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Review Paper

Riparian vegetation and water yield: A synthesis

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SUMMARY

Forested riparian zones perform numerous ecosystem functions, including the following: storing and fixing carbon; serving as wildlife habitats and ecological corridors; stabilizing streambanks; providing shade, organic matter, and food for streams and their biota; retaining sediments and filtering chemicals applied on cultivated/agricultural sites on upslope regions of the catchments. In this paper, we report a synthesis of a different feature of this type of vegetation, which is its effect on water yield. By synthesizing results from studies that used (i) the nested catchment and (ii) the paired catchment approaches, we show that riparian forests decrease water yield on a daily to annual basis. In terms of the treated area increases on average were 1.32 ± 0.85 mm day^{-1} and 483 ± 309 mm yr^{-1}, respectively; $n = 9$. Similarly, riparian forest plantation or regeneration promoted reduced water yield (on average 1.25 ± 0.34 mm day^{-1} and 456 ± 125 mm yr^{-1} on daily and annual basis, respectively, when prorated to the catchment area subjected to treatment; $n = 5$). Although there are substantially fewer paired catchment studies assessing the effect of this vegetation type compared to classical paired catchment studies that manipulate the entire vegetation of small catchments, our results indicate the same trend. Despite the occurrence of many current restoration programs, measurements of the effect on water yield under natural forest restoration conditions are still lacking. We hope that presenting these gaps will encourage the scientific community to enhance the number of observations in these situations as well as produce more data from tropical regions.

Contents

1. Introduction

Riparian vegetation is generally composed of forest but may include other vegetation types such as scrub. These forest ecosystems store and fix carbon, serve as wildlife habitats and ecological corridors, stabilize streambank, provide shade, organic matter and food to the streams and their biota, retain sediment and chemicals (fertilizers and pesticides) applied on the cultivated/agricultural sites on upslope regions of the catchments (Simmons et al., 1992; Groffman et al., 1992; Bren, 1993; Tabacchi et al., 2000; Sparovek et al., 2002; Neill et al., 2006;

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Pollen, 2007; Pires et al., 2009; De Paula et al., 2011; among others).

Based on the outlined ecological functions and perhaps many others, forested riparian zones are widely recognized for their importance. For this reason, riparian zones are being restored in several regions (Bullock et al., 2011; Calmón et al., 2011). Despite this relevance, riparian clearing has also been studied in certain situations for various different purposes (e.g. Dunford and Fletcher, 1947; Dye and Poulter, 1995; Prinsloo and Scott, 1999). These and other ones that planted or regenerated vegetation within riparian zones offer opportunities to understand the effects of removing, planting, and/or regenerating vegetation within riparian zones on various hydrological processes, especially production of water from catchments namely the water yield.

While publications regarding ecological functions of riparian vegetation abound in the literature (e.g. Lovett and Price, 2007), a substantial fewer number of papers have directly dealt with the hydrological effects of this vegetation type on water yield emanating from a catchment.

In this context, in this paper we review the information about this topic in order to synthesize the relationship between riparian forests and water yield at the small catchment scale.

2. Experimental methods applied to examine the effect of riparian vegetation on water yield

Papers on water yield and riparian vegetation have used two methods: (i) the nested catchment and (ii) the paired catchment approaches. We systematically review the scientific literature in English about this subject and attempt to calculate the water gains or losses in millimeters as accurately as possible. As can be seen below, the first method (i) was used to assess riparian vegetation's the role of on water yield in the short term (daily basis results) while the second (ii) was used in the short and long term (annual basis results).

2.1. Results using the nested catchment approach

According to Prinsloo and Scott (1999) this design uses two weirs which are placed in series down a single stream and treatment is confined to the area between the weirs. During the calibration (pretreatment) period of a few days, streamflow on the lower gauge is related to streamflow on the upper (control) gauge. After this period, the riparian vegetation between the two gauging points is removed and streamflow recorded for a post treatment period. As the gauges are in series, changes in streamflow from the treated area can be assessed by comparison with the flow from the untreated (control) area (Nänni, 1972). This can be achieved by using the pretreatment regression relation. This way, water yield of the lower gauge may be predicted as if treatment had not occurred. Differences between the observed and predicted flow are considered as the effect of the treatment. This type of experiment is used to evaluate the effect of riparian clearing on streamflow *during baseflow conditions*. This method's limitation can be found in Prinsloo and Scott (1999).

