Hindawi Publishing Corporation
International Journal of Forestry Research
Volume 2012, Article ID 908465, 8 pages
doi:10.1155/2012/908465

Research Article

Forest Plantations and Water Consumption: A Strategy for Hydrosolidarity

W. P. Lima,[1] R. Laprovitera,[2] S. F. B. Ferraz,[1] C. B. Rodrigues,[3] and M. M. Silva[4]

[1] *Department of Forest Science, University of São Paulo, 13400-970 Piracicaba, SP, Brazil*
[2] *International Paper do Brasil, Forest Management and Sustainability System, 13840-970 Mogi Guaçu, SP, Brazil*
[3] *Institute of Forest Research and Studies (IPEF), Catchment Monitoring Program (PROMAB), 13400-970 Piracicaba, SP, Brazil*
[4] *Department of Forest Science, Laboratory of Forest Hydrology, University of São Paulo, 13400-970 Piracicaba, SP, Brazil*

Correspondence should be addressed to W. P. Lima, wplima@usp.br

Received 11 July 2011; Revised 13 October 2011; Accepted 21 November 2011

Academic Editor: John Sessions

A case study of a deliberate change in the design of a new Eucalyptus plantation, aimed at alleviating water impacts, was carried out in an experimental catchment located in the center part of the State of São Paulo, Brazil. It involved the identification of saturated areas in the catchment, based essentially on topographic analysis, as a tool to help in zoning of the new forest plantation, with the objective of improving the flow of water to downstream users, as well as to avoid water quality changes. The design involved the allocation of part of the identified saturated areas as water conservation areas, as well as a change in the spacing of the planting. Measurements of tree growth at the age of two years of the new plantation reveal that the forest productivity of the new plantation design, in terms of projected annual wood increment at the end of the rotation, will be similar to the old plantation scheme, despite the loss of planted area. Preliminary results of the continuous monitoring of the catchment water balance appear to indicate that the objective of increasing the catchment water yield may possibly also be achieved.

1. Introduction

Awareness about the need to consider watershed management as a tool for the development of forest plantations management strategies that focus on both forest productivity and environmental and social benefits, mainly in terms of maintaining water supply and water quality to downstream users, is increasing.

This hydrosolidary management strategy [1], of course, is driven by the mounting evidence about the hydrological effects of forest plantations, which show that in many situations they can decrease surface water generation and groundwater recharge [2, 3]. It is also a necessary change in management strategy in response to the growing water scarcity [4]. But most importantly, it is also a strategy that derives from the need to devise forest plantation management plans that are based on the concept of adaptive management, that is, a plan that is focused on forest productivity, but also takes into account the site specificities and terrain conditions, as well as the social interests in the landscape, in a process of continuous learning and improving [5].

Available evidence is indicating that plantation forestry may have specific hydrological characteristics that are related to the fast rate of growth of the species used, with corresponding high water consumption, and the short rotation period of the forest stands, which does not permit the catchment water balance to achieve hydrologic stability as the forest cover ages [6, 7]. Catchment scale plantation evapotranspiration tends to increase with mean annual precipitation and can be from about 100 to 250 mm higher than grassed catchments for annual rainfalls of 1000 to 1500 mm, respectively [8, 9]. Available results of hydrological studies of forest plantations in Brazil [10], in terms of evapotranspiration and catchment water balance, are indicating that in some parts of the country the catchment scale plantation evapotranspiration will not differ from the climatic mean, whilst in another conditions it may be higher and quantitatively similar to the values estimated by Zhang et al. [9].

Clearly, these results show that there is no reason to expect that forest plantations are always inherently bad to the water, or that they would produce hydrological effects of the same magnitude in all situations. Instead, these results show that the control of water impacts is very much dependent on the implementation of sustainable strategies of forest plantation management.

For example, considering the different climatic conditions, in water-limited regions the potential reduction of water resources caused by forest plantations is smaller, in absolute terms, than in wetter regions, but the impact can be socially more damaging due to the already scarce water availability [11]. And for a given climatic condition, several options are available for devising sustainable forest management strategies in order to control or minimize the potential water impacts, involving terrain conditions, planting arrangement, species physiology, water use efficiency, variation in stand age, spacing, site productivity, forestry operations, percentage of catchment area planted, and so forth [2, 8, 12–14]. Invariably, all of them are very much dependent on the foremost assumption that the management plan must be based on the catchment, for the catchment is the natural scale of the water in the landscape and, from the standpoint of hydrosolidarity, the most important indicator of the potential hydrological effects of forest plantations is the catchment water balance [1, 4, 15, 16].

