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Hydrological effects of forest plantation clear-cut on water availability: Consequences for downstream water users

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ABSTRACT

Study Region: São Paulo State, Brazil.
Study Focus: This study assessed the influence of forest plantations on streamflow in a gauged catchment (85 ha), covered with fast-growing *Eucalyptus* sp. plantations. One strategy for reducing the effects of plantations on streamflow is to reduce the area of a catchment occupied by forest, and in this context, our objectives were to simulate the effects on streamflow of different proportions of forest cover (70%, 50% and 0% of the forest cover). Moreover, we used low-flow indices (Q90 and 7Q10) to examine the effects of such scenarios on water availability for downstream users.
New Hydrological Insights: Fast-growing forest plantation areas have been expanding globally, with simultaneously increasing concerns about the water consumption of these forests, especially in water-limited regions with consequences for downstream users. Simulations of scenarios with varying forest cover proportions showed an annual streamflow increase of 90% when clear-cutting had removed the forest cover in the catchment. The 100% forest cover scenario produced rates of streamflow below the low flow indices, resulting in less water availability for downstream water users. The reduction in forest cover proportion at the catchment scale promoted an attenuation of water use. Therefore, forest plantation management should adopt management strategies such as regulating the forest cover proportion to minimize the effects on water supply for downstream water users.

1. Introduction

The area occupied by fast-growing forest plantations is expanding in several parts of the world (Payn et al., 2015); at the same time, the area of forest plantation in Brazil currently exceeds 7.5 million hectares (IBA, 2016). These expansions are accompanied by a parallel increase in concerns regarding water use (Jackson et al., 2005; Calder, 2007). Such concerns are mainly related to the decrease in water availability to downstream users (van Dijk and Keenan, 2007; Guzha et al., 2018) and the effects on low flows (Farley et al., 2005; Beck et al., 2013).

The effects on streamflow are high evapotranspiration rates associated with fast growing/highly productive forests, which are typical characteristics of *Eucalyptus* forest plantations (Scott, 2005). These effects are characterized by an observed decrease in

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streamflow following reforestation (Bosch and Hewlett, 1982; Guzha et al., 2018) accompanied by an increase in streamflow following forest clear-cutting (Scott, 2005). Due to this relationship, one way to minimize the effects of forest plantations on streamflow might be to control the proportion of forest cover at the catchment scale, which has the potential to modify the streamflow regime (Zhang et al., 2012). For this reason, it is important to understand the relationship between streamflow and forest cover proportion in order to better manage forest plantations and avoid water-use conflicts (Brown et al., 2013). This is especially necessary in regions where fast-growing forest is the predominant land use (Swanson et al., 2000; DeFries and Eshleman, 2004), as well as in water-limited regions (van Dijk and Keenan, 2007) since decreases in streamflow related to forest expansion can reduce water availability and consequently may enhance water-use conflicts (Farley et al., 2005; Scott, 2005; van Dijk and Keenan, 2007).

In this context, alternative forest management strategies may minimize the effects on streamflow in a catchment(Vanclay, 2009). Some alternative forest management strategies include (i) increasing the rotation cycle to allow the recovery of streamflow to original levels (Scott and Prinsloo, 2008); (ii) choosing species with higher water-use efficiency to increase wood production without increasing water use (Forrester et al., 2010); (iii) establishing forest stands with different ages to minimize the peak water consumption (Vertessy et al., 2003; Ferraz et al., 2013), and (iv) choosing forest plantation locations relative to the stream network for reaching the potential areas in catchment planning (Kalantari et al., 2014). However, some of these management practices are costly, which may hinder their practical implementation.

Taking this difficulty into account, the use of hydrological models can be an alternative tool for providing responses to the effectiveness of alternative strategies for forest management (DeFries and Eshleman, 2004; Guzha et al., 2018). In this study, we used a simple conceptual hydrological model developed by Brown et al. (2006) and widely used by Shao et al. (2009) and Zhang et al. (2012) to predict the effects of forest plantations on streamflow following a change in the proportion of forest cover. Increases in forest plantation area can lead to low flow reduction (Brown et al., 2005), which will affect water availability at the catchment scale and, consequently, water availability for downstream water-users (van Dijk and Keenan 2007). Therefore, understanding these changes in a streamflow regime is necessary to the development of strategies for water resources management (Zhang et al., 2012).