Using this approach several authors attempted to assess the riparian vegetation effect on water yield (Nänni, 1972; Dye and Poulter, 1995; Prinsloo and Scott, 1999) and found that riparian vegetation suppression increased water yield on a daily basis.

The results from using this approach is illustrated by two scenarios in South Africa.

Removal of invasive exotic trees, abundant within the riparian zone, allowed for evaluating the effect of trees within riparian zones on water yield. After removing 3.98 ha (4.7% of the entire catchment) of riparian vegetation (consisting of exotic invasive trees, *Acacia mearnsii* and *Pinus pinaster*) within a 37-m distance on both sides of a stream, Prinsloo and Scott (1999) found a 12-m^3 day^{-1} increase per hectare cleared, equal to a 13% streamflow increase after clearing. In other words, this 1.20 mm day^{-1} extrapolated to the whole year would be 438 mm yr^{-1}. These are similar results to those obtained by Dye and Poulter (1995), who found a 12.2-m^3 day^{-1} ha^{-1} increase (1.22 mm day^{-1} or if extrapolated for the whole year, 445 mm yr^{-1}) in streamflow after removing exotic invasive pine and wattle species (*Pinus patula* and *A. mearnsii*, respectively) from a 2.5-ha riparian zone (25-m distance from a stream).

Using a slightly different approach, with a single streamflow gauge station, Rycroft (1955) studied the removal of riparian vegetation (scrub and grass) from an irrigation furrow in Jonkershoek, South Africa, during periods of baseflow. The tentative treated area corresponded to 1 ha. He compared pre- and post-treatment periods and reported a significant water yield increase. For example, water losses (12-day average) before the treatment were estimated as being 109 m^3 of water per day or 10.9 mm day^{-1}. For the post-treatment period, water loss was estimated to 83 m^3 of water per day (8.3 mm day^{-1}), a 26-m^3 decrease per day (2.6 mm day^{-1}). The author concluded that, 'water loss can be reduced by removing the riparian vegetation during periods of *acute water shortage*'.

Dunford and Fletcher (1947) also used this modified approach in a watershed of the Coweeta Experimental Forest, North Carolina, USA. Based on a treated area, these authors calculated 10-day average gains in water yield of 0.8 mm day^{-1} (if extrapolated, 292 mm yr^{-1}) after removing the stream-bank vegetation (mixed hardwood forest), corresponding to 1.07 ha (12%) of a 8.9-ha watershed.

2.2. Results using the paired catchment approach

According to Hewlett and Hibbert (1961) this method consists of a gauged catchment on which treatment is planned and is associated for a number of years with an adjacent control catchment of approximately the same size and cover conditions. During the calibration (pre-treatment) period of many years, streamflow on the experimental catchment is related to streamflow on the control, which remains undisturbed throughout the experiment. Using the pre-treatment regression relation water yield on the treated catchment may be predicted as if treatment had not occurred and the difference between the predicted and observed flow, if significant, it is attributed to the treatment.

This method was employed for both short- and long-term studies (daily and annual basis respectively). For short-term studies, this approach is based on the diurnal fluctuation of stream/water table height and it is assumed that this variation during rainless periods is attributed to the transpiration from deep-rooted vegetation having access to deep water sources, presumably, groundwater/streamwater. Since the streamflow is recorded simultaneously in two or more catchments, it is possible to predict streamflow within the treatment catchment by the regression relationship between treatment and control watershed streamflow during the pre-treatment period.