The location and spatial arrangement of the plantations within the catchment can influence streamflow generation. There is evidence that the magnitude of this influence is proportional to the fraction of the area planted [8, 17]. On the other hand, water tends to accumulate in the lower parts of the catchments, where the water table is also close to the surface. Trees located in these saturated areas present outstanding growth rate, as compared to those growing in the upper parts of the catchment and early studies demonstrated that the removal of these riparian vegetation increased catchment water yield [18]. Therefore, keeping the plantations away from these saturated areas will contribute to maintain the flow of blue water downstream [1], being thus a recommended management practice of water conservation and also a common land use policy in many countries. In Brazil, for instance, these areas closed to the streams, limited to a fixed 30 m strip in both sides of the stream, as well as along a radius of 50 m of the spring in the catchment headwater, are legally protected. However, saturated areas do not occur linearly and it may thus be that in many situations these fixed limits will not be enough to achieve the purported objectives of water protection.

The knowledge of the functioning of these saturated areas, which can occur wherever the soil's capacity to store water is exceeded, was developed from the early concept of Variable Source Area [19–23], which was useful in explaining streamflow generation in forested catchments in response to rainfall, in contrast with the old established Hortonian concept of overland flow generation [24]. The core of the variable source area concept is a combination of two processes that occur during rainfall: slope soil water movement and channel expansion [21, 25, 26]. Rain falling on the saturated areas of the catchment runs off as saturated overland flow. For the same reason, these areas are also a potential source of contaminants that may impair water quality [27, 28]. Because of that, it is important that these areas be protected by their natural vegetation, in order to preserve its hydrological functioning and prevent catchment degradation [29, 30]. Therefore, it is most important to determine the location of these saturated areas of a catchment, to help in zoning of the forest plantation design, which will contribute to improve the flow of water downstream, as well as to avoid water quality changes and catchment degradation.

Figure 1: Location of the Aguaí experimental catchment in the State of São Paulo, Brazil.

In this paper, we describe a case study of a deliberate change in the design of a new Eucalyptus plantation in an experimental catchment located in the center part of the State of São Paulo, Brazil, with the objective of keeping the Eucalypt trees away from identified saturated areas of the catchment, other than the legally required strip along the stream and headwater.

2. The Study Area

The experimental catchment is part of the PROMAB, a cooperative research program of hydrologic monitoring of forest plantations of IPEF, Institute of Forest Research and Studies, under the coordination of the Forest Hydrology Laboratory of the Forest Science Department of the University of São Paulo. This cooperative program comprises presently 20 experimental catchments in several parts of Brazil. Some of these catchments were installed as a paired catchments project, while most of them follows the single catchment approach, as is the case of the study catchment, which was installed as an experimental catchment for the monitoring program in January 2002.

The experimental catchment is located at International Paper forestland in the municipality of Aguaí, State of São Paulo (22°06′10″S/40°53′25″W) (Figure 1). The catchment has an area of 75.2 ha. Eucalyptus plantations occupy about 61% of the catchment total area. 37% of the remaining area is covered with native vegetation, while forest roads comprise 1.5%.

In terms of soils, Folic Cambisol comprises 72% and Red Podzolic soil comprises 21% of the total catchment area. Both these soils are relatively shallow, with an overall depth not greater than 40 cm, in direct contact with the limestone parent material. Therefore, around 93% of the catchment area is comprised of shallow soils, and such conditions are reflected in the hydrological functioning of the catchment, which is characterized by flashy hydrological response to rainfall events and an intermittent stream flow regime. Usually, stream flows from October through June, as a reflection of the rainy season of the region (October through March). In general, there is no streamflow during the months of July, August, and September.

The Eucalyptus plantation (hybrid of *E. urophylla* and *E. grandis*) was planted in 2000, at a spacing of 3.00 × 2.75 m and was clearfelled in 2007. After the harvesting, besides the exclusion from planting of some of the identified saturated areas, other than the legally prescribed, a new plantation with hybrid of the same species but different clone was established in 2008 in the catchment, at a spacing of 6.00 × 1.40 m. It is expected that this new spacing design will compensate for the loss of planted area, and, hopefully, also for water conservation, because of the possible hydrological effects of the new plantation architecture [14].

3. Methods

The hydrological monitoring of this catchment involves the continuous measurement of precipitation, with a recording rain gauge, and discharge, with the use of a stream gauging station with a mixed triangular and rectangular weir, in which water stage is continuously measured by an electronic device, at a 15 min interval.

Routine field observations indicated the occurrence of wet areas outside the legally protected strip of 30 m of the stream channel (see Figure 3), which prompted a study aiming at the identification and mapping of the saturated areas in the catchment, which was carried out before the clearfelling of the Eucalyptus plantation in 2007.

Catchment limits were handily defined using topographical maps (scale 1 : 10,000, IGC/SP 1979) and digitized on screen. Contours, elevation points, and stream lines were digitized and a digital elevation model (DEM) was generated based on 5 m interval contour lines by the algorithm TOPO to RASTER. These procedures were conducted in ArcGis 9.2 [31], adopting the UTM coordinate system, zone 23S, and datum Córrego Alegre.

