Managing riparian zone vegetation to sustain streamflow: results of paired catchment experiments in South Africa

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Abstract: The reductions in streamflow associated with timber plantations are of particular concern in South Africa and, as a means of sustaining flows, permits granted by the state for the establishment of plantations have required that plantings should be no closer than 20–50 m from streams and other waterbodies. This paper presents the results of three catchment experiments, analysed by the paired catchment method, that aimed to provide a quantitative evaluation of the water yield savings attributable to this practice. These experiments show conclusively that, for South African conditions, riparian vegetation is a more liberal user of water than vegetation in other parts of a catchment and that the clearing of indigenous forest or exotic trees in the riparian zone of the catchment will result in disproportionately greater gains in water yield than would result from clearing similar vegetation elsewhere in the catchment. First year flow increases from clearing of tall woody vegetation in the riparian zone ranged from 55 to 110 mm (9–44%) per 10% of catchment cleared. In the same catchments, clearing of similar vegetation in upslope (nonriparian positions) led to flow increases ranging from 27 to 35 mm (2.5–14%) per 10% of catchment cleared.

Résumé : La diminution du débit de l'écoulement des cours d'eau associée à la plantation pour la production de bois est particulièrement préoccupante en Afrique du Sud. Comme moyen de maintenir l'écoulement, les permis octroyés par l'État pour l'établissement de plantations exigent que la plantation ne s'approche pas à plus de 20 à 50 m des cours d'eau et autres plans d'eau. Cet article présente les résultats d'expériences sur trois bassins, analysés selon la méthode des bassins jumelés, qui visent à évaluer quantitativement les gains d'écoulement attribuables à cette pratique. Ces expériences montrent de manière conclusive que dans les conditions qui prévalent en Afrique du Sud, la végétation riparienne utilise plus d'eau que la végétation des autres parties du bassin et que la coupe de la forêt indigène ou des arbres exotiques dans la zone riparienne d'un bassin provoque un gain d'écoulement disproportionné par rapport à celui qui résulte de la coupe de la même végétation ailleurs sur le bassin. L'augmentation de l'écoulement la première année après la coupe de la végétation ligneuse arborescente dans la zone riparienne varie de 55 à 110 mm (9–44%) pour chaque portion de 10% de l'aire du bassin qui est coupée. Dans les mêmes bassins, la coupe de la végétation similaire sur les versants, à l'extérieur de la zone riparienne, provoque des augmentations de l'écoulement variant de 27 à 35 mm (2,5–14%) pour chaque portion de 10% de l'aire du bassin qui est coupée.

[Traduit par la Rédaction]

Introduction

Riparian zones are of particular interest in forestry. It has long been assumed that vegetation in the riparian zone has preferential access to soil water and hence consumed an amount of water disproportionate to the area of a catchment it occupied. On this basis, since 1972, no new afforestation in South Africa has been permitted within a distance of 20–50 m from streams and other waterbodies. In a further affirmation of this belief, the South African government, as a means of protecting water supplies, is currently sponsoring a programme of clearing invasive woody weeds from mountain catchments (watersheds), in general, and riparian zones, in particular.

Wicht (1941), from a study of diurnal dips in the streamflow trace during dry periods, considered that between 0.8 and 4.2% of annual runoff could be saved by removing woody riparian vegetation from various catchments in the Jonkershoek Valley, Western Cape. His hypothesis was supported by small yield increases measured in brief experiments involving the clearing of scrub along an irrigation furrow at Jonkershoek (Rycroft 1955; Banks 1961) and the clearing of riparian scrub in a subalpine grassland at Cathedral Peak (Nänni 1972). Thus, the clearfelling of a riparian evergreen forest can be expected to result in measurable increases in streamflow.

Similar studies elsewhere in the world have also found that clearing of riparian vegetation increases runoff and that the drier the environment, the greater the increase. In the dry, winter rainfall climate of the Arizonan chaparral, the replacement of deep-rooted shrubs by grasses changed seasonal streams to perennial ones (Hibbert et al. 1982; DeBano and Schmidt 1990). A study in southern Californian chaparral measured increases in runoff of up to 279 mm·ha^{-1} per year of tall riparian trees cleared (Rowe 1963).