The study by Dunford and Fletcher (1947) was probably the first to evaluate the effect of riparian vegetation removal, which accesses the water table, on streamflow by the paired catchment approach. As previously stated, the study was conducted in the Coweeta Experimental Forest in the Appalachian Mountains of western North Carolina, USA and the mean annual precipitation in the area was approximately 1778 mm at the time, which may be considered a humid climate, 'distributed rather uniformly throughout the year'.

For the treatment, the authors assumed that all vegetation within 4.6 m (15 feet) elevation above the stream channel had access to the water table (cut area revealed a total of 3563 stems wider than 1.57 cm in diameter). The total treatment area comprised 1.07 ha

(12%) of an 8.9 ha catchment covered by mixed hardwood forest. In addition, sprouting vegetation was not removed.

As a result, they observed a substantial decrease in diurnal fluctuations during the growing season. The authors concluded that removal of stream-bank vegetation ‘can be of much practical value during drought years for municipal and industrial watersheds, when even small increases in yield area is of unusual importance’. However, they viewed these results with caution since it was a ‘preliminary examination’ due to its short-term nature. One objective of this study was to examine the assumption ‘that vegetation with continuous access to the water table is responsible for losses relatively greater in proportion than the area it occupies’. The complete elimination of diurnal oscillation was not achieved by Dunford and Fletcher (1947) through which may indicate that the vegetation having access to the water table was not completely eradicated by their treatment.

Several years prior to the experiment by Dunford and Fletcher (1947), Wicht (1941) studied the diurnal fluctuation of various streams in the Jonkershoek Valley, Western Cape, South Africa (Jonkershoek Hydrological Research Station). This author estimated that between 0.8% and 4.2% of annual water yield was used by the streambank vegetation during dry periods. Similar observations were made by Croft (1948) and Reigner (1966). These authors studied diurnal fluctuations of streamflow from forested watershed in the Farmington creek, Utah, USA and from the Dilldown watershed, Pennsylvania, USA, respectively. They attributed these oscillations to evapotranspiration within the riparian zone. In the case of the work of Reigner (1966), his evapotranspiration estimates varied from 0.3 to 1.9 mm day^{-1}. For a complete examination on diurnal fluctuations of streams, see Gribovski et al. (2010).

Johnson and Kovner (1954) examined the results from Dunford and Fletcher (1947) and reported that for a 10-day dry period, the effect of cutting a strip of vegetation along the water course increased streamflow from 3.8% to 19%, with an average of 12% for the period. They also reported that, ‘average daily gains from 10.3 to 13.6 m^3 in water yield for dry days were obtained during the growing season of the first year’. If divided by the treated area (1.07 ha), there is an increment equivalent to 1.03–1.27 mm day^{-1} (extrapolated to the whole year, roughly 420 mm yr^{-1}). For the same period, during the second year after cutting, average daily gains were from 3.8 to 8.5 m^3 (0.36–0.80 mm day^{-1} or if extrapolated to the whole year, roughly 212 mm yr^{-1}). By the third year, sprouting vegetation had become well established and no significant increases were detected. Their final evaluation corroborates with that by Dunford and Fletcher (1947) that, ‘cutting of streambank vegetation definitely increased streamflow on rainless days’.

Prinsloo and Scott (1999) evaluated the short-term effect of removing infestations of invasive exotic species, black wattle (*A. mearnsii*) and eucalyptus (*Eucalyptus grandis*), from a catchment site in Oaklands near Wellington, South Africa. Calculating by cleared hectare basis, the authors observed a marked 1.05-mm day^{-1} increase in streamflow after clearing 4.7 ha of riparian vegetation (16.2% of the entire catchment) over 173 days of baseflow.

Prinsloo and Scott (1999) presented an additional case of riparian forest clearcutting at a closed site in Du Toitskloof Pass, South Africa. In this case, black wattle trees comprised up to 76% of the riparian vegetation, accompanied by cluster pines (*P. pinaster*). The treated area was 1.5 ha (8.8% of the entire catchment). A 0.8-mm day^{-1} increase was detected during baseflow conditions.