The identification of the saturated areas was basically done by topographic analysis [22] using the Topographic Index (TI) as a proxy of Variable Source Areas (VSA), and it was used to identify the saturation probability [32–34]. This index represents a physical parameter easily calculated, based on elevation and soil data of the area. Thus, TI could be calculated using hydrological models on most common Geographic Information Systems (GIS) [35].

Topographic index has been successfully used to estimate saturation probability in several studies [34–36]. Notwithstanding the better performance of dynamic models for the prediction of saturation areas, topographic index was able to reach 86% of model effectiveness [34]. However, the use of TI requires some assumptions: steady-state flow, uniform recharge rates, absence of unsaturated lateral flow, subsurface lateral flow, subsurface relief similar to surface relief and hydraulic conductivity exponential and equal over the area [36]. The study catchment appears to attend most of these assumptions, mainly because of the uniformity and shallowness of the two prevailing soils and absence of significant subsurface water storage. These conditions indicate that the main factor governing the movement of surface water is topography.

The topographic index was calculated considering the equation proposed by Beven and Kirkby [37] and also proposed as proxy of saturated areas [35]:

$$\lambda = \ln\left(\frac{\alpha}{\tan(\beta) \cdot K_s \cdot D}\right), \tag{1}$$

where λ is topographic index ($\ln(\mathrm{d} \cdot \mathrm{m}^{-1})$); α is upslope pixel contribution area (m^2); β is local surface topographic slope (radians); K_s is mean saturated hydraulic conductivity of the soil ($\mathrm{m} \cdot \mathrm{d}^{-1}$); D: soil depth (m).

The components α and β were calculated directly on ArcGIS, using a filled DEM as source. For accumulated contribution area (α), a multiple flow direction [38] was used, since it presents better performance than 8-direction flow [34]. Since the catchment soils are predominantly homogenous (72% of Cambisols plus 21% of Red Podzolic soil), K_s was considered as constant over the area. Again taking into account the soils conditions, soil depth was estimated using the methodology proposed by Rennó et al. [39]. Following Aryal and Bates [33], the minimum possible resolution was used according to the original contour maps scale 5 meters. This resolution was also tested by Sorensen and Seibert [40], with good results on the mapping of saturated areas.

Topographic index results in a range of values that is correlated to saturation probability [35]. However, saturation probability varies along the year, according to precipitation regime and amount. Therefore, in order to define a threshold value, some selected hydrographs of the period prior to the clearfelling and for the period after clearfelling were used for stormflow analysis and estimation of the relation between rainfall and stormflow. The separation of direct flow and base flow was made using the procedure developed by Hewlett and Hibbert [20]. An example of the selected hydrographs that were analyzed is given in Figure 2 and the summarized results of such analysis is given in Table 1. As given in this table, we considered that, on average, 12% of typical rainfall becomes stormflow and this percentage was used to define a threshold, also considering that saturated areas are the main sources that contribute to stormflow in forested catchments [20]. In order to establish a threshold to identify saturated areas, TI values obtained for each pixel were sorted and we selected the highest values that represent 12% of the catchment area.

4. Results and Discussion

The results of the identification of saturated areas of the study catchment are presented in Figure 3. Most of the saturated areas occur near the stream channel and large patches are concentrated around the spring in the catchment headwaters,

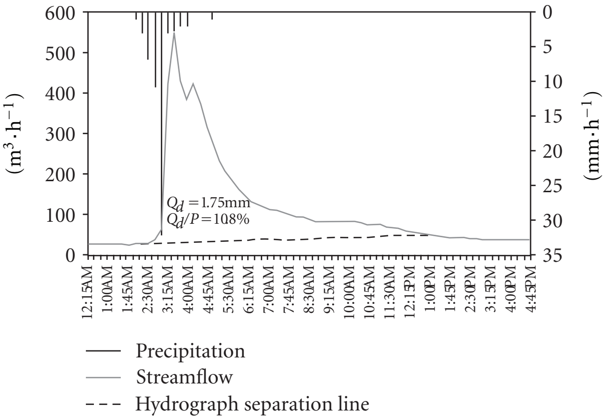


FIGURE 2: The relation between rainfall and stormflow for a typical selected hydrograph. Qd: direct flow; Qd/P: hydrologic response in terms of percentage o direct flow and precipitation.

TABLE 1: Summarized results of the analysis of rainfall-storm flow of selected hydrographs for the period prior to the clear felling of the old Eucalyptus plantation (Mature forest) and after the clear felling (Young plantation).

