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Quantifying the effects of *Eucalyptus* plantations and management on water resources at plot and catchment scales

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Abstract:

Our aim was to quantify the effects of forest plantation and management (clear cut or 30% partial harvest) in relation to pasture, on catchment discharge in southeast Rio Grande do Sul state, Brazil. A paired-catchment approach was implemented in two regions (Eldorado do Sul and São Gabriel municipalities) where discharge was measured for 4 years at three catchments in each region, two of which were predominantly eucalypt plantation (mainly *Eucalyptus saligna*, rotation of approximately 7–9 years) with native forest and grass in streamside zones. The third catchment was covered with grazed pasture. Weather, soils, canopy interception, groundwater level, tree growth, and leaf area index were also measured.

The 3-PG process-based forest productivity model was adapted to predict spatial daily plantation and pasture water balance including precipitation interception, soil evaporation, transpiration, soil moisture, drainage, discharge, and monthly plantation growth. The TOPMODEL framework was used to simulate water pools and fluxes in the catchments.

Discharge was higher under pasture than pre-harvesting plantation and increased for 1–2 years after complete plantation harvest; this change was less pronounced in the catchments under partial harvest. The ratio of discharge to precipitation before harvesting varied from 7% to 13% in the eucalypt catchments and 28% to 29% under pasture. The ratio increases to 23–24% after total harvest, and to 17% after partial harvesting. The ratio under pasture also increases during this period (to 32–44%) owing to increased precipitation. The baseflow, in relation to total discharge, varied from 28% to 62% under *Eucalyptus* and from 38% to 43% in the pasture catchments. Hence, eucalypt plantations in these regions can be expected to influence discharge regimes when compared with pasture land use, and modelling suggests that partial harvesting would moderate the magnitude of discharge variation compared with a full catchment plantation harvesting. The model efficiency coefficient (Nash–Sutcliffe model efficiency coefficient) varied from 0.665 to 0.799 for the total period of the study. Simulation of alternative harvesting scenarios suggested that at least 20% of the catchment planted area must be harvested to increase discharge. This model could be a useful practical tool in various plantation forestry contexts around the world.

KEY WORDS water; discharge; catchment; *Eucalyptus*; pasture; native forest; modelling; 3-PG; harvesting

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INTRODUCTION

Common in many parts of the world, there is pressure in Brazil to understand and minimize potential conflict associated with the impact of plantations on water resources and water availability for downstream uses, particularly in regions where land use has been traditionally grassland (Soares and Almeida, 2001; Almeida and Soares, 2003; Engel *et al.,* 2005; Farley *et al.,* 2005; Nosetto *et al.,* 2005). Therefore, management strategies for maximizing plantation water use efficiency (biomass production per volume of water used by the trees) and minimizing risks to streamflows are current objectives for plantation managers. Reducing the risk of water shortages for local communities is part of corporate social responsibility that can minimize community conflicts over plantation water use. Such strategies need to be based on a quantitative understanding of catchment-specific plantation and hydrological behaviour in association with alternative forest management plans.

Plantation forestry as a driver of change in land use is of particular concern because it is well recognized that evapotranspiration from some forested catchments can be higher than evapotranspiration from grassland (Zhang *et al.,* 2001; Whitehead and Beadle, 2004; Jackson *et al.,* 2005; van Dijk and Keenan, 2007). This difference arises because forest plantations in general, as well as native forest, compared with grass, intercept more radiation and

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precipitation, are aerodynamically rougher and thus well coupled to the atmosphere, and have deeper root systems that allow them to exploit larger soil water volumes.

Zhang *et al.* (2001) analysed runoff data from tropical and temperate ecosystems in more than 250 catchments from 28 countries and developed relationships between precipitation and annual evapotranspiration for forested and grassed catchments. These curves have been applied to estimate the impact of afforestation on streamflow and show that for precipitation above 600 mm year^{-1}, evapotranspiration from forested catchments was higher than that from grassed catchments. While insightful, these generalised relationships are difficult to apply at localised scales as they do not consider the many secondary factors that influence evapotranspiration within catchments such as local biophysical characteristics or management practices (Vanclay, 2009). However, not all climates (tropical to temperate) and soils (shallow and deep) were represented across the full range of precipitation, and the curves describe a steady-state water balance that is not applicable for dynamic assessments of impacts on water resources where changes in land use, plantation age, plantation management and climate occur (Greenwood *et al*, 2011).

Although Smethurst *et al.* (2015) showed that plantation harvest did not affect discharge in a Brazilian catchment (probably owing to interception of lateral subsurface flows by native forest in the streamside zone), many studies indicate that catchment harvesting can increase the discharge regime (Scott and Lesch, 1997; Brown *et al.,* 2005; Brown *et al.,* 2007; Ferraz *et al.,* 2013). These contrasting behaviours indicate a need for more intensive investigations of water use by plantations and modelling tools in order to better understand the effects of management options on hydrology under specific catchment conditions. This is particularly important in South America where plantations are expanding rapidly in drier regions (Almeida *et al.,* 2007).

Polglase and Benyon (2009), in Australia, note that in large catchments, the impacts of plantation establishment on catchment water balance have been somewhat overstated, finding that while plantations are likely to have localized impacts, plantation forests generally occupied only a small proportion of catchment area, and thus, their impacts on catchment water yield were typically less than would be otherwise expected based on conventional wisdom.

We developed and applied a modelling framework that integrates the spatial version of the 3-PG forest process-based model (Landsberg and Waring, 1997; Sands and Landsberg, 2002; Landsberg and Sands, 2010; Almeida and Sands, 2015) with TOPMODEL (TOPographic based hydrological MODEL) (Beven and Kirkby, 1979; Quinn *et al.,* 1991; Beven and Freer, 2001). This framework provides the advantage of predicting forest growth, a full water balance for plantation, native forest, and pasture at plot and catchment scales. Other process-based modelling frameworks have been developed to link plot-scale growth of forest plantations, pasture, or crops to catchment-scale water outcomes (Paydar and Gallant, 2008; Wang *et al.,* 2008; Feikema *et al.,* 2009; Feikema *et al.,* 2010). Feikema *et al.* (2010) integrated an earlier version of 3-PG model (3-PG+) into a catchment model [Catchment Analysis Tool (CAT] (Beverly *et al.*, 2005). The 3-PG+/CAT model predicted plantation growth and discharge in six catchments supporting eucalypt or pine plantations (Feikema *et al.,* 2007), and later for catchments containing multi-species native forest (Feikema *et al.,* 2009). The 3-PGH model used in the current study is similar in concept to 3-PG+/CAT but includes a newer version of 3-PG, the potential for smaller spatial resolution, and application to harvesting scenarios in a tropical climate.

In more of an agricultural context, Paydar and Gallant (2008) and Wang *et al.* (2008) linked plot-scale crop, tree, or pasture simulations (using the APSIM model) with a catchment model called FLUSH. Their interest included groundwater levels and discharge. They concluded that increasing tree cover in an agricultural catchment was likely to lower water tables and reduce discharge.

However, it appears that there has been no substantial model development of application beyond these studies. The current study demonstrates the usefulness of linking plot-scale simulations to a catchment model. As 3-PG is widely used by the plantation forestry industry, linking of the newest version (Almeida and Sands, 2015) to catchment hydrology offers the potential for wider use than those previously developed with the other 1D–3D frameworks.

In this study, we aimed to measure and model the effects of forest plantation and management (clear cut or 30% partial harvest), in relation to pasture, on catchment discharge in southeast Rio Grande do Sul state, Brazil.

METHODOLOGY

A paired-catchment approach was implemented in two regions where the predominant land use is pasture (for cattle production) or short-rotation eucalypt plantations (for pulp production). Calibrated and automatically logged weirs measured discharge for 4 years at six catchments in Eldorado and São Gabriel municipalities in Rio Grande do Sul State in southern Brazil (see Figure 1 and Table I for details). The weirs were located in three catchments in each region, two of which were predominately eucalypt plantation (*Eucalyptus saligna*, and hybrids of *Eucalyptus urophylla* and *Eucalyptus*

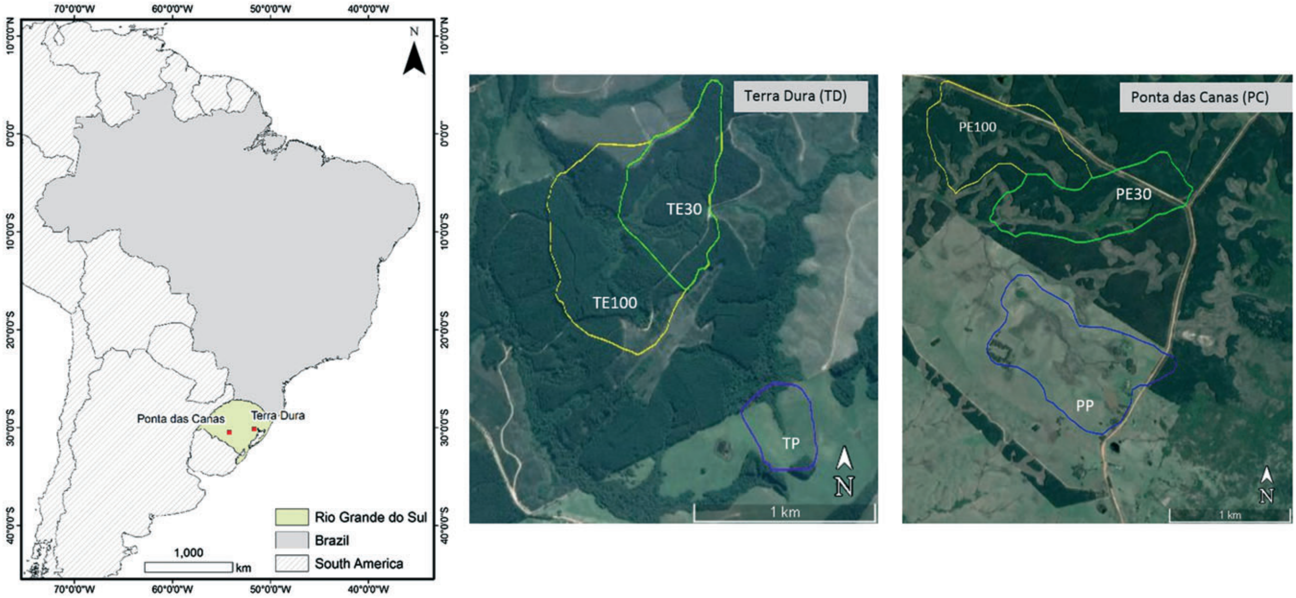


Figure 1. Terra Dura (TD) and Ponta das Canas (PC) experimental catchments locations and boundaries in Rio Grande do Sul State, south of Brazil

globulus) with native forest and grass in streamside zones. The third catchment was covered with pasture with small streamside protection zone. Catchments were instrumented to measure precipitation, air temperature and relative humidity, wind speed and direction and solar radiation, soil moisture, precipitation canopy interception, groundwater level, tree growth, and leaf area index (LAI). Soil and geophysical characteristics including soil texture, hydraulic conductivity, and altimetry and groundwater catchment boundaries were mapped in all catchments. Observations and modelling in these six catchments were used to quantify water balance and *Eucalyptus* plantation growth at plot and catchment scales.