The importance of riparian zones in South African catchment and forestry management is demonstrated by the large amounts of money spent in clearing invasive woody weeds

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Table 1. Physical features of the gauged research catchments used in this study.

Catchment	Area (ha)	Portion afforested (%)	Elevation range (m)	Slope[a]	Mean daily temperature (°C) Hottest month	Coldest month	MAP[b] (mm)	MAR[c] (mm)
Westfalia D (treated)	39.6	83	1050–1320	0.33	24.4	15.3	1611	548
Westfalia B (control)	32.6	0	1140–1420	0.42	24.4	15.3	1597	543
Witklip 2 (treated)	136	34	1100–1470	0.19	21.3	13.4	~996[d]	364[e]
Witklip 3 (control)	160	34	1130–1470	0.18	21.3	13.4	~996[d]	218[e]
Biesievlei (treated)	27.2	98	280–580	0.35	21.1	11.4	1427	663
Langrivier (control)	245.8	0	366–1460	0.4	21.1	11.4	2261	1603

[a]Slope = $(IL)/A$ where I is the contour interval (m), L is the total length of contour in catchment (m), and A is the catchment area (m^2).
[b]Mean annual precipitation.
[c]Mean annual runoff.
[d]Mean of single central rain gauge over 1974–1992.
[e]Mean of 1974–1992, whilst partially afforested.

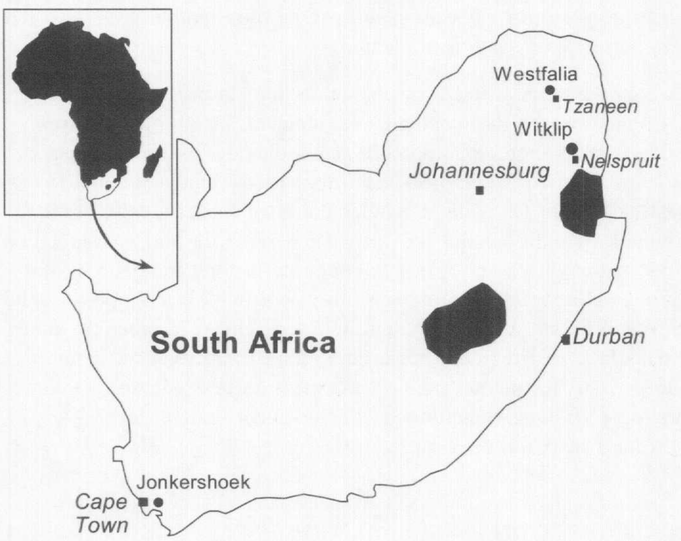

Fig. 1. The location of the research catchments (circles) used in this study relative to the major South African cities and nearby towns (squares).

and the high opportunity cost of not planting these parts of the forest estate. It is therefore important that the hydrological benefits of these practices should be quantified. This paper reports on three catchment experiments that were designed to measure the effect of clearfelling riparian vegetation on the water yield. In each experiment, trees in the proximity of streams were removed, and the runoff was monitored for at least a year to measure any change that may have resulted. The effect of this riparian clearfelling is compared with the effects of subsequent clearfelling on the flanks of the same catchments.

Materials and methods

Description of the experimental areas and treatments

The research catchments are widely spread within the forestry (i.e., high-rainfall) zone of South Africa (Fig. 1): on Westfalia Estate (23°04′S, 30°04′E) near Tzaneen in the Northern Province, on Witklip State Forest (25°14′S, 30°53′E) west of White River on the Mpumalanga escarpment, and in Jonkershoek State Forest (33°57′S, 18°15′E) in the Western Cape. In this section the separate experimental sites and treatments are described.

Westfalia Estate

The Estate is situated in the subtropical summer rainfall area. Annual precipitation is on average 1600 mm, 84% of which falls during October to March (Smith and Bosch 1989) in the form of both soft soaking rains and large, high-intensity thunderstorms. The indigenous vegetation of the area ranges from evergreen high forest to semideciduous scrub forest with dominant species *Nuxia floribunda* Benth. (Loganiaceae), *Rapanea melanophloeos* (L.) Mez (Myrsinaceae), *Syzygium cordatum* Hochst. (Myrtaceae) and *Trichelia dregeana* Sonder (Meliaceae) (Bosch and Versfeld 1984). The forest canopy is dense with an average height of 22 m along the streams, grading to closed canopy at roughly 10 m over 40% of the area and scrub forest with a canopy height between 3 and 10 m over the remaining slopes. The soils developed on weathered Archaean granite gneiss and are deep, well-drained, dystrophic and red, though becoming hydromorphic and rich in organic matter along the streams. The physical features of the catchments are summarised in Table 1. A complete description of the research area is given by Smith and Bosch (1989).