		Precipitation (mm)	Ratio (%)
7 yr old	Jan/03/2008	21.1	1.5
	Jan/17/2008	12.2	1.2
	Jan/19/2008	34.0	17.5
	Feb/03/2008	30.0	16.4
	Average	24.3	9.1
Young plantation	Jan/28/2009	21.6	31.7
	Mar/11/2009	16.2	10.8
	Apr/05/2009	32.8	10.7
	Jun/27/2009	16.8	2.5
	Average	21.8	13.9

which is in agreement with the protection of these areas. Also, it is possible to observe some strips of saturated areas in the northeast portion of the catchment, probably representing intermittent channels that flow in precipitation events. As can be seen in this figure, the legally protected area with a fixed strip around the streams, as determined by the Brazilian Law, is not always enough to protect all saturated areas of a catchment. In some cases, this may create situations where areas of the catchment that could be planted are set aside as protection areas, whilst other areas, hydrologically critical, are free to be planted. Because of that, it may be difficult to establish an ideal catchment management strategy without compromising the main economical objective of forest production. In this case, for instance, the area incorporated as water protection area in the new planting design indeed included part of the identified saturated areas of the catchment, but not all of them, and this had to do with other operational constraints, forest road design, harvesting planning, and so forth.

Nevertheless, this new planting scheme, besides protecting part of the hydrologically critical areas, also decreased the percentage of the catchment area under plantation, which is also a management strategy for water conservation. To illustrate the changes that occurred in the catchment, Figure 4 gives a scaled representation of the areas with plantation, the area legally protected by the Brazilian Forest Code (APP), the identified saturated areas, and the proportion of these saturated areas that has been incorporated as protected areas. As given in this figure, the effective planting area decreased from 72% to 54% of the total area of the catchment. On the other hand, protected areas increased from 21% to 41%. This increase was a result of the incorporation of 13% of the catchment area as a deliberate expansion of the "APP" protected area, and 7% corresponding to the new area incorporated as protected area. With this change in land use, the saturated area under protection increased from 58% to 72%.

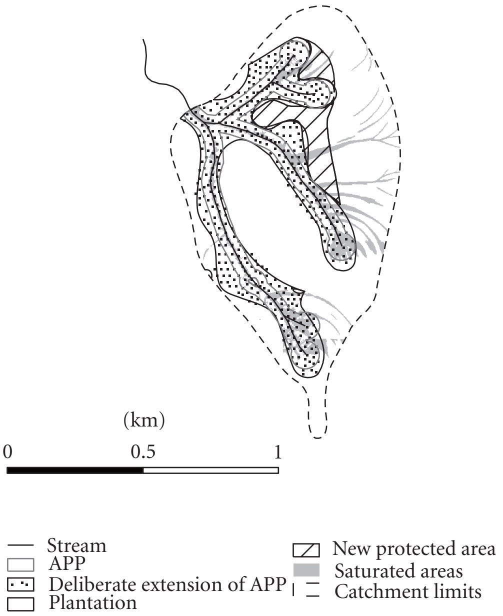


FIGURE 3: Map of the experimental catchment showing the identified hydrologically sensitive areas.

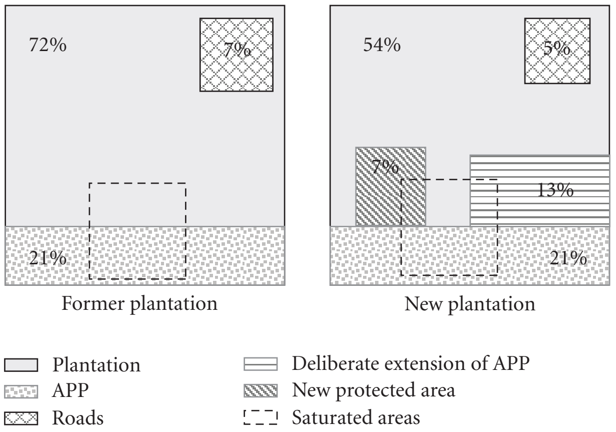


FIGURE 4: Scaled schematic representation of the catchment land use in the former in comparison with the new planting design.

Figure 5: Evidence of hydrologically sensitive area being occupied by the former Eucalyptus plantation in the study catchment.

It is interesting to observe that in this catchment a large proportion of the saturated areas is located in middle slopes, farther from the edges of the intermediate tributary, as well as in the headwaters of the right tributary, and they were under Eucalyptus plantation during the former rotation. Figure 5 shows a field observation of saturated area located in the center part of the new protected area, attested by the green understory grass and accumulated water in the surface. As mentioned before, this area is probably an intermittent channel that concentrates flow in precipitation events. In this case, it is possible to observe that unprotected saturated areas may cause many operational problems like soil compaction, erosion, and road maintenance.

The changes occurred in the catchment, in terms of planted area, saturated areas, area occupied by forest roads, trees height, trees DBH, stand volume, and projected average annual increment, comparatively between the former plantation and the new plantation design, are summarized in Table 2.

An illustration of the comparative DBH classes distribution between the former and the new plantation design can be seen in Figure 6. It can be seen that the new plantation design appear to be growing more uniformly, with concentration of most trees in the central classes of DBH, at the age of 2 years.