Terra Dura and Ponta das Canas experimental catchments

The Terra Dura (TD) region in the Eldorado do Sul municipality has a long history of plantation development (third rotation at the start of this catchment experiment). The Ponta das Canas (PC) region in São Gabriel municipality, in contrast, was in the first rotation at the start of the experiment. For establishing a baseline comparison of water use between catchments, it was desirable to have several years of discharge data prior to plantation establishment, but this was not possible as plantations had already been established at TD and at the initial phase of the first rotation at PC.

At TD, TE100 was a sub-catchment (nested) of the larger catchment (TE30) and TP was under pasture; the numbers 100 and 30 in the treatment code denote the percentage of area harvested (Figure 1). In PC, the two eucalypt catchments and pasture catchment (PP) were independent and plantation harvest followed as planned, i.e. 100% of the planted area in PE100 and 30% in PE30. The catchments within each region had similar total and planted area, predominant soil type, slope, riparian zone vegetation, planted and harvest dates, main planted species and respective stocking, and the harvest or management regime of each catchment (Table I).

Soil characteristics

Soil maps (1:10 000) and characteristics such as texture, hydraulic conductivity, and water retention curves are described in other studies (Costa *et al.,* 2009; Santos *et al.,* 2013). The predominant soil in both TD and PC catchments was Haplic Acrisol with loam surface textures (Table I) and high saturated hydraulic conductivity.

Meteorological data

The meteorological variables, precipitation (mm), air temperature (°C), air relative humidity (%), solar radiation ($MJ\,m^{-2}\,day^{-1}$), wind speed ($m\,s^{-1}$), and wind direction (°) were measured by an automatic weather station installed above the tree canopy in each TD and PC catchment. The instruments were scanned each minute, and the data averaged for various time intervals from 0.5 hourly to annually. Precipitation was also measured in at least one rain gauge (TB4 model) close to the weir in each catchment at 10-min intervals.

Soil water content

Soil water content (SWC) was measured in each catchment using capacitance probes (Diviner 2000 Sentek Pty Ltd, Australia) in fixed access tubes. Six tubes were installed in each catchment along a typical transect from

Table I. Catchment characteristics.

Region	Catchment name	Total area (ha)	Planted area (ha)	% planted area	Location of the weir	Predominant soil classes	Slope (°)	Riparian zone ondition	Dates harvest and replant	Main species	Stocking (tree ha^{-1})	Management
Terra Dura	TE30	95.04	80.44	84.8	30.1769°S 51.6130°W	Ferralic Cambisol, Haplic Acrisol, Molic Leptisol	8.8	Medium stage of altered rainforest	1/11/2012 15/06/2013	*Eucalyptus urophylla* × *Eucalyptus globulus* hybrid	1445	*Eucalyptus* unharvested except in TE30
	TE100	39.87	33.6	84.3	30.1789°S 51.6089°W	Ferralic Cambisol, Haplic Acrisol, Molic Leptisol	9.1	Medium stage of altered rainforest	1/11/2012 15/06/2013	*E. urophylla* × *E. globulus* hybrid	1445	*Eucalyptus* 100% harvested
	TP	14.82	—	—	30.1876 °S 51.6013°W	Haplic Acrisol, Molic Leptisol	7.7	Degraded pasture and signs of soil erosion	—	Planted grass	—	Low intensity use pasture
Ponta das Canas	PE30	75.81	51.02	61.0	30.5101°S 54.1657°W	Ferralic Cambisol, Haplic Acrisol, Molic Leptisol	5.1	Grass and some isolated trees, soil well covered	1/02/2014 16/05/2014	*Eucalyptus saligna* hybrid	1225	*Eucalyptus* 30% harvested
	PE100	79.96	49.2	62.4	30.5069°S 54.1679°W	Ferralic Cambisol, Haplic Acrisol, Molic Leptisol	4.1	Grass and some isolated trees, soil well covered	1/02/2014 16/05/2014	*E. saligna* hybrid	1225	*Eucalyptus* 100% harvested
	PP	99.49	—	—	30.5151°S 54.1614°W	Molic Leptisol	3.2	Native grass	—	Planted grass	—	Pasture

the top to the bottom of the slope. In plantations, access tubes were located between trees on the tree rows. Measurements were made approximately fortnightly at 0.1-m intervals down to 1.6-m depth from the soil surface. Calibrations based on soils collected in dry, moist, and wet conditions produced region-specific calibration equations.

Groundwater

A geophysical study established the sub-surface boundaries of each catchment and identified the groundwater flow directions (CMPC, unpublished report). A small number of piezometers for measuring depth to groundwater surfaces were installed in each catchment (Figure 5). Each piezometer was instrumented with a Levelogger Model Gold (Solinst Limited Canada, Georgetown, Ontario, Canada). Monthly manual measurements of water levels were used to check the accuracy of the automatic data.

Interception

Precipitation canopy interception, throughfall, stemflow, and litter interception were measured at PE100 from August 2012 to September 2013. Precipitation was measured by three rain gauges in the catchment without interference of the plantation. Throughfall was measured using six linear rain gauges in an area of 900 m^2, three rain gauges were installed in the line of the trees and three between lines, and the area of the each rain gauge was 10 cm width by 290 cm length. Stemflow was measured on 12 trees distributed in the same area of throughfall measurements. A similar setup was used in the riparian zones. Details of these measurements are presented in Peláez (2014).

Discharge

In each catchment, a V-notch weir was installed that was built to cope with at least a 1-in-10-year high-flow event and instrumented with a water level CS410-L shaft encoder, datalogger (CR 1000, Campbell Scientific Instruments), and rain gauge model TB4 (Hydrological Services Ltd, Australia). Discharge and precipitation were measured at 10-min intervals in each catchment. In TE100 and TP catchments, previously existing weirs were refurbished and instrumented. Streamflow was calculated based on measured water height and specific conversion equations developed for each weir.

Plantation growth

Measurements of stem diameter and height in permanent sample plots (PSPs) were used to calculate stem volume at different ages of each stand during the rotation in all planted catchments. Genotype-specific allometrics were used for most planted genotypes. The PSPs at PC were measured at ages 2.5, 4.5, and 6.5 years. At TD, the PSPs were measured from December 2010 in blocks with ages varying at 3.3, 4.9, 6.7, 8.3, and 8.9 years.

Leaf area index

Leaf area index ($m^2 m^{-2}$) was monitored seasonally using an LAI-2000 plant canopy analyser in a selection of tree plots per catchment with eucalypt plantations. The two-sensor method (Li-Cor, 1992) was used, with a reference sensor collecting data in a nearby open area and the measuring sensor located below the canopy. Values obtained from the LAI-2000 were modified using the equation described in Almeida *et al.* (2007) to convert plant canopy data to LAI.

Modelling description

Our modelling approach to quantify tree growth and water balance at plot scale, and discharge at catchment scale, combined the spatial version of the 3-PG forest process-based model (Landsberg and Waring, 1997; Sands and Landsberg, 2002; Landsberg and Sands, 2010; Almeida and Sands, 2015) with TOPMODEL (Beven and Kirkby, 1979; Quinn *et al.,* 1991; Beven and Freer, 2001). The 3-PG model was developed to predict plantation growth and water balance spatially (3-PGS) by integrating it with a geographic information system and spatial input layers for soil attributes, plantation age, species or genotype and daily or monthly precipitation, solar radiation, temperature, vapour pressure deficit, and occurrence of frost (Almeida *et al.,* 2010). The 3-PGS model generates tree growth data outputs of stand volume (SV), mean annual increment, current volume increment, diameter at breast height, basal area, and LAI. The model also generates water balance predictions represented as canopy interception (I), tree transpiration (T), soil evaporation (E), evapotranspiration (ET) (the sum of I + T + E), drainage (D), SWC, and available soil water (ASW).

Specific parameter files were developed to estimate growth and water use by the planted genotypes and for an adaptation of the parameter set for native forest modified from Forrester and Tang (2015). A simple pasture submodel was based on pasture LAI and stomatal conductance.

The 3-PGS was run at a daily time step using specific parameterization for each planted genotype and, native forest, or pasture, to predict ET for every landscape cell. Owing to limitations on the resolution of the climate and soils data available, the finest spatial resolution possible was 5 m by 5 m. A lumped daily ET for the catchment was then generated from the 3-PGS output. The R statistical TOPMODEL module was then used to predict the discharge at weir locations, using the lumped catchment rainfall, the lumped catchment ET, and a digital elevation model to calculate the topographic index (Beven and Kirkby, 1979; Ambroise *et al.,* 1996; Beven and Freer, 2001). As the TOPMODEL parameters for each study catchment were unknown, initial bounds on the parameters were based on data from literature, and a Monte Carlo simulation was run to determine the best model parameters for each catchment based on Nash–Sutcliffe model efficiency coefficient (NSE) predictions against observed streamflow data. The combination of 3-PGS and TOPMODEL is referred to as 3PGH.

Modelling of TD used the actual planting date of each block at TE30 and TE100, which ranged from 1989 to 2004, and harvesting of 100% of TE100 plantation in November 2012, when 73% of the plantation was 10 years old. The harvested area was equivalent to 30% of TE30. For the PC catchments, PE100 and PE30 were planted in August 2006 and harvested in February 2014 (100% PE100 and 30% PE30). The model assumed no change in the streamside zone. A new plantation was established in the harvested blocks in June 2013 at TE100, and in May 2014 at PE100 and PE30.

The 3-PGH ran at a daily time step using the actual plantation management dates, soil types, and genotypes. During the period between harvesting and replanting, the model assumed bare soil (except on riparian zones covered by aggrading native rainforest at TD and mainly grass at PC), with daily ET being based on soil evaporation estimates.

Flow separation

We used the recursive digital filter developed by Lyne and Hollick (1979) to separate the components of discharge and estimate baseflow and quickflow of the three catchments each at TD and PC.

Model evaluation

The NSE (Nash and Sutcliffe, 1970; Pushpalatha *et al.,* 2012; Ritter and Muñoz-Carpena, 2013) was used to assess model efficiency for predicted discharge. This index is commonly used to assess the predictive power of hydrological models. The value of NSE can range from $-\infty$ to 1, and the closer NSE is to 1, the more accurate the model. Linear regression between observed and predicted monthly and annual discharge was also used to indicate model efficiency. The model performance was complementary indicated by the coefficient of determination (R^2) and the root-mean-square error (RMSE) obtained in each catchment for the periods before and after harvesting and for the total period of the study (Table II).