The aim of this study is to simulate the hydrological effects of different forest cover scenarios and discuss forest plantation occupation planning as a tool for water conservation and implementation of the hydrosolidarity concept in forestry activities.

2. Material and methods

2.1. Study area

Aiming to best represent the climatic conditions and management practices under which fast-growing planted forests are distributed in Brazil, we used a gauged catchment located in the State of São Paulo (23°02′01″ S; 48°37′30″ W) (Fig. 1). This region is representative of the climatic conditions and management practices of fast-growing plantation forests in Brazil.

The catchment area is 85.8 ha with 95% forest cover (85% fast-growing forest plantations - in which *Eucalyptus* spp. and *Pinus* spp. occupy 76% and 9% of the catchment area, respectively - and 10% native vegetation buffer along the stream) and 5% of the area consisting of roads.

The mean annual temperature in the region is 19.4 °C, with a mean annual precipitation of 1319 mm, with rainfall mostly concentrated in the summer period (October to March), based on a 40-year time series – 1950–1990 (Alvares et al., 2013).

Soil types are both Typic Hapludox and Rhodic Hapludox (Gonçalves et al., 2012), which are typical tropical soils.

2.2. Datasets

Streamflow was measured using an H-flume equipped with an automatic stage recorder (Thalimedes Shaft Enconder sensor) with a 15-minute resolution, coupled with a datalogger.

Precipitation was measured with an automatic rain gauge (TR-525I, Texas Electronics) and recorded at 30 min intervals by a data logger located 1 km from the stream gauge. The streamflow and rainfall data used in this paper are from August 2009 to December 2016 (Fig. 2).

Potential evaporation (PET in mm. h^{-1}) was estimated using Penman's formulation, as given in Shuttleworth (1993). For this estimation, the meteorological data of net radiation (MJ. $m^{-2}.d^{-1}$), air temperature (°C), relative humidity (%) and wind speed at 2 m height ($m.s^{-1}$) were obtained from an automatic station located 1 km from the streamflow gauge, with a 30 min recording interval.

2.3. Forest cover change simulations

To simulate the effects of forest cover changes (by forest cover proportion) on streamflow, we used the Forest Cover Flow Change (FCFC) model (Brown et al., 2006), which is based on a downward approach (Sivapalan et al., 2003). This model uses streamflow observations to simulate the effects of forest cover due to management (Podger et al., 2005) and requires few inputs, such as daily precipitation, daily flow, and daily potential evapotranspiration. In addition, the proportion of the catchment area under forest cover before and after changes is required, input as a percentage (Brown et al., 2006).

The effects of forest cover changes on the Flow Duration Curve (FDC) were simulated by linking the area under the curve parameters (five parameters of the FDC that capture the key components of the curve, see Best et al., 2003) and mean annual streamflow, as predicted by Zhang's curve (Zhang et al., 2001). The FDC parameters are optimized to fit observed and predicted data. The CTF (cease to flow percentile) and Q_{50} parameters were derived directly from measured data, while the other three parameters