Table 2: Comparative values of the changes occurred in the experimental catchment, in terms of planted area, water conservation area, area of forest roads, fertilizer consumption, average stand height, DBH and volume, at the age of 2 years, and projected average annual increment of wood at the end of the rotation period (7 years), also based on the parameters measured at the age of 2 years, pulp production and tons of pulp per hectare, between the former plantation and the new plantation design.

Parameter	Former plantation	New plantation
Planted area (ha)	49	45
Protected areas (ha)	24.84	29.98
Forest roads area (ha)	5	4
Fertilizer consumption (ton$\cdot$ha^{-1})	370	345
Average stand height at the age of 2 yr (m)	11.98	11.66
Average stand d.b.h. at the age of 2 yr (cm)	9.71	8.97
Average stand volume (m^3)	48.05	43.64
Average annual increment (m$^3\cdot$ha$^{-1}\cdot$year^{-1})	39.73	38.34
Pulp production (ton)	3,370	3,124
Tons of pulp per hectare	67.5	70.8

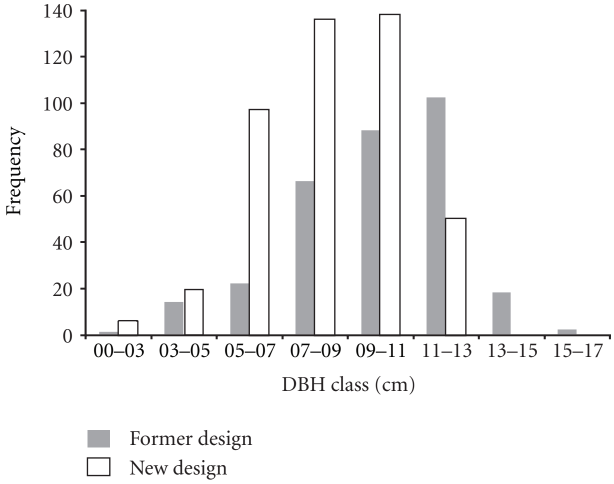


Figure 6: Comparative distribution of the DBH classes between the old and the new plantation design.

The results of the field measurements of the comparative growth of the former and the new plantation in the study catchment, at the age of two years of both plantations, as well as the projected average annual increment of wood at the end of the rotation period of the new planting (7 years), given in Table 2, show clearly that it is possible to develop new forest management designs, aimed, of course, at the primary objective of maintaining plantation productivity, but now imbedded with water conservation values, when the management plan is focused on the catchment. In the present study, this water conservation value strategy was based on the protection of hydrologically critical saturated areas of the catchment, which is intended to increase the flow of water to downstream users, and on a different design of the new planting, which intends to result in increased net precipitation, by reducing interception losses [41, 42] and decreasing percentage of the occupation of the catchment area by the new plantation, which is related to a decrease in water consumption [2]. On the long run, these changes together will probably result in a more conservative catchment water balance. This is equivalent to a more equitable distribution of the income rainfall between green water (evapotranspiration) and blue water (streamflow), which attends the social objective of hydrosolidary management of plantation forests.

Table 3 summarizes the results of the hydrologic monitoring of the study catchment, with the annual values of the catchment water balance, comparatively between the period of monitoring of the former plantation with the period of

Table 3: Comparative results of the measurements of the study catchment water balance between the former Eucalyptus plantation (2002–2008) and the first two years of the new plantation (2008–2010). The water year runs from August through September. P: annual precipitation. Q: annual water yield. ET: catchment scale evapotranspiration.

Water year	P (mm)	Q (mm)	ET (mm)
2002-2003	1150	206	943
2003-2004(*)	—	—	—
2004-2005	1202	225	978
2005-2006	1276	146	1130
2006-2007	1310	219	1091
2007-2008(**)	1601	237	1364
Average for the period	1308	207	1101
2008-2009	1553	313	1240
2009-2010	1716	767	949
2010-2011	1537	420	1107
Average for the period	1602	500	1099

(*) Data from this water year was dropped because of electronic equipment failure. (**) The harvesting of the former plantation was carried out in July (dry season) of 2008, immediately followed by the new planting.

monitoring of the first three years of the new plantation design.

For comparison, the 30-year mean climatic water balance for the region where the study catchment is located is as follows: precipitation = 1346 mm; potential evapotranspiration = 1026 mm; actual evapotranspiration = 946 mm; water surplus = 400 mm. As can be seen, the average catchment water balance is very similar to the climatic mean. As expected, the catchment scale evapotranspiration is higher than the mean climatic actual evapotranspiration, as a result of the plantation growth. Nevertheless, in this case the average value of the relation of catchment scale evapotranspiration and precipitation is around 80%. In some situations, this can be as high as 95% [43].