Plantation management scenarios

To quantify the predicted effects of plantation management on water resources, we ran scenarios of

Table II. Precipitation, observed and predicted discharge, discharge : precipitation ratio, and baseflow before and after plantation harvest and for the total period of monitoring for the six catchments.

		TE30	TE100	TP	PE100	PE30	PP
Before harvest	Precipitation (mm)	2446	2359	2348	3593	3526	3907
	Observed discharge (mm)	242	160	656	248	483	1146
	Observed % of discharge	9.9	6.8	27.9	6.9	13.7	29.3
	Predicted discharge (mm)	169	172	699	273	469	1216
	Predicted % of discharge	6.9	7.3	29.8	7.6	13.3	31.1
	NSE	0.692	0.587	0.643	0.536	0.619	0.774
	RMSE	0.587	0.652	2.157	0.554	0.477	1.361
	R^2	0.712	0.774	0.668	0.578	0.621	0.775
	Intercept	0.035	0.053	0.265	0.162	0.148	0.322
	Slope	0.793	1.438	0.796	0.423	0.654	0.774
	Number of days (*n*)	668	639	669	1027	1034	1023
	Baseflow (mm)	113	45	282	76	295	434
	% of baseflow	47.2	28.5	43.5	30.5	62.2	38.7
After harvest	Precipitation (mm)	3430	3349	3537	1958	2500	1978
	Observed discharge (mm)	580	819	1140	459	433	883
	Observed % of discharge	16.9	24.5	32.2	23.5	17.3	44.6
	Predicted discharge (mm)	653	816	1231	455	394	814
	Predicted % of discharge	19.0	24.4	34.8	23.2	15.7	41.1
	NSE	0.757	0.935	0.777	0.682	0.690	0.650
	RMSE	0.984	0.966	2.387	0.879	0.779	2.28
	R^2	0.759	0.809	0.777	0.718	0.703	0.653
	Intercept	0.251	0.379	0.401	0.119	0.1285	0.511
	Slope	0.757	0.79	0.785	0.879	0.7823	0.676
	Number of days (*n*)	852	877	851	424	424	424
	Baseflow (mm)	243	230	382	236	251	333
	% of baseflow	41.7	28.2	33.5	51.4	57.8	37.8
Total	Precipitation (mm)	5870	5707	5852	5552	6026	5885
	Observed discharge (mm)	822	979	1788	708	916	2028
	Observed % of discharge	14.0	17.2	30.6	12.8	15.2	34.5
	Predicted discharge (mm)	821	988	1931	728	859	2030
	Predicted % of discharge	14.0	17.3	33.0	13.1	14.3	34.5
	NSE	0.748	0.799	0.739	0.665	0.680	0.726
	RMSE	0.833	1.326	2.288	0.665	0.581	1.682
	R^2	0.748	0.774	0.742	0.670	0.685	0.726
	Intercept	0.123	0.245	0.342	0.148	0.129	0.376
	Slope	0.771	0.769	0.789	0.727	0.735	0.733
	Number of days (*n*)	1520	1516	1520	1451	1458	1447
	Baseflow (mm)	356	276	664	312	551	767
	% of baseflow	47.2	28.5	43.5	44.0	60.2	38.3

harvesting in one of the catchments (PE100) that simulated harvesting of 100% (as occurred), 75%, 45%, and 20% of the planted area.

RESULTS

Climate

Owing to the short distances between catchments within each region, precipitation amongst all TD and amongst all PC catchments was highly correlated, but with some minor day-to-day variations. Averaging the three catchments in each region, mean annual precipitation from 2002 to 2014 was 1600 mm year^{-1} at TD and 1580 mm year^{-1} at PC from 2007 to 2014 (Figure 2). The years 2012 and 2013 had lower precipitation than historical mean annual precipitation, 1252 and 1391 mm, respectively, at TD, and 1236 and 1189 mm at PC; but in 2014, TD received 1716 and PC 1889 mm.

Compared with PC catchments, TD catchments received slightly less solar radiation and were approximately 5 °C warmer (Figure 2).

Soil water

Soil water content measurements in TE100 had higher temporal than spatial variability within a slope transect. In TP, the mid-slope positions were consistently moister than upper or lower slope positions, showing high variability of soil water between access tubes in the same period (Figure 3).

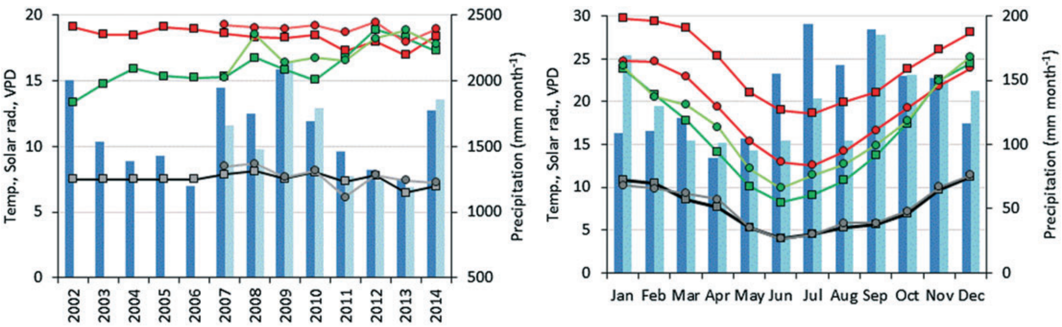


Figure 2. Annual average (left) and monthly average (right) air temperature (°C) (red), solar radiation (MJ m^{2} day^{-1}) (green), vapour pressure deficit (mb) (grey), and precipitation (mm year^{-1}) (blue bars). For both figures, Terra Dura is represented by squares or dark blue bars, and Ponta das Canas by circles and light blue bars

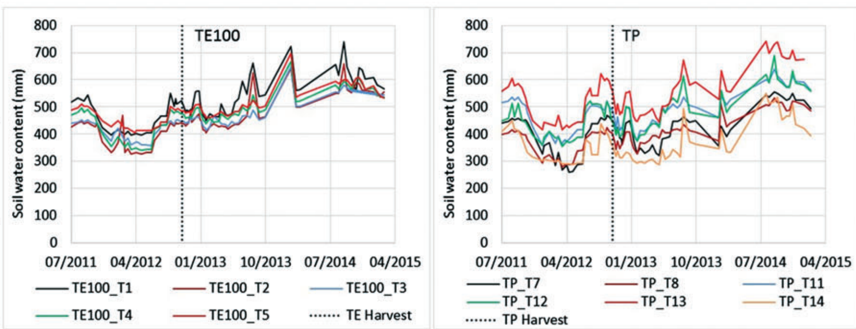
Soil water in PE100 and PE30 had similar trends; i.e. lower elevation (McVicar and Körner, 2013) tubes were slighter drier than the ones at higher altitudes. Also, for the last few measurements in 2015, SWC was higher than in the previous months and years, which coincided with harvesting and replanting, but also with higher precipitation than the previous period. In contrast, in PP, variability was less pronounced and soil moisture in general was higher than in PE100 and PE30 (Figure 3). Soil samples collected close to the access tubes show that soils at higher altitudes had higher clay contents than those at lower altitudes.

Although 3-PG modelling of SWC and ASW considered only a depth of 1.6 m, model predictions were highly correlated with observations ($R^2 = 0.79$ to 0.81) (Figure 4).

Groundwater

Some groundwater levels fluctuated during the measurement period in response to precipitation, but responses and levels depended mainly on vegetation type (pasture *versus* plantation) and slope position (Figure 5). At TD, there was up to an 18-m difference between catchments or topographic positions, but there were no discernible effects of harvesting. Water levels at a high slope position in TE30 (and therefore unaffected by harvesting in TE100) varied between 3.5 and 13 m below the soil surface. During the 6 months following harvesting, water levels dropped 4 m and then increased. This pattern appears to be related to precipitation amounts and intensity, and the same relative behaviour occurred in all

Region Terra Dura (TD)			Region Ponta das Canas (PC)		
Catchment	Tube	Elevation (m asl)	Catchment	Tube	Elevation (m asl)
TE30/TE100	1	152	PE100	15	280
TE30/TE100	2	148	PE100	16	275
TE30/TE100	3	138	PE100	17	272
TE30/TE100	4	132	PE100	18	270
TE30/TE100	5	125	PE100	19	265
TP	14	168	PE30	21	281
TP	13	161	PE30	22	278
TP	12	153	PE30	23	275
TP	11	146	PE30	24	273
TP	8	141	PE30	25	272
TP	7	139	PE30	26	269
			PP	27	307
			PP	28	302
			PP	29	298
			PP	30	295
			PP	31	289
			PP	32	281



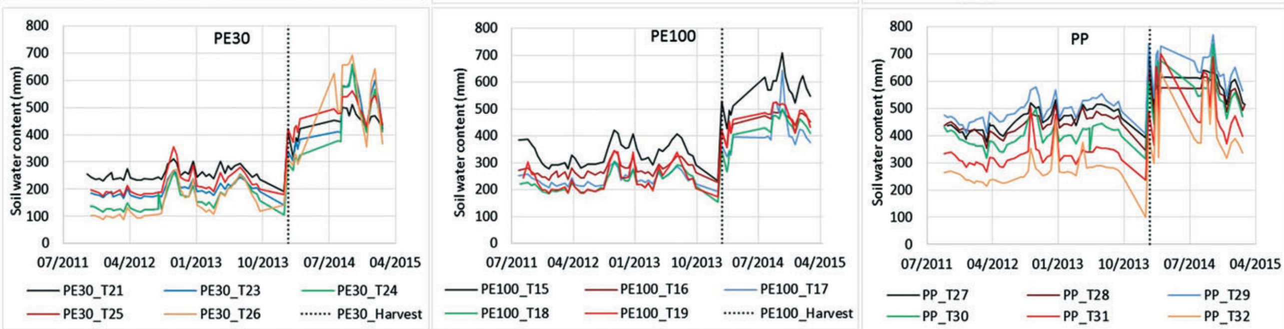


Figure 3. Temporal patterns of observed soil water content measured from the high to low slope positions in the catchments TE100, TP, PE100, PE30, and PP. Vertical dotted line represents the date of plantation harvest for the plantation catchments. The table shows tube locations and elevation (m asl)

