling in October 2012, six years after planting *A. mearnsii* trees. The depth to water table for the centre borehole, measured during the wet season in 2012, was ~20.3 m (Everson et al., 2014), which was probably too deep for roots of all our crops to come into direct contact with ground water resources as the roots would still have been relatively shallow. As a result, groundwater resources and hydraulic lift were excluded as an input in the water balance calculation in our study and only precipitation was included. The only possible available water extraction by trees was soil water stored in the soil profile from previous wet years, water in perched aquifers, soil water that occur within the unsaturated zone or subsurface water flow from nearby unplanted areas. The challenge in such water balance studies where soils are deep and underlain by deep unspecified material down to 20 m, is that measurement of water content in these zones is challenging but possibly critical in understanding water balance deficits measured in afforested areas.

4.1.1. Evapotranspiration

Evapotranspiration is one of the variables that is not commonly available in water balance studies, and it is a significant strength of this data set to have measured values of ET. In the studied catchment, ET for the three measuring periods significantly exceeded gross precipitation by 25–30 %, resulting in a negative catchment water balance, even more so if effective precipitation is considered. These results are consistent with two previous ET studies conducted on the same catchment; 1) Dye and Jarmain (2004) used the Bowen ratio technique on four-year-old *A. mearnsii* and found ET to exceed precipitation by 18 %, and 2) a study by Clulow et al. (2011) using a large aperture scintillometer on two-year old *A. mearnsii* reported 46 % greater ET than precipitation. In our study, the two young crops (*Amear₃* and *Edun₃*) had a slightly higher ET than the mature crop, although not statistically different. These results were expected as literature reports that ET by commercial forestry species decreases with an increase in tree age (Roberts et al., 2001; Kostner et al.,

2002; Delzon and Loustau, 2005; Soares and Almeida, 2001). For example, in a Brazilian study by Almeida et al. (2007), maximum annual transpiration (> 1000 mm) was measured when *E. grandis* hybrid trees were between 2.75 and 5.6 years old and a significant decrease in transpiration was observed when trees were older than 5.6 years. This age-related decline in water-use was reported to be driven by the fact that mature trees are taller and have a lower transpiration per unit leaf area than young trees (Delzon and Loustau, 2005; Scott and Prinsloo, 2008). In our study, the slightly lower ET in the mature trees (*Amea₇*), compared to the younger crops (*Amea₃* and *Edun₃*), could be associated with lower transpiration per unit leaf area in *Amea₇*.

Evapotranspiration consistently exceeding precipitation at the Two Streams research catchment suggests that trees have access to water not quantified in the surface water balance such as, (1) soil water accumulated from periods when the catchment was fallow, (2) water from unplanted nearby areas moving laterally and vertically in response to gradients in soil water potential (Dye, 1996) or (3) water from the perched aquifer. Isotope studies are needed to determine the source of the water, although extracting isotope samples from soil and tree sap is challenging (Penna et al., 2018).

4.1.2. Impact of commercial forestry plantations on streamflow

Several South African studies (van Lill et al., 1980; Smith and Scott, 1992; Scott and Lesch, 1997; Scott and Smith, 1997; Scott et al., 2000) have quantified the impact of commercial forest plantations on the Q. The study by Scott and Lesch (1997) on the Q response to afforestation with *E. grandis* and *P. patula* in Mokobulaan experimental catchment in South Africa indicated that eucalypts cause a faster reduction in Q (90–100 %) compared to afforestation with pines (40–60 %). These results were verified in a study conducted by Scott et al. (2000) where peak reductions in Q were reported between 5 and 10 years after establishing eucalypts, and between 10 and 20 years after planting pines, with the reduction driven by soil water availability. A study by Dye and Jarman (2004) from various catchments in South Africa indicated that a complete removal of *A. mearnsii* resulted in a significant increase in Q.