The results of Table 3, of course, should not be taken as indication of the hydrological effects of the new planting scheme, since there are only three years of the new plantation, and also because the annual precipitation of these three years was greater than the historical mean, which could be part of the increase in the catchment water yield. It should also be considered that the new plantation scheme is still in the early stage, meaning that the water demand during this early stage may be lower [3]. Nevertheless, the comparison of the water balance of the last year of the former period with the average of the new period shows that the annual precipitation is about the same, whilst catchment water yield is about 300 mm higher, and this may be a result of the increase in the protection of the catchment saturated critical areas.

The comparative results of catchment water balance of forest plantation in different parts of Brazil given by Lima [10] show that the region where the study catchment is located is characterized by a climatic water balance that lies between the balance observed in the drier northeast region of the country, with very low water surplus (less that 100 mm), and the wetter southern region, where the climatic water balance is characterized by large water surplus (over 700 mm). Therefore, the greater evapotranspiration of forest plantations evidenced in experimental catchment studies, as compared to lower vegetation, could result in a decrease of the already low water surplus in the study region. Thus, management strategies that are intended to water conservation, such as the ones described in the present study, may decrease possible water impacts and therefore be more hydrologically sustainable.

The search for sustainable forestry, through adaptive management, involves processual changes, innovation, continuous improvement, and continuous learning guided by monitoring results.

5. Conclusion

Evidence indicates that forest plantations, because of their fast rate of growth, present higher water consumption, as compared to other vegetation. The magnitude of the possible impacts of this higher water consumption is very much depended on the interaction with local climatic and soil conditions. Where needed, management strategies can be devised to alleviate water impacts. Plantation design, in terms of spacing and percentage of occupation of the catchment area, as well as deliberate inclusion of hydrologically critical areas of the catchment as water protection areas appear to produce encouraging results. The Brazilian Forest Code indeed contributes for this objective of hydrosolidarity, in the sense of increased flow of water to downstream users. However, as shown in this study, the legally protected areas are not always enough to encompass the entire range of the catchment saturated areas.

References

[1] M. Falkenmark and C. Folke, “The ethics of socio-ecohydrological catchment management: towards hydrosolidarity,” *Hydrology and Earth System Sciences*, vol. 6, no. 1, pp. 1–9, 2002.

[2] A. I. J. M. van Dijk and R. J. Keenan, “Planted forests and water in perspective,” *Forest Ecology and Management*, vol. 251, no. 1-2, pp. 1–9, 2007.

[3] J. A. Rodríguez-Suárez, B. Soto, R. Perez, and F. Diaz-Fierros, "Influence of *Eucalyptus globulus* plantation growth on water table levels and low flows in a small catchment," *Journal of Hydrology*, vol. 396, no. 3-4, pp. 321–326, 2011.

[4] N. Johnson, C. Revenga, and J. Echeverria, "Managing water for people and nature," *Science*, vol. 292, no. 5519, pp. 1071–1072, 2001.

[5] D. Ludwig, "The era of management is over," *Ecosystems*, vol. 4, no. 8, pp. 758–764, 2001.

[6] D. F. Scott, "On the hydrology of industrial timber plantations," *Hydrological Processes*, vol. 19, no. 20, pp. 4203–4206, 2005.

[7] G. Kuczera, "Prediction of water yield reductions following a bushfire in ash-mixed species eucalypt forest," *Journal of Hydrology*, vol. 94, no. 3-4, pp. 215–236, 1987.

[8] R. A. Vertessy, "Impacts of plantation forestry on catchment runoff," in *Plantations, Farm Forestry and Water*, E. K. S. Nambiar and A. G. Brown, Eds., no. 01/20, pp. 9–19, RIRDC, Barton, Australia, 2000.

[9] L. Zhang, W. R. Dawes, and G. R. Walker, "Response of mean annual evapotranspiration to vegetation changes at catchment scale," *Water Resources Research*, vol. 37, no. 3, pp. 701–708, 2001.

[10] W. P. Lima, *Plantation Forestry and Water: Science, Dogmas, Challenges. Writings of the Dialogue*, Instituto BioAtlântica, Rio de Janeiro, Brazil, 2011.

[11] K. A. Farley, E. G. Jobbagy, and R. B. Jackson, "Effects of afforestation on water yield: a global synthesis with implications for policy," *Global Change Biology*, vol. 11, no. 10, pp. 1565–1576, 2005.

[12] B. W. Olbrich, D. le Roux, A. G. Poulter, W. J. Bond, and W. D. Stock, "Variation in water use efficiency and δ^{13} levels in *Eucalyptus grandis* clones," *Journal of Hydrology*, vol. 150, no. 2–4, pp. 615–633, 1993.

[13] D. A. White, C. L. Beadle, M. Battaglia, R. G. Benyon, F. X. Dunin, and J. L. Medhurst, "A physiological basis for management of water use by tree crops," in *Plantations, Farm Forestry and Water*, E. K. S. Nambiar and A. G. Brown, Eds., no. 01/20, pp. 20–27, RIRDC, Barton, Australia, 2001.