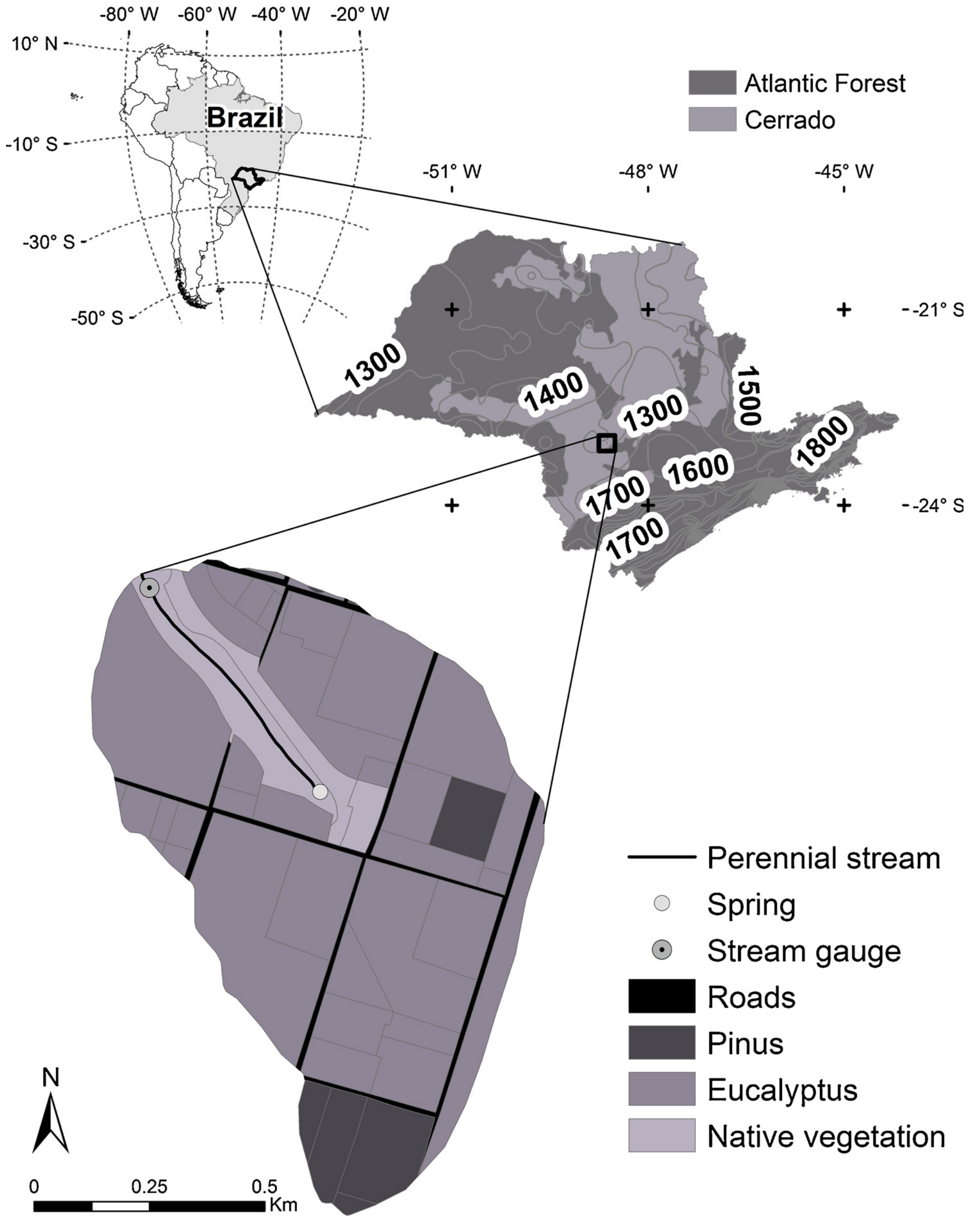

Fig. 1. Experimental catchment location in the State of Sao Paulo, Brazil. Top right: State of Sao Paulo and biomes (Atlantic Forest and Cerrado). Numbers indicate mean annual precipitation.

(slope at the origin of the normalized FDC, exponent for the upper sections of the normalized FDC and lower section of the normalized FDC) were obtained by maximizing the Nash and Sutcliffe coefficient of efficiency (NSE) (Nash and Sutcliffe, 1970). The coefficient of efficiency can be used to obtain a measure of goodness-of-fit, with values closer to one reflecting the best fit (Zhang et al., 2012).

Calibration was carried out with the catchment completely forested (i.e., 100% forest cover). In this work, forest cover in a catchment was considered to be the sum of forest plantation and native vegetation. The proportions of simulated forest cover were 70%, 50% and 0% of the catchment area. Scenarios with 100% forest cover were considered as observed data for treatment comparisons.