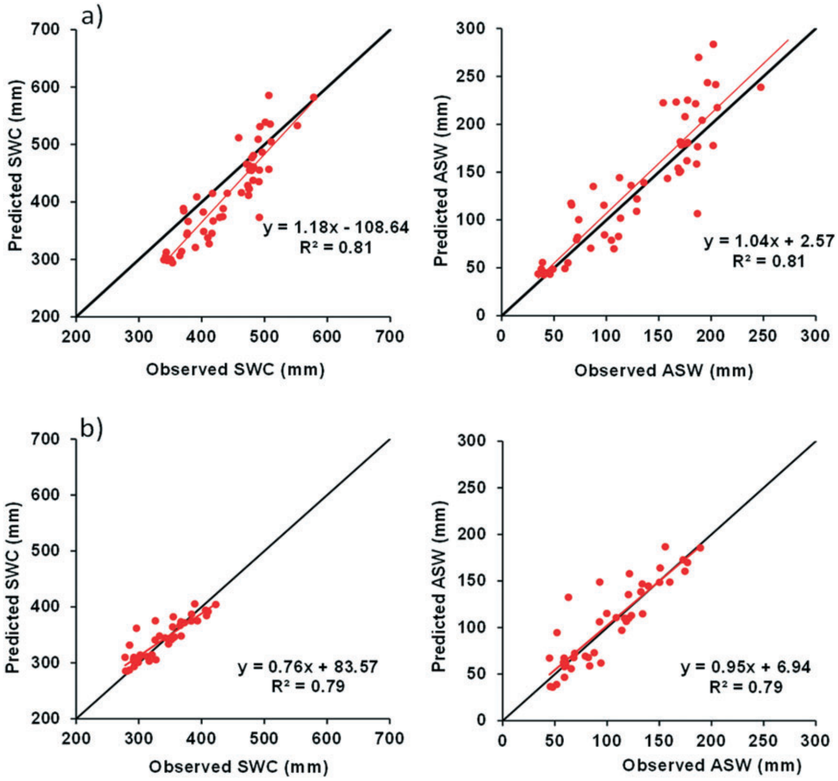


Figure 4. Comparison of observed and 3-PG-predicted soil water content (SWC) and available soil water (ASW) at (a) TE100 and (b) PE30 in the middle of the transects in relation to the 1:1 line

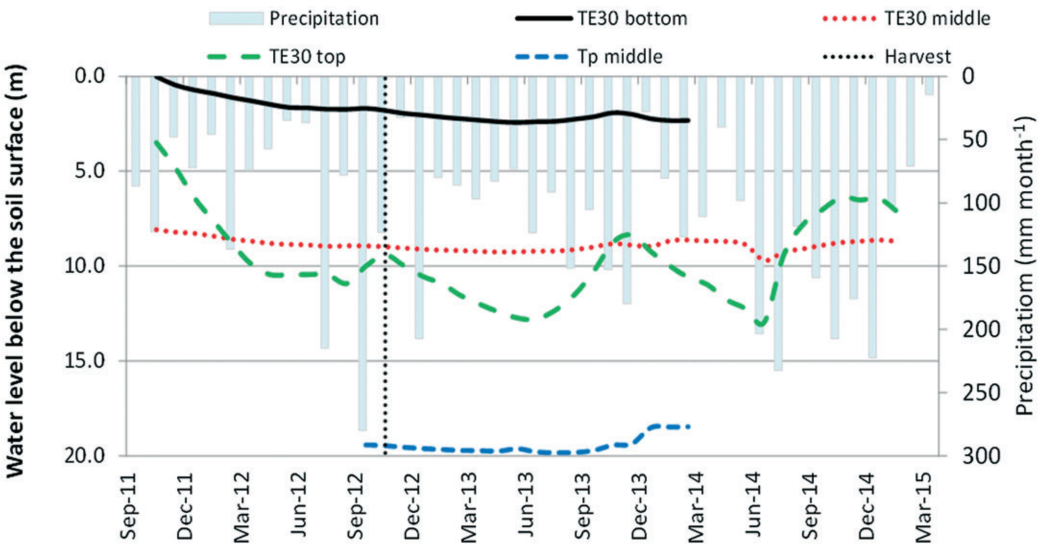
three slope positions, but with different absolute levels. At PC, groundwater levels were also more strongly influenced by precipitation than by vegetation. Water levels under pasture (PP) at both slope positions were consistently higher than in the catchments with *Eucalyptus* (PE100 and PE30). After plantation harvest, groundwater levels rose by about 1 m at PE100, but at the top slope position in PE30 levels, it rose more than 3 m within 6 months after harvesting (Figure 5). Concurrently, the pasture catchment (PP) had an increase of approximately 0.5 m in groundwater level that coincided with higher precipitation during the period after harvesting of *Eucalyptus* in PE100 and PE30.

Discharge

Daily discharge in the pasture catchments was usually higher than in the eucalypt catchments prior to harvesting in both regions (Figure 6). In the pre-harvest period, the peak flows in the TP catchment were 90–130 and 50–120 mm month^{-1} in PP, but 45 mm month^{-1} in TE30 and TE100 and 30–40 mm month^{-1} in PE30 and PE100. At post-harvesting, peak flows in PP (pasture) were 120–170 mm month^{-1} in TP compared with 110–190 mm month^{-1} in TE100 and 44–63 mm month^{-1} in TE30 and 43–101 mm month^{-1} in PE100 and 28–78 mm month^{-1} in PE30 (Figure 7).

The importance of precipitation as a determinant of discharge is accounted for to some degree by examining discharge monthly ratios (discharge : precipitation), i.e. discharge per unit of precipitation. Prior to harvesting of TE100, PE100, and PE30, this ratio was consistently highest in the pasture catchments. At PE30, the ratio was higher than at PE100 (Figure 7 and Table II).

With a delay of 6 months, harvesting markedly increased daily and monthly flows and discharge ratios in the 100% harvest catchment (TE100) compared with that of the other two catchments at TD (Figure 8). This delay was in part related to the dry period immediately after harvesting. The hydrologic behaviour of the 100% harvest catchment (TE100) was then similar to the pasture catchment for about 14 months, persisting until the end of 2014. During the same period, patterns in the 30% harvested catchment (TE30 that included the nested and totally harvested catchment TE100) were intermediate of the other two catchments. In the case of PC, there was an increase on the percentage of discharge after harvest at PE100 and less pronounced in PE30. Surprisingly, there was a marked increase in the discharge ratio of the pasture catchment (PP) from 29% to 45%. This result may be



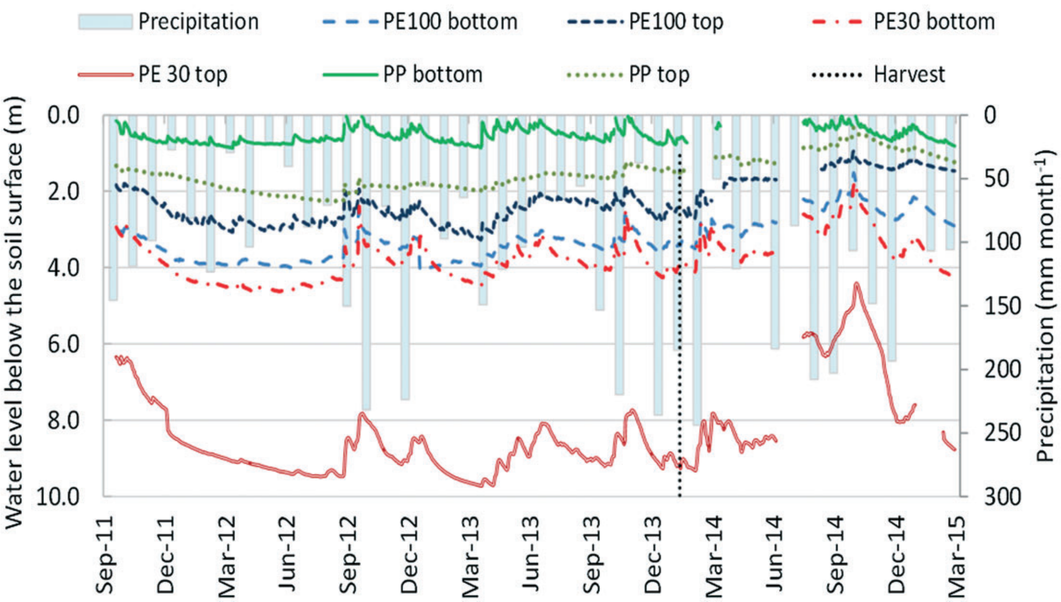


Figure 5. Groundwater levels measured at the top, middle, and bottom slope positions, and precipitation at Terra Dura (top) and Ponta das Canas (bottom) catchments

related to high-intensity precipitation events that occurred during March and July of 2014, and infiltration rates under pasture were probably lower than those under plantations. At PE100, after 30% plantation harvesting, there was an increase in discharge ratio compared with PE30 (100% harvesting), but the difference took around 5 months to develop.

Daily discharge became similar between PE100 and PE30 catchments around 6–7 months after harvesting. During the last 6 months of measurements (September 2014 to February 2015), PP had a much more similar discharge : precipitation ratio of PE100 than the previous period, and also a quicker reduction in discharge than at the plantation catchments (PE100 and PE30).

Flow duration curves from TE30, TE100, and TP for the period from April 2011 to November 2012 (before harvest) show that TP (pasture) had 100% of the time produced minimum discharge of at least 0.2 mm day^{-1} and only 20% of the time at discharge ≥1 mm day^{-1}. At the TE30 and TE100 catchments, discharge was ≥1 mm day^{-1} only 7% of the time. Discharge at TE30 was, almost all the time, higher than at TE100, e.g. flows of >0.1 mm day^{-1} occurred 80% of the time at TE30 and only 27% of the time in TE100 (Figure 8). This result is unexpected considering that TE100 flow contributes to TE30.

Before harvesting, low flows (assumed as flows that exceeded 75% of the time) were lowest in the catchment TE30, intermediate in the TE100, and highest in the