Results from our study indicated that the annual Q was lowest when the catchment was afforested with the mature crop (*Amea₇*) and higher when the catchment was planted with the younger crops (*Amea₃* and *Edun₃*). This could be caused, in part, by annual interception loss, which was higher for the *Amea₇* (226 mm) than in *Amea₃* (169.1 mm) and *Edun₃* (195.2 mm), resulting in a reduced effective precipitation and thereby possibly reducing the Q. These results are corroborated by other studies. For example, Ferraz et al. (2013) reported a significantly high annual Q (384 mm) in catchments planted with young *Eucalyptus* plantations (2-years-old) compared to matured plantation (5-years-old) in which annual Q was measured to be 235.1 mm. This difference was partly attributed to mature trees having high leaf area index and high forest litter, therefore intercepting water runoff to the stream. In our study, *Amea₇* peak LAI was slightly higher than the *Amea₃* LAI, but lower than *Edun₃*, whereas the forest litter, though not measured, is considered to be higher in mature crops than in young crops. This suggests the possibility that *Amea₇* trees and litter intercepted more runoff than the younger crops. In another study by Farley et al. (2005) where 26 catchments datasets were modelled to understand the effect of afforestation on Q, results indicated 1) a runoff reduction of more than 10 % of Q in the first two to three years after catchment afforestation 2) on average, *Eucalyptus* reduced runoff by 75 % as trees matured, compared with 40 % average decrease by pines.

4.2. Implications of negative catchment water balance

The results from this study and those of previous studies, including the long-term paired catchment studies in South Africa, have all indicated a negative catchment water balance as a result of commercial afforestation, particularly eucalypts. Of the measured components of the catchment surface water balance, tree ET was found to be the greatest loss, while Q was found to be the least and particularly so for the mature *Amea₇* window period. These results are critical in terms of planning, since most commercial forest plantations are established in high precipitation regions and are planted adjacent to catchments that provide freshwater for downstream users (Albaugh et al., 2013). Therefore, the management of commercial forestry plantations should consider the principles of human rights, ecosystem resilience and ecosystem services sustainability. Afforestation of commercial plantation in water-limited areas should consider water use for drinking and downstream activities, such that forest management balances wood production and water resource conservation.

The previous paired catchment experiments in South Africa showed the impact of forestry on streamflow and current legislation has focussed on blue water and the impact of commercial forestry through streamflow reduction activity (SFRA). This led to forestry being declared a SFRA and a licensing system for planting was put in place. However, these studies typically didn't have measured ET and didn't show the immediate difference in ET with age and between species.

5. Conclusion

Studies that investigate catchment surface water balances in South Africa with actual measurements of ET are few, due to time and costs associated with conducting such studies. Other confounding factors in determining the differences in ET with age and between species, include differences in site characteristics such as slope and soil type. This study provides the surface water balance by young *Acacia mearnsii*, mature *Acacia mearnsii* and young eucalypts at the same site and with similar climatic conditions, eliminating site characteristic differences. The strategy of comparing measurement windows periods with complete records and of similar climatic conditions, due to missing water balance records at various times, worked well, but does not accommodate lags in the water balance annual cycle.

Surface water balance results for all our measurement windows indicated a negative catchment surface water balance. This is similar to results from previous studies on the same catchment, suggesting that trees were accessing water from water balance components that were not measured in this study, such as water deep in the soil profile or in areas adjacent to the catchment. The

evapotranspiration by trees was found to be the largest contributor to the negative catchment surface water balance relative to other terms, suggesting that adequate planning is necessary in terms of water conservation and distribution before catchment can be afforested with commercial forestry species. It was concluded that at any stage of development, both *A. mearnsii* and *E. dunnii* have a potential to cause a reduction in the streamflow, which may affect downstream water users who are reliant on the flow of a stream for their livelihood. Despite the challenges in using isotopes, it would be beneficial to use isotope studies to understand the source of the water used by the trees in the Two Streams research catchment.

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CRedit authorship contribution statement

Michele Toucher: Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition, Conceptualization. **Alistair Clulow:** Writing – review & editing, Supervision, Project administration, Methodology. **Colin Everson:** Writing – review & editing, Supervision, Methodology. **Iaria Germishuizen:** Writing – review & editing, Supervision. **Nkosinathi David Kaptein:** Writing – review & editing, Writing – original draft.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: ML Toucher reports financial support was provided by Water Research Commission. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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