Returning to Dunford and Fletcher’s work, Hewlett and Hibbert (1961) were probably the first researchers to employ the paired catchment approach in evaluating the effect of riparian vegetation removal on streamflow *on an annual basis*. These authors concluded that riparian forest removal led to a 50-mm yr^{-1} increase, which was only a small gain within the experimental error. According to the authors, small increases were detected immediately after cutting (non-significant on an annual basis). These annual basis results were clearly different from those predicted on an annual basis by simple extrapolation in the present paper.

Rowe (1963) observed increased annual water yield after removing woodland-riparian vegetation in an experiment conducted in the San Dimas Experimental Forest, southern California, USA. The first of two treatments was applied in 1958, removing 6.1 ha of riparian vegetation followed by removal of sprouting vegetation and herbs via herbicides. No appreciable increase in streamflow was detected during the rainy season. However, for the dry season, there was a 352-mm increase in terms of treated area. There was an additional treatment in 1959, removing 9.3 ha during the first rainy season. However, according to the authors, the 335-mm rainfall at the time of the second treatment was not sufficient to replenish water losses from the root zone within the area. Thus, the author attributed the increased streamflow (260 mm) to the previously treated 6.1 ha, which equals a 612-mm yr^{-1} annual increase. At the onset of the dry season in 1959, a 171-mm increase was observed (15.4 ha treated area). The author concluded that the highest water yield increase occurred during the dry season (summer). During rainy periods, removal of the deep-rooted vegetation also increased streamflow. This is probably due to bank drainage, which reflects differences in the amount of rainfall required to wet the streamside soils of the cleared and untreated slope bottoms.

Similarly, even more drastic results were found by Ingebo (1971) in two watersheds located approximately 6 miles southwest of Prescott, central Arizona, USA. The author reported that suppressed channel-side chaparral cover (15% of the watershed area) in 1968 and 1969 increased the streamflow, transforming a stream from intermittent to perennial. Streamflow increased by 16 mm yr^{-1} and 25 mm yr^{-1} (104 mm yr^{-1} and 160 mm yr^{-1} in terms of the treated area), respectively. According to Hibbert et al. (1982), the channel-side conversion created continuous flow for 5 years in the main channel, but dried each year during pretreatment periods (up to 8- or 9-month durations).

Rich and Gottfried (1976) studied the effects of manipulating mixed conifer forest vegetation on the hydrology of small catchments, also in central Arizona, USA, but within the Workman Creek watershed (Sierra Ancha Experimental Forest). Annual precipitation averaged 835 mm. The authors reported that a small riparian cut (0.6%) of total basal area of the catchment (treated area not available but presumably very small) on North Fork catchment did not increase water yield. In contrast, a subsequent treatment with a substantially higher area (32.4 ha), converting ‘moist sites forests’ into grass, significantly increased water yield. Thus, removing a small quantity of deciduous riparian trees on the North Fork (representing probably a very small treated area) did not significantly increase water yield.

Attempting to increase nutrient retention in pasture catchments using forested riparian zones, the experiment by Smith (1992) was the only one that could evaluate the consequences of tree plantation (*Pinus radiata*) within riparian zones (25- to 35-m distance from the stream) in Nelson, New Zealand. The planted area was estimated to be 20% of the total catchment area, corresponding to 0.5 ha of the treated catchment. This author demonstrated that forest plantation within riparian area substantially reduced water yield. This decreased streamflow ranged from 93 to 104 mm yr^{-1} when the pine trees were 8–10 years old and observed for 2 years. However, minor effect (52–68 mm yr^{-1}) was also detected with an additional 2 years. If prorated to the actual planted forest area, the annual decreases were estimated to be 282, 369, 504, and 564 mm yr^{-1}.