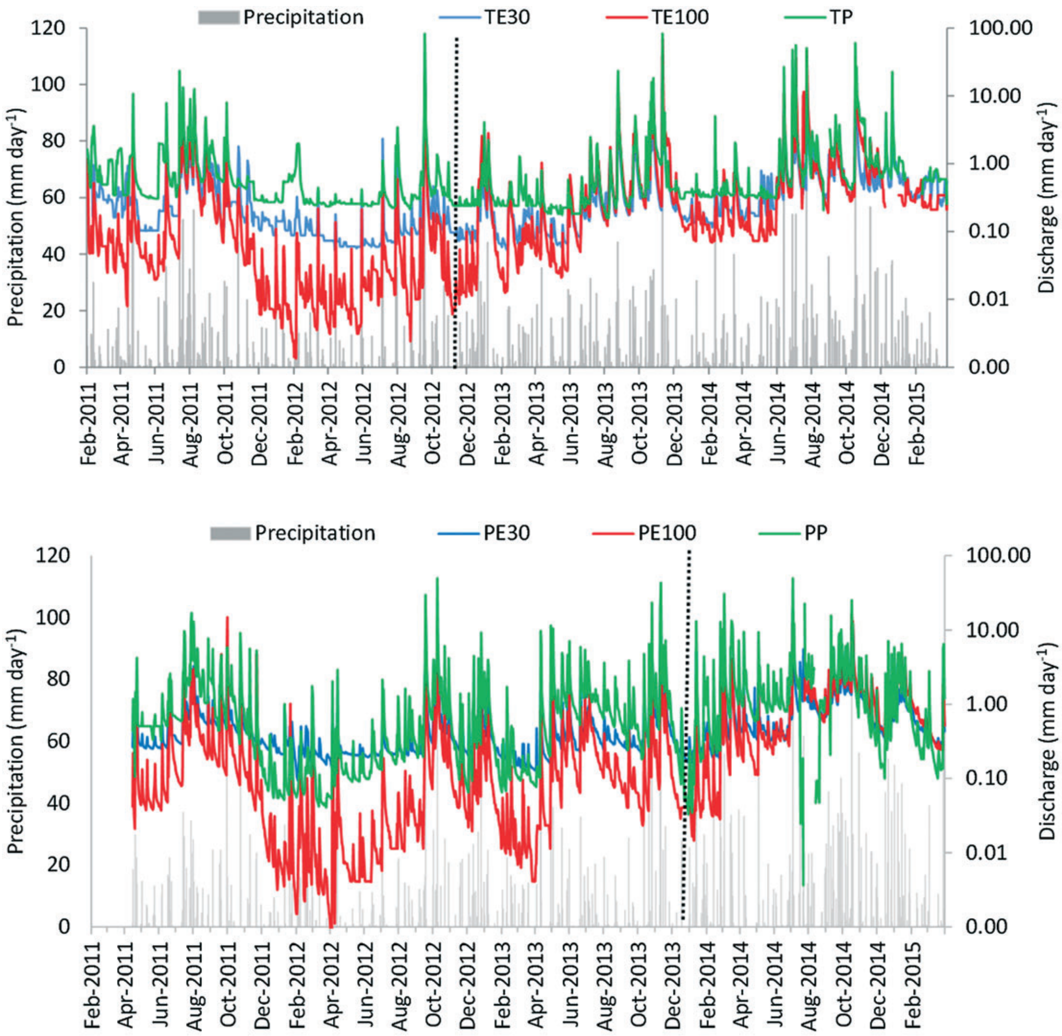


Figure 6. Daily average precipitation (mm day^{-1}) and daily discharge (logarithmic scale) for Terra Dura catchments (top; TE30, TE100, and TP) from February 2011 to March 2015, and for Ponta das Canas catchments (bottom; PE100, PE30, and PP) from February 2011 to March 2015. Vertical dotted lines represent the date of plantation harvest for the plantation catchments

pasture catchment (TP). The flow duration curves from TE30, TE100, and TP for the period after harvesting (from December 2012 to February 2015) were very similar across all catchments for at least 60% of the time, showing that in the harvested catchments, mainly in TE100, there was a shift towards a greater proportion of high flows.

By comparing the flow duration curves of PP for the period before and after the eucalypt harvesting, there was an increase in both high flows and lower flows. This change probably has been influenced by the precipitation events of higher intensity since a comparison (not shown) of PP flow duration curves, using periods with similar total precipitations for before harvesting that match with after harvesting, shows similar patterns. Before harvesting, the catchment PE100 exhibited a much lower proportion of both low and high flows than in the pasture catchment. The flow duration curve for PP was more similar to that in the PE30 before harvest, but after harvest, PE100 became very similar with PP and PE30; this is an evident effect of the harvesting (Figure 8).

Before harvest, flows of magnitude of 0.5 mm day^{-1} were exceeded only 10% of the time in PE100, 22% in PE30, and 50% in PP; this indicates the difference between vegetation and between other characteristics of the plantation catchments. After harvest, flows of 0.5 mm day^{-1} were exceeded 60% of the time in PE100, 63% of the time in PE30, and 72% of the time in PP. In PP, the percentage of time flow exceeded 0.5 mm day^{-1} increased by 22% when compared with the observed period before harvest; this indicates the effect of precipitation for the two periods, and it is important to take into consideration that the period before harvest accounts for 34 months of data and post-harvest only 14 months. The same comparison for PE100 shows a

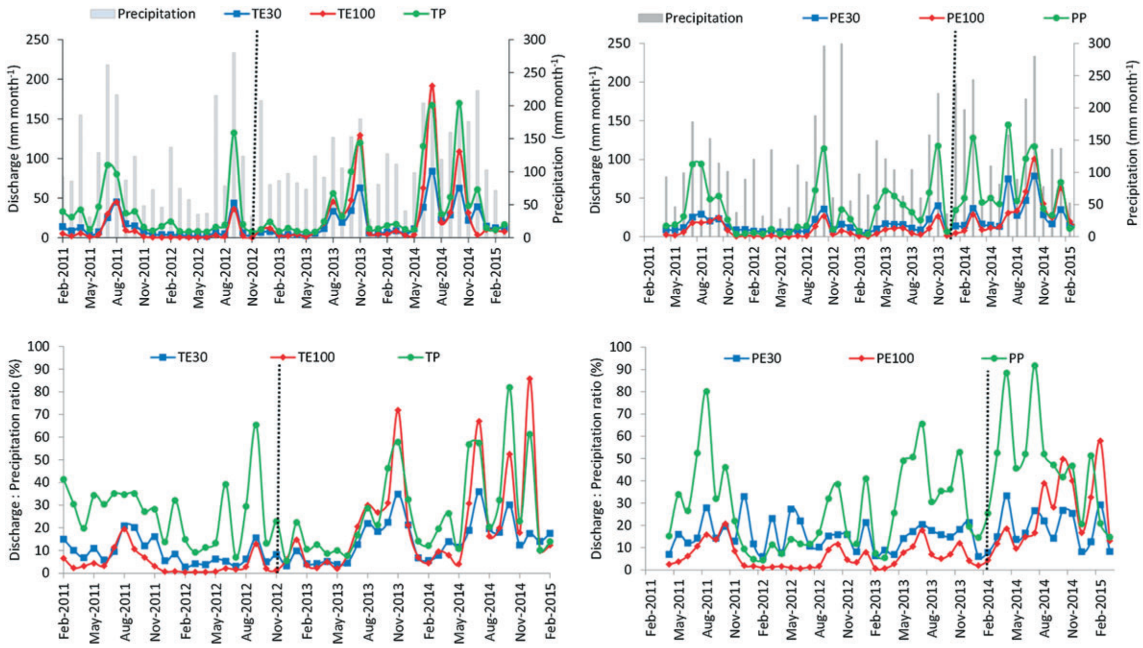


Figure 7. Monthly discharge and precipitation (top) and discharge : precipitation ratio (bottom) for Terra Dura (left) (TE30, TE100, and TP) and Ponta das Canas (right) (PE100, PE30, and PP) catchments. Vertical dotted lines represent the date of plantation harvest for the plantation catchments

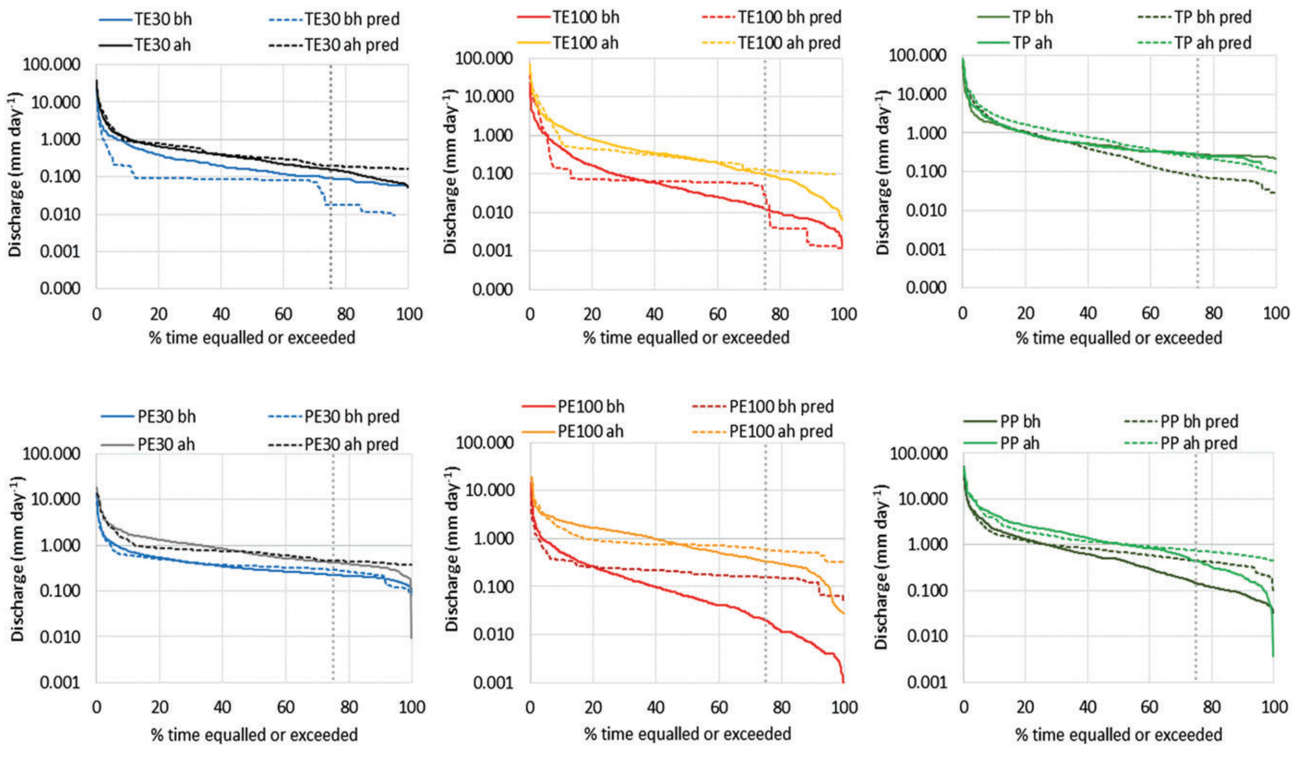


Figure 8. Observed (solid lines) and predicted (dashed lines) of flow duration curves for Terra Dura (top) and Ponta das Canas (bottom) catchments before (bh) and after (ah) plantation harvesting. Graphics in the left represent the catchments partially harvested (30%), in the middle the catchments 100% harvested, and in the right the pasture catchments. Vertical dotted lines represent 75% of the time equalled or exceeded representing the points of high (left) and low (right) flow

difference of 50% (60–10%) in PE100 and also 41% (63–20%) in PE30. This demonstrates in both cases that the harvest promoted an increase in flows.

Figure 8 shows modelled flow duration curves for each catchment for the periods before and after harvesting. Comparison with the observed flow duration curves indicates that the model overestimated the lower flows in PE100 and PP and underestimate in TE30TP and TE100, in the period before harvesting.

Monthly precipitation, discharge, and discharge : precipitation ratio for the six catchments are used to produce the data shown Table II.