[14] J. K. Vanclay, "Managing water use from forest plantations," *Forest Ecology and Management*, vol. 257, no. 2, pp. 385–389, 2009.

[15] B. Aylward, "Towards watershed science that matters," *Hydrological Processes*, vol. 19, no. 13, pp. 2643–2647, 2005.

[16] I. R. Calder, "Forests and water: ensuring forest benefits outweigh water costs," *Forest Ecology and Management*, vol. 251, no. 1-2, pp. 110–120, 2007.

[17] J. M. Bosch and J. D. Hewlett, "A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration," *Journal of Hydrology*, vol. 55, no. 1–4, pp. 3–22, 1982.

[18] E. G. Dunford and P. W. Fletcher, "Effect of removal of streambank vegetation upon water yield," *Transactions American Geophysical Union*, vol. 28, no. 1, pp. 105–110, 1947.

[19] J. D. Hewlett and A. R. Hibbert, "Moisture and energy conditions within a sloping soil mass during drainage," *Journal of Geophysical Research*, vol. 68, no. 4, pp. 1081–1087, 1963.

[20] J. D. Hewlett and A. R. Hibbert, "Factors affecting the response of small watersheds to precipitation in humid areas," in *International Symposium on Forest Hydrology*, W. E. Sopper and H. W. Lull, Eds., pp. 275–290, Pergamon Press, New York, NY, USA, 1967.

[21] T. Dunne and R. D. Black, "An experimental investigation of runoff production in permeable soils," *Water Resources Research*, vol. 6, no. 2, pp. 478–490, 1970.

[22] E. M. O'Loughlin, "Prediction of surface saturation zones in natural catchments by topographic analysis," *Water Resources Research*, vol. 22, no. 5, pp. 794–804, 1986.

[23] K. Bishop, I. Buffam, M. Erlandsson et al., "*Aqua Incognita*: the unknown headwaters," *Hydrological Processes*, vol. 22, no. 8, pp. 1239–1242, 2008.

[24] R. E. Horton, "The role of infiltration in the hydrologic cycle," *Transactions of the American Geophysical Union*, vol. 14, pp. 446–460, 1933.

[25] T. Dunne and R. D. Black, "Partial area contributions to storm runoff in a small New England watershed," *Water Resources Research*, vol. 6, no. 5, pp. 1296–1311, 1970.

[26] T. Dunne, T. R. Moore, and C. H. Taylor, "Recognition and prediction of runoff-producing zones in humid regions," *Hydrological Sciences Bulletin*, vol. 20, no. 3, pp. 305–327, 1975.

[27] E. M. O'Loughlin, "Water pathways through catchments and their relation to nutrient losses," in *Proceedings of the IUFRO Workshop on Water and Nutrient Simulation Models*, pp. 123–134, Birmensdorf, Zurich, Switzerland, 1981.

[28] M. T. Walter, M. F. Walter, E. S. Brooks, T. S. Steenhuis, J. Boll, and K. Weiler, "Hydrologically sensitive areas: variable source area hydrology implications for water quality risk assessment," *Journal of Soil and Water Conservation*, vol. 55, no. 3, pp. 277–284, 2000.

[29] J. L. Fail, B. L. Haines, and R. l. Todd, "Riparian forest communities and their role in nutrient conservation in agriculture watershed," *American Journal of Alternative Agriculture*, vol. 2, no. 3, pp. 114–121, 1987.

[30] S. V. Gregory, F. J. Swanson, W. A. Mckee, and K. W. Cummins, "An ecosystem perspective of riparian zones," *BioScience*, vol. 41, pp. 540–551, 1992.

[31] Environmental Systems Research Institute, *What's New in ArcGIS 9.2. White Paper from ESRI*, ESRI Press, Redlands, Calif, USA, 2006.

[32] X. Cai and D. Wang, "Spatial autocorrelation of topographic index in catchments," *Journal of Hydrology*, vol. 328, no. 3-4, pp. 581–591, 2006.

[33] S. K. Aryal and B. C. Bates, "Effects of catchment discretization on topographic index distributions," *Journal of Hydrology*, vol. 359, no. 1-2, pp. 150–163, 2008.

[34] T. Grabs, J. Seibert, K. Bishop, and H. Laudon, "Modeling spatial patterns of saturated areas: a comparison of the topographic wetness index and a dynamic distributed model," *Journal of Hydrology*, vol. 373, no. 1-2, pp. 15–23, 2009.

[35] L. J. Agnew, S. Lyon, P. Gerard-Marchant et al., "Identifying hydrologically sensitive areas: bridging the gap between science and application," *Journal of Environmental Management*, vol. 78, no. 1, pp. 63–76, 2006.

[36] A. Rodhe and J. Seibert, "Wetland occurrence in relation to topography: a test of topographic indices as moisture indicators," *Agricultural and Forest Meteorology*, vol. 98-99, pp. 325–340, 1999.