2.4. Clear-cut scenarios and implications for water availability

Values for streamflow were obtained by integrating the area under the FDC in each simulated scenario. This was done by calculating the sum of the flow (axis ‘y’ in the curve) for the full percentage of time the flow is exceeded (axis ‘x’ in the curve).

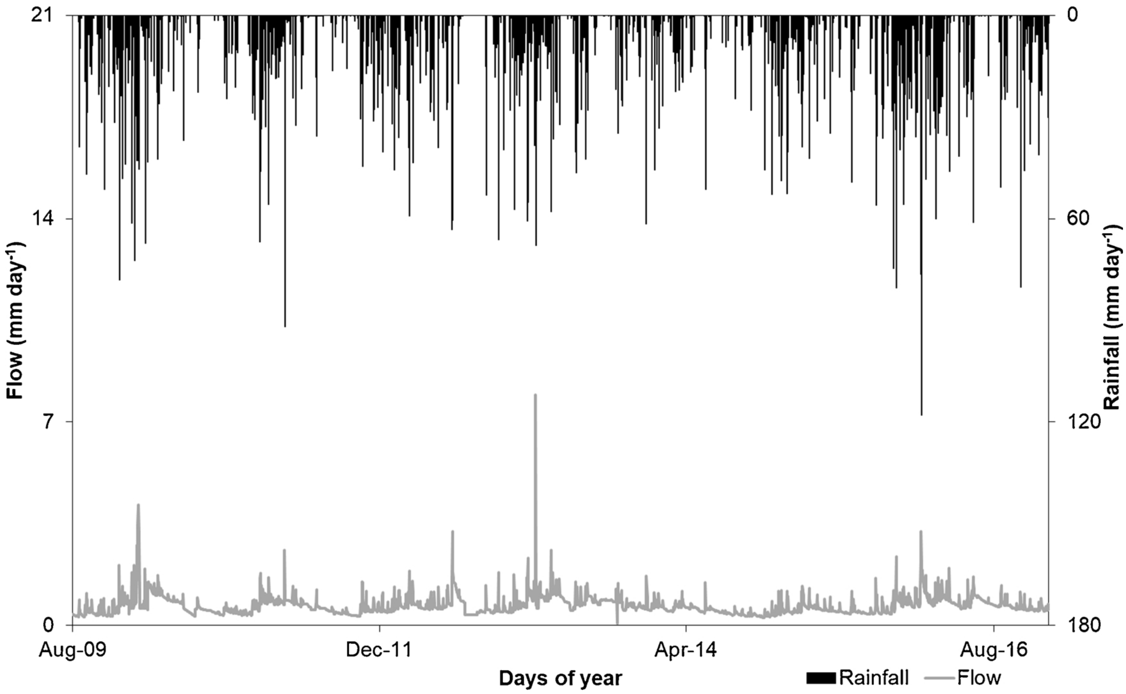

Fig. 2. Observed daily values of rainfall and flow in the experimental catchment from August 2009 to December 2016.

Afterwards, these values were compared with the 100% forest cover scenario for calculating the effects of changes in forest cover on streamflow.

Based on the analysis of the effects of forest cover change on high and low flows, we considered flow between 70% and 99% of the time to be exceeding the low-flow index (Smakhtin, 2001); in this study, we used 70% of the time as the low flow index. Then, changes in the values of high and low flow from the different simulation scenarios were compared to the 100% forest cover scenario in order to calculate relative changes.

Low-flow indices (Q90 and 7Q10) were obtained using a regional regression approach for the State of São Paulo (see Liazi et al., 1988 and Wolff et al., 2014). Thus, based on these indices, it is possible to assess the proportion of forest plantation cover under which the low flows are kept above such indices. Forest plantation effects on streamflow were estimated by comparing simulated FDCs with low-flow indices.

3. Results

3.1. Model calibration and simulated forest cover scenarios

Observed and simulated data indicated a good agreement during calibration (NSE = 0.92). All water years presented efficiency coefficient values greater than 0.8, which is consistent with results from previous studies (e.g., Zhang et al., 2012). Based on these analyses, the model was considered an acceptable simulation.