The experimental network on Westfalia Estate consists of four gauged catchments, two of which have been used in this study. Catchment D (39.6 ha) was treated, while catchment B (32.6 ha) was maintained as a control. In January 1981, all vegetation in the riparian zone of catchment D, consisting of tall trees, shrubs, and some herbaceous understorey, was cleared by hand and left on site. A zone of 20 m on either side of the stream was cleared for the length of the stream, approximately 1000 m. This meant an area of roughly 4 ha or 10% of the catchment was cleared. Regrowth of this riparian vegetation by sprouting was rapid, and followup clearing was done by hand in November 1981. Two years after this riparian clearing (i.e., December 1982 and January 1983), as a second, discrete treatment, all the remaining vegetation in catchment D was clearfelled, stacked, and burned. The entire catchment, including the riparian zone, was then planted to *Eucalyptus grandis* Hill ex Maid. seedlings at a density of 1370 stems/ha during March and April 1983. The control catchment remained under its natural forest cover.

Witklip

The Witklip research area, like Westfalia, has a humid subtropical climate, with a predominantly summer rainfall. The indigenous vegetation is montane grassland, with evergreen forest developing in the sheltered valleys and grading into riparian scrub at higher altitudes. The upper portion the catchments is steeply sloping with a

Table 2. Details of the calibration models for streamflow in the treated catchments.

Treated catchment	Type of model	Control catchment	Model*	Intercept (β_0)	Regression coefficient	Error df	Adjusted R^2
Westfalia D	Total runoff	Westfalia B	$T = e^{\beta_0} C^{\beta_1} AW^{\beta_2}$	0.677	0.808 (β_1) –0.027 (β_2)	298	0.96
Witklip 2	Total runoff	Witklip 3	$T = e^{\beta_0} \cdot (C+1)^{\beta_1} - 1$	0.239	1.339 (β_1)	141	0.99
Biesievlei	Total runoff	Langrivier	$T = \beta_0 + \beta_1 C$	0.517	0.134 (β_1)	209	0.74
	Dry season runoff	Langrivier	$T = e^{\beta_0} C^{\beta_1}$	–0.925	0.691 (β_1)	63	0.63

*T and C, runoff from treated and control catchments respectively (mm); β_0 and β_1, fitted regression coefficients; AW, antecedent wetness index.

short grassland cover; in the lower portions the grasslands have been afforested. The soils are formed on deeply weathered granites and are highly leached and well drained. The physical characteristics of the research catchments are given in Table 1.

Both the treated catchment (Witklip 2) and control (Witklip 3) have been partially afforested (34% in both cases) with pine (mainly *Pinus patula* Schlechtend. & Cham.) and some eucalypts (*Eucalyptus paniculata* Sm. and *Eucalyptus maculata* Hook.). The riparian zones were not afforested, but in the absence of fire, these zones had a dense cover of riparian scrub forest, with tree heights ranging from 4 to 20 m, and a light scattering of self-sown (exotic) pine and eucalypt trees. The treatments in Witklip 2 aimed to remove the large woody vegetation in the riparian zone of 11.2 ha (8.2% of catchment) and to keep the vegetation short. The result was a series of treatments (see summary in Table 4) commencing, in August 1979, with the clearfelling of all trees and shrubs with a diameter at breast height (DBH) above 100 mm. Two years later (June 1981) all remaining woody vegetation in this riparian zone was slashed; in February 1982 and again in 1983 the riparian zone was sprayed from the air with herbicide (Roundup®: active ingredient: glyphosate) to suppress the regrowth of vegetation. Commencing in August 1983, 42.6 ha of the 46.4 ha of predominantly pine plantation in the catchment were progressively clearfelled over a 12-month period. In 1985 the riparian zone was burned to encourage the development of a grass cover.