Baseflow

Flow separation analysis for quickflow and baseflow showed a clear difference between the TD catchments. As a percentage of total flow, baseflow was 47% at TE30, 28% at TE100, and 43% at TP for the period before harvesting of TE100. The percentage of baseflow at TE100 remained constant despite harvesting. Baseflow before harvesting at PC was also different between catchments. At TE30, only 30% of total flow was baseflow, 62% at PE30, and 38% at PP. An increase to 51% of baseflow occurred at PE100 after harvesting, but this did not occur for 30% harvesting at PE30, which actually decreased slightly to 58% (Figure 9).

Simulated and observed discharge

The results of modelled and observed monthly discharge for each catchment during the total period of monitoring are presented in Figure 10, and the basic statistics of the observed *versus* predicted regression lines, coefficient of determination (R^2), RMSE, and NSE are presented in Table II.

Plantation growth and water balance

Predicted and observed plantation growth at PC is shown for SV for the most planted clone in Figure 11. The modelling framework enabled us to spatially predict growth (monthly time step), of which an example is also

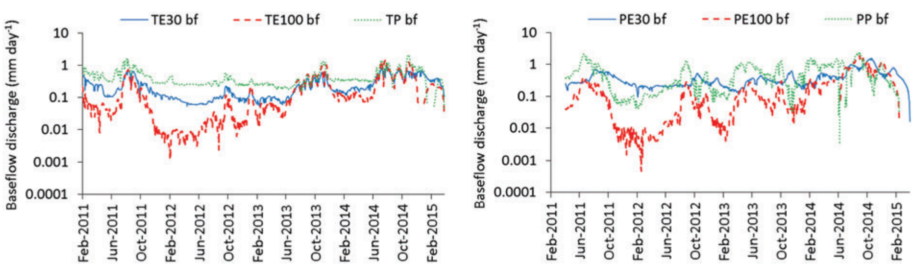


Figure 9. Predicted baseflow (bf) discharge at Terra Dura (left) and Ponta das Canas (right) catchments

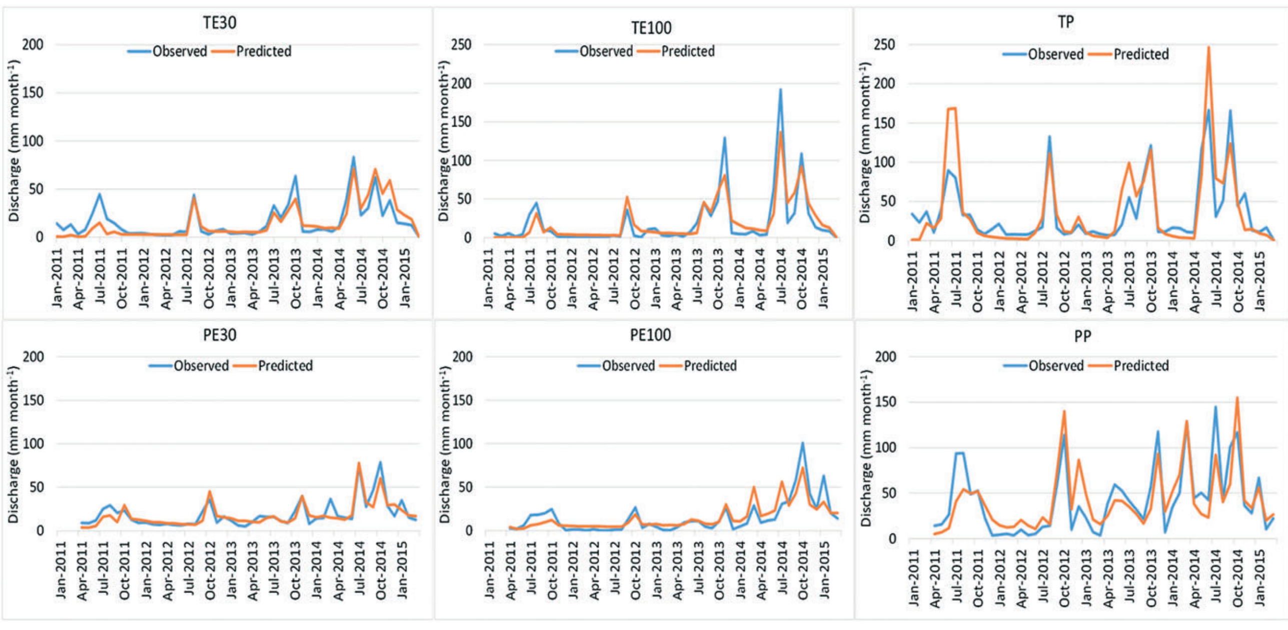


Figure 10. Monthly observed and predicted discharge of the individual catchments

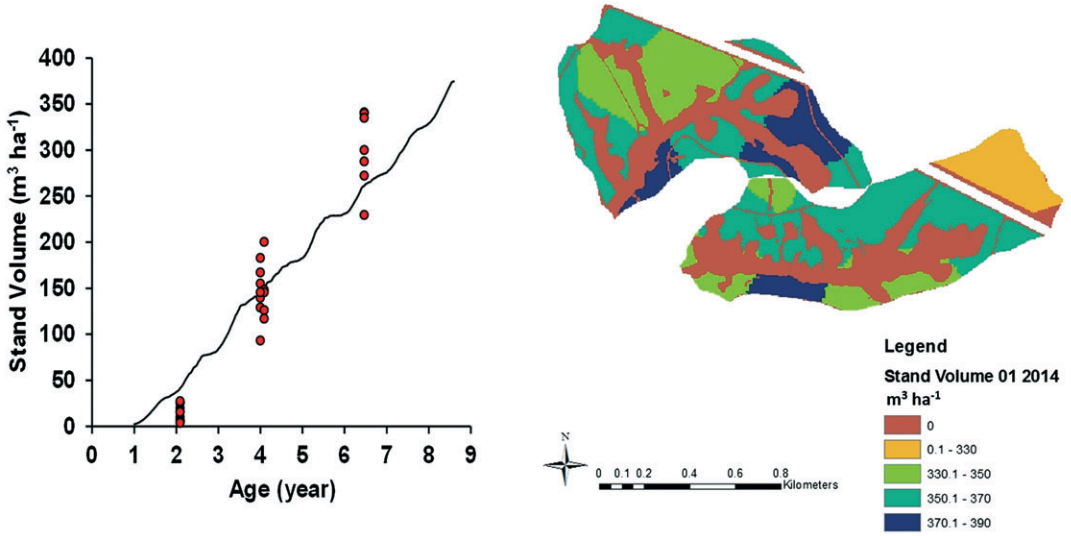


Figure 11. Predicted (black line) and observed (red dots) stand volume (left), and map of predicted wood production before harvest at Ponta das Canas PE100 and PE30 catchments (right). The value 0 in the legend represents an unplanted area covered with native forest or grass

provided in Figure 11, i.e. predicted stem volume before the harvesting in February 2014.

Prediction of water balance of the eucalypt catchments at TD and PC using 3-PG at plot scale for the entire rotation shows that evapotranspiration processes used around 80% of total precipitation (Table III).

Comparison of observed monthly canopy interception (Peláez, 2014) and its prediction by 3-PG for a period of 9 months between June 2012 to February 2014 shows a similar average ratio of interception : precipitation. Observed interception was 13.8% of the precipitation, and modelled was 14.1%.

Management scenarios

As an example of model application, the virtual experiment compared the effects of different levels of harvesting in PE100 (Figure 12). There were intermediate effects of smaller percentages of harvesting, but small differences in flows between 20% and 45% and 75% harvesting suggests there may be a threshold percentage before flows increase.

Table III. 3-PG-predicted water balance for the rotation cycle, from May 2005 to October 2012, at TE30 and from September 2007 to January 2014 at PE100.

	TE30		PE100	
	mm	%	mm	%
Precipitation (mm)	12 199		10 032	
Evapotranspiration	9732	79.8	8189	81.6
Soil evaporation	1372	11.2	1477	14.7
Transpiration	6030	49.4	5362	53.4
Interception	2330	19.1	1350	13.5
Drainage	2446	20.1	1846	18.4

DISCUSSION

Long-term monitoring of stand growth and water resources such as soil moisture, groundwater, and discharge was essential to develop, calibrate, and validate the modelling presented in this study and to understand and quantify the factors that influence discharge in the catchments. This combined, process-based, model concurrently simulated wood and water outcomes at spatial and temporal resolution consistent with previously separate models. The datasets came from paired-catchment studies that are known to be robust in quantifying and understanding water balance in catchments and the effects of land-use change. However, as such studies are expensive, the complementary modelling framework linking plot-scale plantation production and water balance to catchment-scale water discharge could become an important tool for applying this knowledge to other catchments and regions. This approach enables virtual experiments examining the effects of vegetation type (pasture and native forest) and management (harvesting, replanting, fertilizing, etc.) on water resources and provides essential information to improve the decision-making processes in order to optimize wood production and water availability.

Predictions of plantation growth at plot scale using 3-PG are useful, and species-specific growth parameters are required, as has been shown in other studies of eucalypt plantations in Brazil and other countries (Stape *et al.,* 2003; Almeida *et al.,* 2004a, b; Fontes *et al.,* 2006;

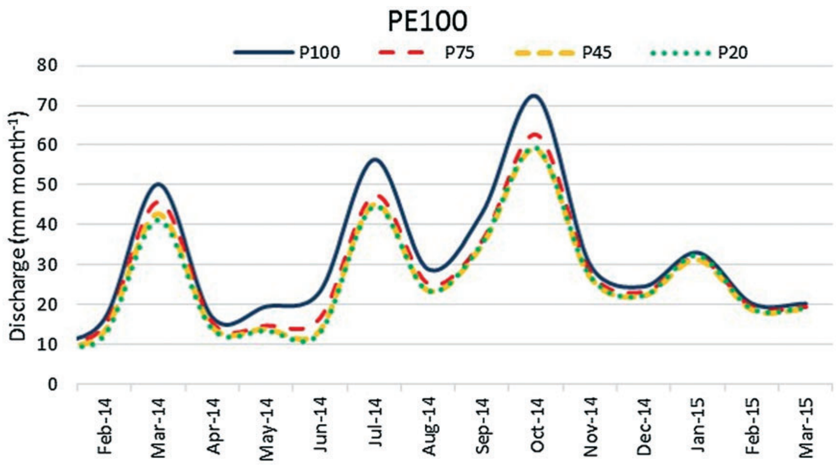


Figure 12. Simulated scenarios of discharge for harvest of 100% (P100), 75% (P75), 45% (P45), and 20% (P20) of the area of the plantation at PE100

Almeida and Sands, 2015). Spatial applications also have been used elsewhere (Coops and Waring, 2001; Tickle *et al.,* 2001; Almeida *et al.,* 2010; González-García *et al.,* 2015), and the model is used for research and operations by some forest plantation companies (Almeida *et al.,* 2004b; Almeida *et al.,* 2010). However, 3-PG integration with a hydrological model (TOPMODEL) allows predictions of water balance at catchment scale that can take account of different land-use and management options. Results demonstrate that the model was able to adequately predict both growth and water balance when compared with observed data of SV, soil moisture, and discharge. We recognize that the pasture component of the model is simplistic and should be improved with existing pasture growth models, e.g. as in APSIM or DAIRYMOD (Johnson *et al.,* 2008; Holzworth *et al.,* 2014). With the addition of crop models, 3-PGH could become useful also in agroforestry contexts, as recently called for by Luedeling *et al.* (2016).