Predicted FDCs differ in slope and shape between the different forest cover scenarios (Fig. 3).

Flow indices obtained from a regional regression approach were 0.41 mm for 7Q10 and 0.51 mm for Q90. The FDC from the simulated 0% forest cover scenario remained above both 7Q10 and Q90 indices for all periods. This was not the case for the FDCs of the 50%, 70% and 100% forest cover simulations that remained below the low flow indices for different periods of time (Fig. 3).

Forest loss correlated directly with increasing total discharge, as shown in the FDCs (Fig. 3). For example, with 0% forest cover, the increase was approximately 90% (1610.7 mm) relative to the 100% forest cover scenario. The 70% and 50% forest cover simulations, in turn, generated relatively smaller increases in total streamflow of 27% (483.6 mm) and 45% (805.6 mm), respectively.

Considering low flows (70% of time), the 100% forest cover scenario resulted in a 12.36 mm streamflow. The 0% forest cover scenario produced streamflow increases of 91% (112 mm) relative to the 100% forest cover scenario. For 70% and 50% forest cover, the values of low-flow increased 27% (3.4 mm) and 45% (5.6 mm), respectively, relative to 100% forest cover (see Fig. 3).

3.2. Downstream water availability

Comparing our simulated flow values with the reference indices, we found a direct relationship between water use and the proportion of forest cover. Our results indicated that under 100% forest cover, daily flows values were below the reference low-flow

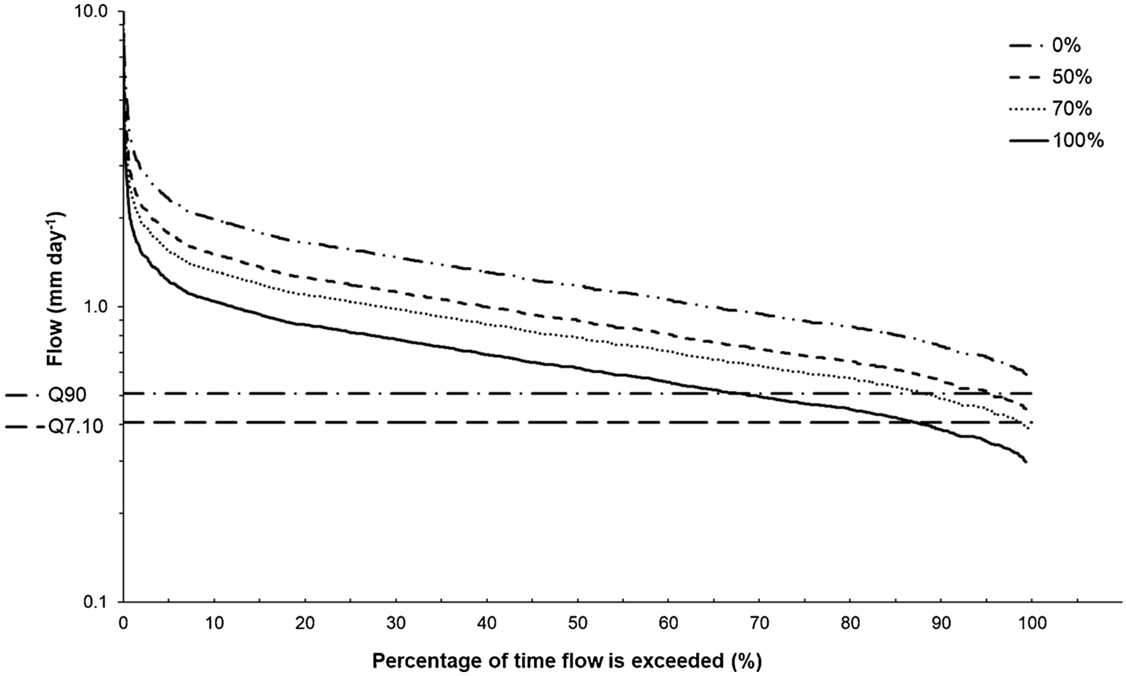

Fig. 3. Flow duration curves for simulated scenarios (70%, 50% and 0% forest cover) and observed data (100% forest cover). Horizontal lines represent low flow indices Q90 and 7Q10.

indices 13% and 31% of the time for 7Q10 and Q90, respectively (Fig. 3). In other words, our results indicate a water use of 21.1 and 79.2 mm higher than 7Q10 and Q90, respectively, resulting in lower water availability for downstream water users.