In South Africa, Scott and Lesch (1996) reported that removal of riparian vegetation (20-m distance on either side of the stream, along its entirety), including tall trees, shrubs, and herbaceous understory, resulted in a small 55-mm yr^{-1} (9%) increase in streamflow within the first year (13.7 mm yr^{-1} per cleared hectare). If distributed solely within the approximate 4-ha treated area (10% of the entire catchment), a 550-mm yr^{-1} increase was estimated per cleared hectare. By the second year, regrowth of sprouting vegetation was rapid and total streamflow decreased to 56 mm yr^{-1} (19%) or 560 mm yr^{-1} (cleared hectare calculation). Increased annual streamflow volume was most pronounced during the rainy season following removal of the riparian vegetation, corresponding to 39 mm yr^{-1} or 390 mm yr^{-1} (prorated to the cleared hectare), but gradually decreased until the onset of the following rainy season. The decrease during the second year was probably due to the rapid regrowth of vegetation within the cleared riparian zone.

Scott (1999) also reported two additional catchment scenarios involving riparian vegetation removal. This author studied the Witklip 2 catchment (Witklip State Forest, South Africa) when removing riparian vegetation composed of densely covered riparian scrub forest with larger woody plants, tree heights ranging from 4 to 20 m and light scattering of exotic pine and eucalyptus trees. Scott observed an approximate 57-mm yr^{-1} increase during a 2-year period. If prorated to the area actually treated (11.2 ha or 8.2% of the entire catchment), this value corresponds to 695 mm yr^{-1}. For Biesievlei catchment (Jonkershoek State Forest, South Africa), after removing mature pines (*P. radiata*) within a 3-ha riparian zone (11% of the catchment), there was an annual 123-mm yr^{-1} streamflow increase, if distributed to the whole catchment (1115 mm yr^{-1} if prorated to treatment area).

Compiling these two catchment results with the one presented by Scott and Lesch (1996), Scott (1999) reported that subsequent removal of all remaining vegetation of the catchments allowed for comparing the effect of riparian vegetation removal with the effect of removal of the vegetation of the entire catchment. Using such a comparison, the author demonstrated that the streamflow increases varied from 55 to 110 mm per 10% of the catchment cleared for these three catchments (after riparian vegetation removal). When compared to other zones (non-riparian) within the same catchments, removal of similar vegetation on the upslope led to streamflow increases from 27 to 35 mm per 10% of the catchment cleared.

3. Synthesizing the effect of riparian vegetation on streamflow

In summarizing all the results of the studies presented, it seems clear that removal of riparian vegetation results in reduced diurnal fluctuations of ground/streamwater (Table 1). This consequently leads to increased water yield on a daily basis (1.32 ± 0.85 mm day^{-1}; $n = 9$) and, if the effect persists, on an annual basis (483 ± 309 mm yr^{-1}; $n = 9$), where both estimates were prorated to the area treated. Increased water yield reflects savings in transpiration and interception losses caused by clearing vegetation, consequently leading to higher flow of water from soil storage to groundwater storage, sustaining the baseflow (Scott, 1999). Nonetheless, the highly varied results indicate that the effect of suppressed riparian vegetation varies from null to significant water yield increases. In addition, when vegetation (tree) was allowed to regenerate or was planted in riparian zones, the water yield decreased (Johnson and Kovner, 1954; Smith, 1992; Scott and Lesch, 1996) from 1.25 ± 0.34 mm day^{-1} on a daily to 456 ± 125 mm yr^{-1} on an annual basis (both prorated to area treated; $n = 5$). Thus this reflects the effect of increasing transpiration and interception losses within the riparian zones.

In an attempt to compare results from different regions of the world, we follow what has been suggested in Scott (1999), expressing gains or losses as mm of increase/decrease per 10% of area treated. For this, a linear relationship was assumed between the area treated and the increase/decrease to normalize the data (Table 1). As a result, we found a water yield increase of 62 ± 35 mm yr^{-1} ($n = 9$) for suppressed riparian forest and a decrease of 47 ± 13 mm yr^{-1} ($n = 5$) for regenerated or planted riparian forests.

Compared to paired catchment studies that manipulated all vegetation of a small catchment, there are much fewer studies that only manipulated riparian forest. However, the general trend shown in this paper corroborates the trend seen in classical paired catchment studies, where forest removal led to increased annual water yield, while forest plantation/regeneration led to decreased annual water yield (Hibbert, 1967; Bosch and Hewlett, 1982; Hornbeck et al., 1993; Sahin and Hall, 1996; Stednick, 1996; Andréassian, 2004; Brown et al., 2005).