The nested paired-catchment design of TD adapted from a previous catchment study required that the harvested proportion of the plantation was concentrated in the most up-stream section of the catchment. The un-nested paired-catchment design used in PC better facilitated the interpretation of results, as the catchments were independent of each other. However, harvesting in the PC catchment coincided with a change from a period of low-precipitation years to a high volume and intense-precipitation year that affected hydrology in all PC catchments, and the effect of partial harvesting was less clear than in the nested design. Intense precipitations occur with relative high frequency in this region (Zepka *et al.,* 2014) and need to be carefully considered in the modelling predictions and interpretation of discharge affected by these events.

These results demonstrate that there are many factors that influence discharge and water use by plantation and pasture (Vanclay, 2009), such as precipitation distribution and intensity, age of plantation, LAI, stocking, soil characteristics, riparian zone vegetation, slope, and litterfall, which need to be adequately considered and understood. Some of these factors can be influenced by how plantations are managed, such as age distribution and harvesting proportion and location in the catchment, as well as the vegetation characteristics and size of the APP.

Soil water content increased after eucalypt harvesting in both regions, but this period coincided with increased precipitation that produced a similar signal in pasture catchments (TP and PP). Although SWC under pasture during the dry years was higher than that under plantation, its increase after substantial rain was to levels similar to those under harvested plantation. There was an increase in soil moisture over 2 years at TE100 after harvest, relative to TP; however, part of the increase in both catchments was due to increased precipitation. Despite establishment of the new plantation in June 2013 in TE100 and in June 2014 in PE100 and PE30, soil moisture still increased compared with the pre-harvest period. These results indicate that precipitation distribution and intensity, and soil type, were more determinant of soil moisture content than vegetation or topographic position.

Data collected in the piezometers indicated that, despite the harvest of TE100, PE100, and PE30, there was no evidence of large changes in the level of the groundwater directly related to the harvesting as identified in one other study in Brazil (Almeida *et al.,* 2007; Smethurst *et al.,* 2015). In the current study, values of groundwater rise after eucalypt harvesting are less but quicker than those found in a study in the Aracruz catchment in the Espírito Santo state on the east coast of Brazil. Although variations in groundwater levels were not associated with harvesting at TD, levels at the bottom of the transect varied in the range 1.8–2.5 m despite this period coinciding with relatively low annual precipitation. At the start of monitoring at this point, groundwater was closer to the surface, which occurred after 4 years of relatively high precipitation. Higher up in the transect, groundwater levels were deeper (measured down to 13.4 m) and also responsive to precipitation over periods of several months. At PC with about a 6-month delay, groundwater levels reflected the increase in SWC after harvesting and increased precipitation, but absolute levels were highest in the pasture catchment, with no apparent effect of increased precipitation on water levels at the bottom of the transect, which was always relatively shallow. Overall, groundwater levels in this study did not provide clear insights into the links between discharge and vegetation, management, or precipitation.

Our study showed that discharge was affected by eucalypt harvesting, as has been shown in other studies in South America (Iroumé *et al.,* 2005; Ferraz *et al.,* 2013). However, patterns of precipitation (duration and intensity) can have substantial effects on discharge that were evidenced here before and after the harvest of TE100 in 2012 and at PE100 and PE30 in 2014. These patterns of precipitation appeared to account for some changes in flow at TD when comparing 2012 with 2013, as these years had relatively low and similar total precipitation (i.e. at least 2 years of lower-than-average precipitation), yet the pattern of precipitation in 2012 included 3 months of higher monthly values and many months of lower precipitation compared with 2013 that had a more even distribution of monthly precipitation. Discharge was higher in 2013 than in 2012 and was restricted to the second half of 2013, which was after several months of soil wetting up in 2013 and that of the previous year following harvest. The 3-PGH model works on a daily time step for precipitation, which was proven to incorporate an adequate level of precipitation intensity and distribution information for this type of modelling.

Flow duration curves for the pasture catchment at TD (TP) did not change at the time of harvest, and the curve changed little in response to partial harvest (TE30). However, the curve for the 100% harvested catchment (TE100) showed a substantial increase in both high and low flows. Hence, flow characteristics appear not to revert completely to the pastured condition after harvesting, which is probably due to the retention of forested cover in the area of permanent preservation (APP) (approximately 15% of catchment area) even after 100% harvesting of the plantation part of the TE100 catchment. Pastured catchments are also generally known to have lower infiltration rates associated with stock traffic (Greenwood and McKenzie, 2001) causing soil compaction and loss of structure, increasing surface runoff with more likelihood of soil erosion (van Dijk and Keenan, 2007).

The flow duration curves for the pasture catchment at PC (PP) changed at the time of harvest as effect of precipitation intensity, and the curve also had similar change in response to partial harvest (PE30). The change at PE30 has increased both low and high flow proportionally. However, the curve for the 100% harvested catchment (PE100) showed a marked increase also in high and low flows. With this change, flow characteristics reverted almost completely closer to the pastured condition after harvesting, which may reflect the low vigour of forest cover in much of the APP (approximately 15% of catchment area) at this site.

Using the control (pasture) catchment to account for precipitation effects on the discharge : precipitation ratio after harvesting (which was 15% higher in TP), actual discharge was 3.3 times higher in TE100 and 1.4 times higher in TE30 (with partial harvest). Hence, partial harvest (approximately 30%) had a similar proportional effect on discharge : precipitation ratio. In contrast, full harvesting at PC (PE100) led to 2.2 times the increase in flow compared with that expected due to precipitation alone in the pasture catchment (PP), and partial harvesting (PE30) led to only 1.03 of the flows. Ferraz *et al.* (2013) suggested that a maximum 30% reduction in annual discharge occurred in the Tinga catchment due to plantation growth (i.e. conversely a maximum 1.4-fold increase due to harvesting), which is less than our observation for full harvesting in the TD and PC catchments. However, the basis of the Ferraz *et al.* (2013) comparison is questionable, because discharge in the year immediately after harvesting coincided with the year of highest annual precipitation.

The results of Smethurst *et al.* (2015) for a catchment in Espírito Santo state in Brazil are also in contrast to current results. In that catchment, plantation harvesting had no effect on discharge or discharge : precipitation ratios, despite a large response in groundwater levels under the harvested plantation. The lack of response was attributed to very low slope and very deep soils under the plantation with high capacity for water storage, and a wide and heavily forested area of deep root native vegetation next to the stream. Together, the current results and those of Smethurst *et al.* (2015) and Ferraz *et al.* (2013) emphasize that plantation establishment and management links to catchment water outcomes can be very catchment specific, requiring quantitative integration of temporal and spatial components of water balance. This reinforces the need of robust modelling framework to adequately predict the water availability and the uncertainties of generalizations or application of empirical curves of water use based on vegetation type.

It is clear that discharge increases are not linearly related to the proportion of plantation area harvested. To better understand and quantify this relationship for the current catchments, it would be useful to complete the research program for several more partial harvests and complete one whole plantation.

Based on current results, it appears likely that frequent partial harvesting (approximately two-yearly) will moderate the hydrological response compared with less frequent complete harvesting, i.e. a more even flow regime with fewer harvested- and regrowth-related high and low flows. However, the hydrological signal of harvesting was not outside the range of daily, seasonal, and annual variability resulting from landscape and climate variability. If an aim of a management is to minimize the hydrological response to plantation management, or maintain low–medium flows, partial harvesting should be considered, but many factors will come into play that have not been studied, especially the value of moderating the hydrological response and the cost of doing so.

CONCLUSIONS

A paired and nested catchment study was effective for quantifying the impacts of plantation management in relation to pasture, and it provided reliable information for validating linked forest and hydrological process-based models. Such a combination of observation and simulation offers the opportunity to improve catchment water outcomes while increasing wood production.

Catchments covered with pasture produced higher discharge than the eucalypt catchments. That this occurred even after harvesting indicates that pasture soils might have lower water infiltration rates and higher and more variable surface flow.

The model developed and applied in this study is a tool for testing scenarios of plantation management in diverse catchments or regions. Here, we simulated the effects of clear cutting or partial harvesting on discharge that incorporated climate variability impacts on plantation productivity and water availability. Partial harvesting in the study catchments moderated flow patterns, which was adequately simulated by the linked models.

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REFERENCES

Almeida A, Soares J, Landsberg J, Rezende G. 2007. Growth and water balance of *Eucalyptus grandis* hybrid plantations in Brazil during a rotation for pulp production. *Forest Ecology and Management* **251**: 10–21.

Almeida AC, Landsberg JJ, Sands PJ. 2004a. Parameterisation of 3-PG model for fast-growing *Eucalyptus grandis* plantations. *Forest Ecology and Management* **193**: 179–195.

Almeida AC, Landsberg JJ, Sands PJ, Ambrogi MS, Fonseca S, Barddal SM, Bertolucci FL. 2004b. Needs and opportunities for using a process-based productivity model as a practical tool in *Eucalyptus* plantations. *Forest Ecology and Management* **193**: 167–177.

Almeida AC, Sands PJ. 2015. Improving the ability of 3-PG to model the water balance of forest plantations in contrasting environments. *Ecohydrology* DOI:10.1002/eco.1661

Almeida AC, Siggins A, Batista TR, Beadle C, Fonseca S, Loos R. 2010. Mapping the effect of spatial and temporal variation in climate and soils on *Eucalyptus* plantation production with 3-PG, a process-based growth model. *Forest Ecology and Management* **259**: 1730–1740.

Almeida AC, Soares JV. 2003. Comparação entre o uso de água em plantações de *Eucaliptus grandis* e floresta ombrófila densa (Mata Atlântica) na costa leste do Brasil. *Revista Árvore* **27**: 159–170.

Ambroise B, Beven K, Freer J. 1996. Toward a generalization of the TOPMODEL concepts: topographic indices of hydrological similarity. *Water Resources Research* **32**: 2135–2145. DOI:10.1029/95WR03716

Beven K, Freer J. 2001. A dynamic TOPMODEL. *Hydrological Processes* **15**: 1993–2011.

Beven KJ, Kirkby MJ. 1979. A physically based, variable contributing area model of basin hydrology/Un modèle à base physique de zone d'appel variable de l'hydrologie du bassin versant. *Hydrological Sciences Bulletin* **24**: 43–69. DOI:10.1080/02626667909491834

Beverly C, Bari M, Christy B, Hocking M, Smettem K. 2005. Salinity impacts from land use change; comparison between a rapid assessment approach and a detailed modelling framework. *Australian Journal of Experimental Agriculture* **45**: 1453–1469. DOI:10.1071/EA04192

Brown AE, Podger GM, Davidson AJ, Dowling TI, Zhang L. 2007. Predicting the impact of plantation forestry on water users at local and regional scales: an example for the Murrumbidgee River Basin, Australia. *Forest Ecology and Management* **251**: 82–93.