[37] K. J. Beven and M. J. Kirkby, "A physically based, variable contributing area model of basin hydrology," *Hydrological Sciences Journal*, vol. 24, no. 1, pp. 43–69, 1979.

[38] D. G. Tarboton, "A new method for the determination of flow directions and upslope areas in grid digital elevation models," *Water Resources Research*, vol. 33, no. 2, pp. 309–319, 1997.

[39] C. D. Rennó, A. D. Nobre, L. A. Cuartas et al., "HAND, a new terrain descriptor using SRTM-DEM: mapping terra-firme rainforest environments in Amazonia," *Remote Sensing of Environment*, vol. 112, no. 9, pp. 3469–3481, 2008.

[40] R. Sorensen and J. Seibert, "Effects of DEM resolution on the calculation of topographical indices: TWI and its components," *Journal of Hydrology*, vol. 347, no. 1-2, pp. 79–89, 2007.

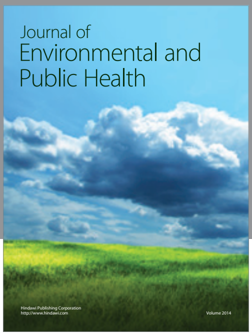
[41] D. Whitehead and E. M. Kelliher, “A canopy water balance model for a *Pinus radiata* stand before and after thinning,” *Agricultural and Forest Meteorology*, vol. 55, no. 1-2, pp. 109–126, 1991.

[42] W. Lesch and D. E. Scott, “The response in water yield to the thinning of *Pinus radiata*, *Pinus patula* and *Eucalyptus grandis* plantations,” *Forest Ecology and Management*, vol. 99, no. 3, pp. 295–307, 1997.

[43] A. C. Almeida, J. V. Soares, J. J. Landsberg, and G. D. Rezende, “Growth and water balance of *Eucalyptus grandis* hybrid plantations in Brazil during a rotation for pulp production,” *Forest Ecology and Management*, vol. 251, no. 1-2, pp. 10–21, 2007.

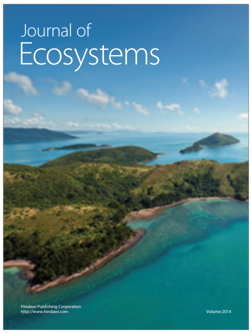

Journal of
Waste Management

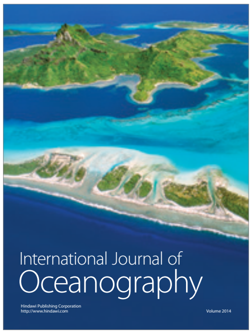

The Scientific World Journal

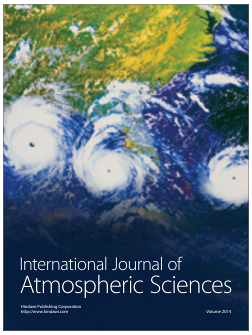

Journal of
Environmental and Public Health


Scientifica


International Journal of
Ecology


Journal of
Ecosystems


International Journal of
Oceanography

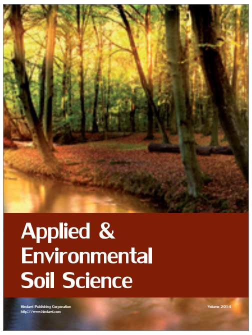

International Journal of
Atmospheric Sciences

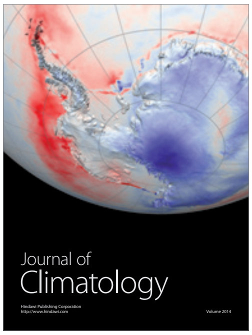

Journal of
Marine Biology

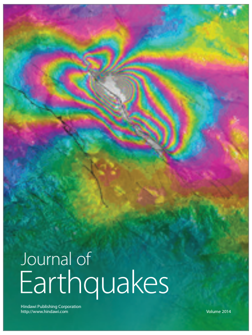

International Journal of
Biodiversity


Journal of
Geological Research


International Journal of
Forestry Research

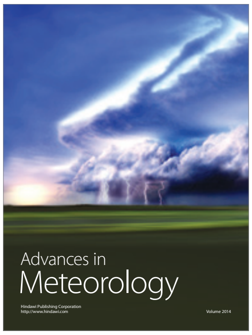

Applied &
Environmental
Soil Science

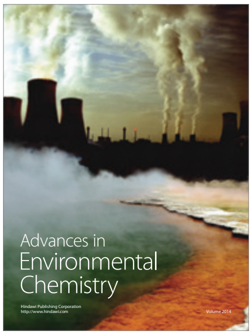

Journal of
Climatology


Journal of
Earthquakes


Journal of
Computational Environmental Sciences


International Journal of
Geophysics


Advances in
Meteorology


Advances in
Environmental Chemistry