The variation between null to significant water yield increases may be explained by the study by Rich and Gottfried (1976), who demonstrated that a small decrease in basal area (0.6%) of vegetation within riparian zones (presumably a very small area) had no material effect on water yield on an annual basis. Thus, when riparian zones are deforested, increased water yield is expected to be dependent on the riparian zone's size in relation to the whole catchment. In other words, forms of management which reduce the density of vegetation to higher degree increase discharge in streams proportionally (Banks, 1961).

Additionally, if regrowth remains uninhibited, as was the case in some studies (Dunford and Fletcher, 1947; Johnson and Kovner, 1954; Scott and Lesch, 1996), regeneration may use the water and is thus reflected in reduced water yield. We hypothesize that these explanations clarify the non-significant results (annual basis) found by Dunford and Fletcher (1947), which were highlighted by Hewlett and Hibbert (1961). We speculate that if higher basal area were removed in the study by Dunford and Fletcher (increasing the clearcutting area along the stream), in addition to preventing regrowth, these management practices would have resulted in a significant water yield increase on an annual basis.

However, the results found by Scott (1999) that vegetation removal within a riparian zone is likely to increase water yield up to three times more than clearing the same area of similar vegetation at an upslope position in the catchment seem to accept the initial hypothesis proposed by Dunford and Fletcher (1947) that 'vegetation having continuous access to the water table is responsible for losses relatively greater in proportion than the area it occupies'. This finding highlights that vegetation in the riparian zone uses more water than similar vegetation located elsewhere (upslope positions) in the catchment. Thus, riparian zones exhibit a disproportional water-use effect (Smith, 1992). Similarly, trees that are closer to streams can access groundwater, while those further away have less access to soil water and hence transpire at a lower rate (Dye and Poulter, 1995). This spatial variation in evapotranspiration at the catchment scale should be included in distributed models to predict effects of afforestation/reforestation/restoration on water yield. Understanding evapotranspiration losses due to vegetation within riparian zones is still a matter of discussion in the literature (see Gribovski et al., 2008 and many references therein).

4. Gaps, uncertainties and perspectives

Based on our synthesis, some points regarding uncertainties and lacking information must be addressed. First, we refer to the different climates present where studies on suppressed riparian vegetation were conducted. Some studies on removal of riparian vegetation were conducted in arid to semiarid regions where water is usually scarce (Rycroft, 1955; Banks, 1961; Rowe, 1963; Ingebo,

Table 1
Summary of the results from studies that assessed the effect of riparian vegetation on water yield. Positive (+) and negative (−) signs denote increased and decreased water yield after treatment, respectively.

Reference	Catchment region	Method	Catchment area (ha)	Area treated (ha; %)	Treatment	Effect on a daily basis (mm day^{-1})	Effect on an annual basis (mm yr^{-1})	Effect on an annual basis – prorated to area treated (mm yr^{-1})	Effect for each 10% of area treated (mm yr^{-1})
Prinsloo and Scott (1999)	*Knorhoek* South Africa	Nested catchment	85	∼4; 4.7	Removal of exotic trees	+1.2[a]	+21	+438[b]	+45
	Oaklands South Africa	Paired catchment	29	4.7; 16.2	Removal of exotic trees	+1.05[a]	+170	+383[b]	+105
	Du Toitskloof South Africa	Paired catchment	17	1.5; 8.8	Removal of exotic trees	+0.8[a]	+71	+292[b]	+81
Dye and Poulter (1995)	*Kalmoesfontein* South Africa	Nested catchment	–	2.5; –	Removal of exotic trees	+1.22[a]	–	+445[b]	–
Rowe (1963)	*Monroe* USA	Paired catchment	354	6.1; 1.7	Removal of native trees	+1.7[a]	+10.5	+612	+62
Ingebo (1971)	*Whitespar B* USA	Paired catchment	100	15; 15	Removal of native trees	+0.3[a]	+16	+104	+11
						+0.4[a]	+25	+160	+17
Smith (1992)	*C4* New Zealand	Paired catchment	2.7	0.5; 18	*Pinus radiata* plantation only in riparian area	−0.77[a]	−52	−282	−29
						−1.01[a]	−68	−369	−38
						−1.38[a]	−93	−504	−52
						−1.55[a]	−104	−564	−58
Scott and Lesch (1996)	*Westfalia D* South Africa	Paired catchment	39.6	4; 10	Removal of native trees	+1.51[a]	+55	+550	+55
					Regeneration of native trees	−1.53[a]	−56	−560	−56
Scott (1999)	*Witklip 2* South Africa	Paired catchment	136	11.2; 8.2	Removal of exotic trees	+1.9[a]	+57	+695	+70
	Biesievlei South Africa	Paired catchment	27.2	3; 11	Removal of exotic trees	+3.05[a]	+123	+1115	+112