Brown AE, Zhang L, McMahon TA, Western AW, Vertessy RA. 2005. A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. *Journal of Hydrology* **310**: 28–61.

Coops NC, Waring RH. 2001. Assessing forest growth across southwestern Oregon under a range of current and future global change scenarios using a process model, 3-PG. *Global Change Biology* **7**: 15–29.

Costa AM, Curi N, Menezes MD, Araújo EF, Marques JJ. 2009. Levantamento detalhado de solos da microbacia hidrográfica do horto florestal Terra Dura (RS) e considerações sobre escalas de mapeamento. *Ciencia e Agrotecnologia* **33**: 1272–1279.

Engel V, Jobbágy EG, Stieglitz M, Williams M, Jackson RB. 2005. Hydrological consequences of *Eucalyptus* afforestation in the Argentine Pampas. *Water Resources Research* **41**: DOI:10.1029/2004WR003761

Farley KA, Jobbágy EG, Jackson RB. 2005. Effects of afforestation on water yield: a global synthesis with implications for policy. *Global Change Biology* **11**: 1565–1576. DOI:10.1111/j.1365-2486.2005.01011.x

Feikema P, Lane P, Beverly C, Baker T. 2009. *Application of Macaque and 3PG+ in CAT catchment-scale hydrological models: limitations and opportunities*. 18th World IMACS Congress and MODSIM09 INternational Congress on Modelling and Simulation: Cairns, Australia.

Feikema PM, Beverly CR, Morris JD, Collopy JJ, Baker TG, Lane PNJ, Oxley L, Kulasiri D. 2007. Predicting the impacts of plantations on catchment water balances using the 3PG forest growth model. Modelling and Simulation Society of Australia and New Zealand.

Feikema PM, Morris JD, Beverly CR, Collopy JJ, Baker TG, Lane PNJ. 2010. Validation of plantation transpiration in south-eastern Australia estimated using the 3PG+ forest growth model. *Forest Ecology and Management* **260**: 663–678.

Ferraz SFB, Lima WDP, Rodrigues CB. 2013. Managing forest plantation landscapes for water conservation. *Forest Ecology and Management* **301**: 58–66.

Fontes L, Landsberg J, Tomé J, Tomé M, Pacheco CA, Soares P, Araujo C. 2006. Calibration and testing of a generalized process-based model for use in Portuguese *Eucalyptus* plantations. *Canadian Journal of Forest Research* **36**: 3209–3221.

Forrester DI, Tang X. 2015. Analysing the spatial and temporal dynamics of species interactions in mixed-species forests and the effects of stand density using the 3-PG model. *Ecological Modelling* DOI:10.1016/j.ecolmodel.2015.07.010

González-García M, Almeida AC, Hevia A, Majada J, Beadle C. 2015. Application of a process-based model for predicting the productivity of *Eucalyptus nitens* bioenergy plantations in Spain. *GCB Bioenergy* DOI:10.1111/gcbb.12256

Greenwood AJB, Benyon RG, Lane NJ. 2011. A method for assessing the hydrological impact of afforestation using mean annual data and empirical rainfall-runoff curves. *Journal of Hydrology* **411**: 49–65.

Greenwood KL, McKenzie BM. 2001. Grazing effects on soil physical properties and the consequences for pastures: a review. *Australian Journal of Experimental Agriculture* **41**: 1231–1250. DOI:10.1071/EA00102

Holzworth DP, Huth NI, deVoil PG, Zurcher EJ, Herrmann NI, McLean G, Chenu K, van Oosterom EJ, Snow V, Murphy C, Moore AD, Brown H, Whish JPM, Verrall S, Fainges J, Bell LW, Peake AS, Poulton PL, Hochman Z, Thorburn PJ, Gaydon DS, Dalgliesh NP, Rodriguez D, Cox H, Chapman S, Doherty A, Teixeira E, Sharp J, Cichota R, Vogeler I, Li FY, Wang E, Hammer GL, Robertson MJ, Dimes JP, Whitbread AM, Hunt J, van Rees H, McClelland T, Carberry PS, Hargreaves JNG, MacLeod N, McDonald C, Harsdorf J, Wedgwood S, Keating BA. 2014. APSIM – evolution towards a new generation of agricultural systems simulation. *Environmental Modelling & Software* **62**: 327–350. DOI:10.1016/j.envsoft.2014.07.009

Iroumé A, Huber A, Schulz K. 2005. Summer flows in experimental catchments with different forest covers, Chile. *Journal of Hydrology* **300**: 300–313. DOI:10.1016/j.jhydrol.2004.06.014

Jackson RBJ, Esteban G, Avissar R, Roy SB, Barrett DJ, Cook CW, Farley KA, le Maitre DC, McCarl BA, Murray BC. 2005. Trading water for carbon with biological carbon sequestration. *Science* **310**: 1944–1947. DOI:10.1126/science.1119282

Johnson IR, Chapman DF, Snow VO, Eckard RJ, Parsons AJ, Lambert MG, Cullen BR. 2008. DairyMod and EcoMod: biophysical pasture-simulation models for Australia and New Zealand. *Australian Journal of Experimental Agriculture* **48**: 621–631. DOI:10.1071/EA07133

Landsberg J, Sands P. 2010. Physiological ecology of forest production. In *Principles, Processes and Models*. Elsevier: London, 352 pp.

Landsberg JJ, Waring RH. 1997. A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. *Forest Ecology and Management* **95**: 209–228.

Lyne V, Hollick M. 1979. Stochastic timevariable rainfall-runoff modelling, *Proceedings of the Hydrology and Water Resources Symposium*, Perth, 10-12 September, Institution of Engineers National Conference Publication, No. 79/10, pp. 89–92.

Luedeling E, Smethurst PJ, Baudron F, Bayala J, Huth NI, van Noordwijk M, Ong CK, Mulia R, Lusiana B, Muthuri C, Sinclair FL. 2016. Field-scale modeling of tree–crop interactions: challenges and development needs. *Agricultural Systems* **142**: 51–69. DOI:10.1016/j.agsy.2015.11.005

McVicar TR, Körner C. 2013. On the use of elevation, altitude, and height in the ecological and climatological literature. *Oecologia* **171**: 335–337. DOI:10.1007/s00442-012-2416-7

Nash JE, Sutcliffe JV. 1970. River flow forecasting through conceptual models part I – a discussion of principles. *Journal of Hydrology* **10**: 282–290.

Nosetto MD, Jobbágy EG, Paruelo JM. 2005. Land-use change and water losses: the case of grassland afforestation across a soil textural gradient in central Argentina. *Global Change Biology* **11**: 1101–1117. DOI:10.1111/j.1365-2486.2005.00975.x

Paydar Z, Gallant J. 2008. A catchment framework for one-dimensional models: introducing FLUSH and its application. *Hydrological Processes* **22**: 2094–2104.

Peláez JJZ. 2014. Hidrologia comparativa em bacias hidrográficas com eucalipto e campo. PhD Thesis. In *Centro de Ciências Rurais*. Universidade Federal de Santa Maria: RS, Brazil, 156 pp.

Polglase PJ, Benyon RG. 2009. The impacts of plantations and native forests on water security: review and scientific assessment of regional issues and research needs.pp: 72.

Pushpalatha R, Perrin C, Moine NL, Andréassian V. 2012. A review of efficiency criteria suitable for evaluating low-flow simulations. *Journal of Hydrology*, **420–421**: 171–182. DOI: 10.1016/j.jhydrol.2011.11.055.

Quinn P, Beven K, Chevallier P, Planchon O. 1991. The prediction of hillslope flow paths for distributed hydrological modelling using digital terrain models. *Hydrological Processes* **5**: 59–79.

Ritter A, Muñoz-Carpena R. 2013. Performance evaluation of hydrological models: statistical significance for reducing subjectivity in goodness-of-fit assessments. *Journal of Hydrology* **480**: 33–45. DOI:10.1016/j.jhydrol.2012.12.004

Sands PJ, Landsberg JJ. 2002. Parameterisation of 3-PG for plantation grown *Eucalyptus globulus*. *Forest Ecology and Management* **163**: 273–292.

Santos WJR, Curi N, Silva SHG, Araújo EF, Marques JJ. 2013. Pedotransfer functions for water retention in different soil classes from the center-southern Rio Grande do Sul State. *Ciencia e Agrotecnologia* **37**: 49–60.

Scott DF, Lesch W. 1997. Streamflow responses to afforestation with *Eucalyptus grandis* and *Pinus patula* and to felling in the Mokobulaan experimental catchments, South Africa. *Journal of Hydrology* **199**: 360–377.

Smethurst PJ, Almeida AC, Loos RA. 2015. Stream flow unaffected by *Eucalyptus* plantation harvesting implicates water use by the native forest streamside reserve. *Journal of Hydrology: Regional Studies* **3**: 187–198. DOI:10.1016/j.ejrh.2014.11.002

Soares JV, Almeida AC. 2001. Modeling the water balance and soil water fluxes in a fast growing *Eucalyptus* plantation in Brazil. *Journal of Hydrology* **253**: 130–147.

Stape JL, Ryan MG, Binkley D. 2003. Testing the 3-PG process-based model to simulate *Eucalyptus* growth with an objective approach to the soil fertility rating parameter. *Forest Ecology and Management* **193**: 219–234. DOI:10.1016/j.foreco.2004.01.031

Tickle PK, Coops NC, Hafner SD, Team TBS. 2001. Assessing forest productivity at local scales across a native eucalypt forest using a process model, 3PG-SPATIAL. *Forest Ecology and Management* **152**: 275–291.

van Dijk AIJM, Keenan RJ. 2007. Planted forests and water in perspective. *Forest Ecology and Management* **251**: 1–9.

Vanclay JK. 2009. Managing water use from forest plantations. *Forest Ecology and Management* **257**: 385–389.

Wang E, Cresswell H, Paydar Z, Gallant J. 2008. Opportunities for manipulating catchment water balance by changing vegetation type on a topographic sequence: a simulation study. *Hydrological Processes* **22**: 736–749.

Whitehead D, Beadle CL. 2004. Physiological regulation of productivity and water use in *Eucalyptus*: a review. *Forest Ecology and Management* **193**: 113–140.

Zepka GS, Azambuja RR, Jr VRV, Saraiva ACV, Jr OP. 2014. Predicting heavy precipitation and lightning for a mesoscale convective system case over Southern Brazil.

Zhang L, Dawes WR, Walker GR. 2001. Response of mean annual evapotranspiration to vegetation changes at catchment scale. *Water Resources Research* **37**: 701–708. DOI:10.1029/2000WR900325