In the 70% forest cover scenario, most of the daily flows were higher than 7Q10 (only 1% of the time were below this threshold). In addition, daily streamflow was lower than Q90 11% of the time (or 17.1 mm).

As for the 50% forest cover simulation, all daily streamflow values were higher than 7Q10, and only 4% of the time were the values lower than Q90 (4.1 mm of water use above Q90).

4. Discussion

4.1. Flow duration curve changes related to forest cover

The relationship between changes in simulated forest cover proportions and variations in FDCs is in line with previously reported effects of land use change on streamflow dynamics (Bosch and Hewlett, 1982; Sikka et al., 2003; Brown et al., 2013). That is, our results showed an increase in annual streamflow for all simulations that decreased forest cover. These results are in line with previous studies that have also found that a decrease in forest cover results in an annual flow increase (Stednick, 1996; Brown et al., 2005; Guzha et al., 2018). This increase is associated with a decrease in evapotranspiration(Hewlett and Hibbert, 1967; Burt and Swank, 1992), and it could be more evident at short-rotation forest plantations since they have higher evapotranspiration rates (Lima et al., 2012a; Gonçalves et al., 2013).

Taking low-flow indices into account, the 0% forest cover results (increases of 60% relative to the 100% forest cover scenario) are in accordance with studies that assessed increases in streamflow following reductions in forest cover in temperate regions (Hornbeck et al., 1993; Brown et al., 2005) and in tropical regions (Guzha et al., 2018).

4.2. Downstream water availability

In the 100% forest cover scenario, streamflow spends the highest percentage of time below the low-flow indices as a result of higher evapotranspiration rates when the catchment is entirely under forest. Consequently, less water is available for downstream water users.

The results presented here were obtained in a region with a mean annual rainfall of 1300 mm (Alvares et al., 2013). In regions with lower mean annual precipitation or in regions with a precipitation deficiency expected from climate change (e.g., southwestern Europe, Africa, and the USA) (Payn et al., 2015), it is possible that the effect of forest plantations on streamflow might be more severe (Farley et al., 2005; van Dijk and Keenan, 2007; Lima et al., 2012a, 2012b). For regions with high annual rainfall levels, the probability of flow falling below the low-flow reference indices is reduced, although it is still very likely to occur (Keenan and van Dijk, 2010) as forest plantation water use also depends on the occurrence of rainfall (Carvalho et al., 2016).

Our simulations indicate that a forest mosaic (i.e., different proportions of forest cover within the catchment area) has a lower impact on streamflow because of differences in evapotranspiration rates between forest and non-forest-areas, as evidenced in the work of Zhang et al. (2001).

The search for hydrosolidarity forest management strategies (Lima et al., 2012a, 2012b) has increasing importance for forest plantations since conflicts of water use are being debated and climatic scenarios of reduced rainfall could exacerbate this problem (van Dijk and Keenan 2007). For instance, in years with precipitation levels lower than the average (e.g., drought in Sao Paulo state, 2014 Coelho et al., 2016a, 2016b), low flow values could be lower than the low flow indices, increasing water-use conflicts (Calder, 2007; Lima et al., 2012a, 2012b).

If the area of fast-growing forest relative to the total catchment area is known, it is possible to predict and avoid water use conflicts and to guide management practices and policies that contribute to water conservation (Farley et al., 2005). In this paper, it is a notable finding that varying the type of forest cover in different areas of the catchment (as a consequence of deliberate forest occupation planning) includes forest management practices that may have positive impacts on diminishing conflicts concerning water use at the catchment scale.

4.3. Management strategies

Fast-growing forest plantations are characterized by management strategies aimed at increasing production on short rotations. However, since the sustainability of forest plantations is demanded by both society and government (Alexandra and Campbell, 2003; Payn et al., 2015), several studies have highlighted management strategies that promote soil conservation and water quality sustainability (Ullrich and Volk, 2009; Her et al., 2016).