[a] Prorated to area treated.
[b] Extrapolated to 1 year based on daily values.

1971). Under these conditions, any water yield increase was considered by the authors as a great benefit to the water supply, despite the fact that conversion of forest into grass has a minor effect on annual water yield in low-rainfall climates compared to high-rainfall climates (Zhang et al., 2001). Other studies conducted in other regions recommended removing riparian vegetation only during periods of drought (Dunford and Fletcher, 1947; Reigner, 1966). Thus, it seems clear that riparian vegetation removal was only recommended for treatment under extremely dry conditions.

Another point that must be considered is rooting depth of the riparian vegetation under investigation. It is most likely that if riparian vegetation does not root into the stream (and/or groundwater, capillary fringe, etc.), the effect of removing this vegetation on streamflow/groundwater fluctuation during baseflow may be negligible. Therefore, the age of the plants within the riparian zone's community, which is related to rooting depth (Dawson and Ehleringer, 1991) may influence treatment results.

Considering the annual distribution of streamflow, the work of Rowe (1963) showed that the effect of woodland-riparian clearing on streamflow became proportionately greater as the flow decreased during the dry season. This found is in line with what has been described by Bruijnzeel (1986, 2004) in which the dry season flow is augmented if infiltration opportunities are sufficiently high to allow soil water recharge and drainage during the wet season. Additional observations made by Scott (1999) on Biesievlei catchment also showed that a more marked effect on the

Table A1
Additional characteristics of the treated catchments in assessing the effect of riparian vegetation on streamflow over the short- and long-term using the paired catchments approach.

Catchment	Slope (%)	Mean elevation (m)	Climate	Vegetation type	Post-treatment vegetation	Mean annual rainfall (mm)	Mean annual streamflow (mm)	References
Coweeta Experimental Forest, North Carolina, USA								
Number 6	53		Humid tempearate climate	Hard wood	Regrowth	1780	830	Dunford and Fletcher (1947)
San Dimas Experimental Forest, California, USA								
Monroe Canyon				Chaparral		647	63	Rowe (1963)
Rocky Mountain Forest and Range Experiment Station, Arizona, USA								
Whitespar B		1800	Semi-arid	Chaparral		610	30.5	Ingebo (1971)
Sierra Ancha Experimental Forest, Arizona, USA								
North Fork		2010		Mixed conifer		835	87	Rich and Gottfried (1976)
Westfalia, Northern Province, South Africa								
Catchment D				Forest	No vegetation	1611	548	Scott and Lesch (1996)
					Regrowth			Scott and Lesch (1996)
Mountere hills, southwest of Nelson, New Zealand								
C4				Pasture	Only pine trees in the riparian zones	1051		Smith (1992)
Various parts of South Africa								
Witklip 2	19	1285	Humid subtropical climate	Grasslands with evergreen forest on valley bottom	No vegetation	996	218	Scott (1999)
Biesievlei	35	430	Mediterranean	Fynbos (sclerophyllous vegetation)		1427	663	Scott (1999)
Western Cape Province, South Africa								
Oaklands		410		Fynbos (sclerophyllous vegetation) with invasive *Acacia* and *Eucalyptus* in the riparian zone		1050		Prinsloo and Scott (1999)
Du Toitskloof		560		Fynbos (sclerophyllous vegetation) with invasive *Acacia* and *Pinus* in the riparian zone		1050		Prinsloo and Scott (1999)

dry season flows than total flows (81% and 48% respectively). However, this trend does not appear to be a rule since streamflow increased mostly during major flows (wet season) for Ingebo (1971) and Scott and Lesch (1996).