Following this discussion, our objective is to promote water availability at the catchment scale as the main objective of management strategies for the sustainability of fast-growing forest plantations.

Our results show that the proportion of forest cover at the catchment scale could be used to avoid water-use conflicts. We propose to use low-flow indices as a tool to create a threshold for water availability. Therefore, management strategies should be used to limit forest cover effects on streamflow, keeping low-flow above low-flow indices.

Although native vegetation differs from fast-growing forest plantations, including by water consumption (Ferraz et al., 2013), planning the land use/land cover of a catchment must include the native vegetation cover proportion. In Brazil, native vegetation covers approximately 30% of private land (Sparovek et al., 2010) and is correlated with the evapotranspiration rates of the catchment (Ferraz et al., 2013). The other 70% of the catchment area could be used for production and to mitigate forest plantation effects on streamflow via alternative management strategies.

Therefore, mosaic land use at the catchment scale (e.g., forest plantation and native vegetation, forest plantation and cultures with different evapotranspiration rates, or areas with no cultures) could be used as a management strategy to enhance water availability in forest plantations (Ferraz et al., 2013).

On the other hand, water availability is strongly related to rainfall (Brown et al., 2005; Lane et al., 2005). In non-water-limited regions, water-use conflicts could be less pronounced, and hence, increases in forest cover proportion at the catchment scale could be suitable. However, dry seasons and drought should be taken into consideration for this decision (Coelho et al., 2016b). Special attention should be taken in water-limited regions in which water availability could be drastically reduced by dry seasons and drought (Pinheiro et al., 2017). Water availability issues in these regions could be avoided if management strategies were used to mitigate the effects of fast-growing forest on water yield.

To reduce the effects of forest plantations on streamflow, some countries are using strategies which limit expansion to manage the hydrological effects of forest plantations (Dye and Versfeld, 2007; Greenwood, 2013). In Brazil, the amount of forest plantation is not limited, despite expansions in water-limited regions and water-use conflicts with downstream users (Ferraz et al., 2013). Management strategies such as those discussed here should be adopted to avoid future policies that could limit the expansion of fast-growing forest plantations in Brazil. For example, employing mosaic land use and planning the forest cover proportion (plantation and native vegetation) in a catchment can be a strategy for conciliation of conservation and production needs in the same area. When some catchment areas are used for production (fast-growing forest plantation), other catchment areas could be used to increase water availability for downstream users. We can then utilize a land-sharing strategy to conciliate conservation and production at the catchment scale.

However, forest management practices - with respect to forest harvesting and planting - could be economically unfeasible at the catchment scale. Scale issues were discussed in previous studies (Zhang et al., 2003, 2017; Brown et al., 2007), and the effects on water resources are higher at the local scale (catchment) than at the regional scale (landscape) (van Dijk et al., 2007). Although forest management planning has been conducted at the landscape scale due to the large areas covered with forest, it should be noted that water conservation decisions must be made at the catchment scale since, at this local scale, the effects of forest cover are more relevant (van Dijk et al., 2007). Planning water use on the catchment scale is a challenge to decision makers.

This paper highlights the importance of controlling forest cover proportion as a management strategy for mitigating conflicts between water users in the same catchment. Based on our results, management strategies concerned with forest cover proportion and water management planning on the catchment scale should be used for water regulation, especially in water-limited-regions.

5. Conclusion

The lack of hydrological forest planning can lead to water conflicts involving local populations and the forestry sector, mainly as a result of decreases in low flow. In this context, it is possible to conclude that planning the amount of forest at the catchment scale could be used as a management strategy to reduce the effects of plantations on streamflow. Furthermore, with the use of low-flow indices, it is possible to define forest cover thresholds for attenuating plantation effects and water availability to downstream water use. Thus, low-flow indices can be used as a reference to guide forest management planning in mitigating water conflicts.

Conflict of interest

None.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ejrh.2018.06.007.

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