Tree species within riparian areas is another factor that must be emphasized. Removing or planting exotic invasive species (e.g. *Acacia*, *Eucalyptus*, or *Pinus*) may not represent the real hydrologic behavior of suppressed or planted/regenerated natural vegetation that generally exhibits lower growth rate, and consequently, lower water-use (Scott, 1999, 2005).

Regarding regions of the world where riparian experiments were conducted, the present authors were not able to find results from studies of this nature in the tropics. Therefore, it seems clear that there are opportunities for such studies in this region because an increase of both agricultural and secondary forests areas (including restored riparian tropical forests) is occurring (Giambelluca, 2002; Bruijnzeel, 2004; Bonell et al., 2010; Calmón et al., 2011; Hayhoe et al., 2011).

While robust prediction of water yield is possible using paired catchment experiments that manipulate vegetation within small catchments (Zhang et al., 2001), this does not appear to be applicable to riparian vegetation. Such data is scarce and scattered, thus robust modeling for the whole world is still not possible.

As highlighted by Banks (1961) in relation to riparian vegetation removal as a form of treatment. In cases where this is the treatment to be applied, deforestation has to be accompanied reestablishment of new vegetation cover to diminish the possible risks of such practices (e.g. soil erosion). Similarly, riparian zones need to have healthy vegetation cover to prevent water quality from being negatively affected (Prinsloo and Scott, 1999).

Several studies aimed to increase water yield by reducing riparian vegetation water-use (due to reduced transpiration losses) without necessarily removing riparian vegetation (Davenport et al., 1976, 1982). Davenport et al. (1982) reported a case where antitranspirants were applied in saltcedar (*Tamarix chinensis*, Lour.), a riparian deep-rooted plant (phreatophyte), to decrease plant water-use while maintaining the plants in their original habitat. Thus, the benefits of vegetation (i.e., reduced soil erosion) would remain intact because the plants would still be in place. However, antitranspirants not only interfere in water losses via stomata, but also via carbon fixation, and consequently, affect many plant physiological processes (Taiz and Zeiger, 2009). Therefore, if this treatment is applied to an entire riparian ecosystem, it will affect ecosystem functionality as a whole. Thus, it seems clear that if riparian forests are needed for various ecosystem functions, such as sediment retention and others (i.e., fixing carbon, serving as wildlife habitats and ecological corridors; stabilizing streambanks; providing shade, organic matter, food for streams and their biota; filtering chemicals; etc.), it is not possible to inhibit their water-use and at the same time maintain all forest functions intact (Hewlett, 1964). This water and forest trade-off (water and carbon) has been reported in several paired catchment reviews (e.g., Brown et al., 2005) and it is still a matter of discussion for industrial timber plantations (Scott, 2005; Jackson et al., 2005; Malmer et al., 2010). However, it is well established that forests generally use more water than smaller vegetation types (Zhang et al., 2001). Our synthesis indicates that riparian forests are not an exception to this rule.

5. Final considerations

It is clear that riparian vegetation has effect on water yield. However, there are still opportunities for further investigations since there are many current restoration programs in degraded riparian zones. We hope this synthesis will encourage hydrologists to work towards describing the functional role of these restored and regenerated natural riparian forests. In this respect, it is important to study the effect on water yield in a changing world and thus in a changing landscape, where agricultural areas are growing and enhancing their planted areas, therefore water resources are being increasingly affected.

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Appendix A

See Table A1.

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