Biesiesvlei catchment

This catchment is part of the Jonkershoek research network in the Western Cape Province, which has a Mediterranean climate, i.e., hot, dry summers and cool, wet winters, with over 80% of the rain falling in a 7-month wet season between April and October (Wicht et al. 1969). The indigenous vegetation of the area is fynbos, a sclerophyllous scrub dominated by species of the Proteaceae, Ericaceae, and Restionaceae. The treatment catchment, Biesievlei, is afforested with *Pinus radiata* D. Don, which is managed as a sawtimber crop on a 35- to 40-year rotation. The control catchment, Langrivier, is covered mainly in fynbos with patches of evergreen riparian forest. It is protected from fire, and over the periods of comparison used in this study, the fynbos cover has been mature, affording good experimental control. The physical characteristics of the Biesievlei and Langrivier catchments are summarised in Table 1.

In 1948, most (98%) of the Biesievlei catchment, including the riparian zone, was afforested with *Pinus radiata*. The mature pines in the riparian zone were clearfelled in two stages: the lower elevation riparian zone (~1.5 ha: roughly 370 m long, 20 m wide on the eastern side of the stream and between 20 and 30 m on the western side) was clearfelled between April and June 1984, and the upper portion (~1.5 ha) was clearfelled between August and November of the same year. In May 1985, clearfelling of the remainder of the plantation commenced and was completed in March 1986. The execution of the experiment was not ideal in that the clearing of the fairly small riparian zones was rather protracted, and the period between the clearing of the riparian area and the rest of the catchment was short and did not include a full wet season.

Data collection and analysis

Streamflow was measured by continuous recording of stage heights above sharp-crested compound 90° V-notch weirs. The streamflow charts were digitized, and runoff was calculated from rating tables developed specifically for each weir and then summed over weekly intervals. The runoff was divided by the catchment area, and this volume per unit area was expressed in rainfall depth equivalents (mm).

The paired catchment approach was used to assess the effect of a vegetation cover treatment on streamflow (Hewlett and Pienaar 1973). The method is based on the assumption that the relationship between the streamflow of two physiographically similar catchments will remain the same provided that the vegetation of these catchments remains the same or changes in a similar fashion. Streamflow in each of the treatment catchments (Westfalia D, Witklip 2, and Biesievlei) was calibrated against their control catchments (Westfalia B, Witklip 3, and Langrivier, respectively) over a pretreatment period when the vegetation in each was mature and did not change. These periods were July 1978 to December 1980 for Westfalia D, November 1976 to July 1979 for Witklip 2, and April 1980 to March 1984 for Biesievlei. During these periods the trees in the riparian zones to be treated were mature, and consequently, the calibration relationships are expected to be reliable and robust.

An index of catchment antecedent wetness (Dunne and Leopold 1987) was tested as a predictor variable in the calibration models as an adjunct to the control catchment streamflow. The antecedent wetness index for any week i (AW_i) was calculated from weekly rainfall as follows: $AW_i = 0.75(AW_{i-1}) + P$ where P is the weekly rainfall in the treatment catchment, and AW_{i-1} is the wetness index for the previous week. Only in the Westfalia catchment did this term significantly improve the calibration model.

Several regression models were tested to best express the relationship between flows in the treatment and control catchments during the calibration periods. Model selection was done on the basis of R^2 and an inspection of residuals. The calibration model for total flow in Biesievlei is simple linear, while the others are multiplicative models that are intrinsically linear when one works with the logarithmic transform of the variables (Table 2). The better the fit of the calibration model, the more readily treatment effects can be detected; however, the form of the calibration model used had no effect on the nature of the results. Clearfelling effects were measured as the difference between the expected or predicted streamflow (based on the derived calibration relationship) and the observed streamflow measurements.

The significance of any treatment (clearing) effect was assessed by the dummy variable method of multiple regression analysis (Draper and Smith 1966). The t test for entry of a dummy variable into the regression models can be shown to be the equivalent of an F test for the extra sum of squares due to the entry of an

Fig. 2. The predicted and observed monthly streamflow in treated catchment Westfalia D for the period starting with the felling in November 1981 of native riparian forest and ending with the clearfelling of the remaining 90% of the catchment.

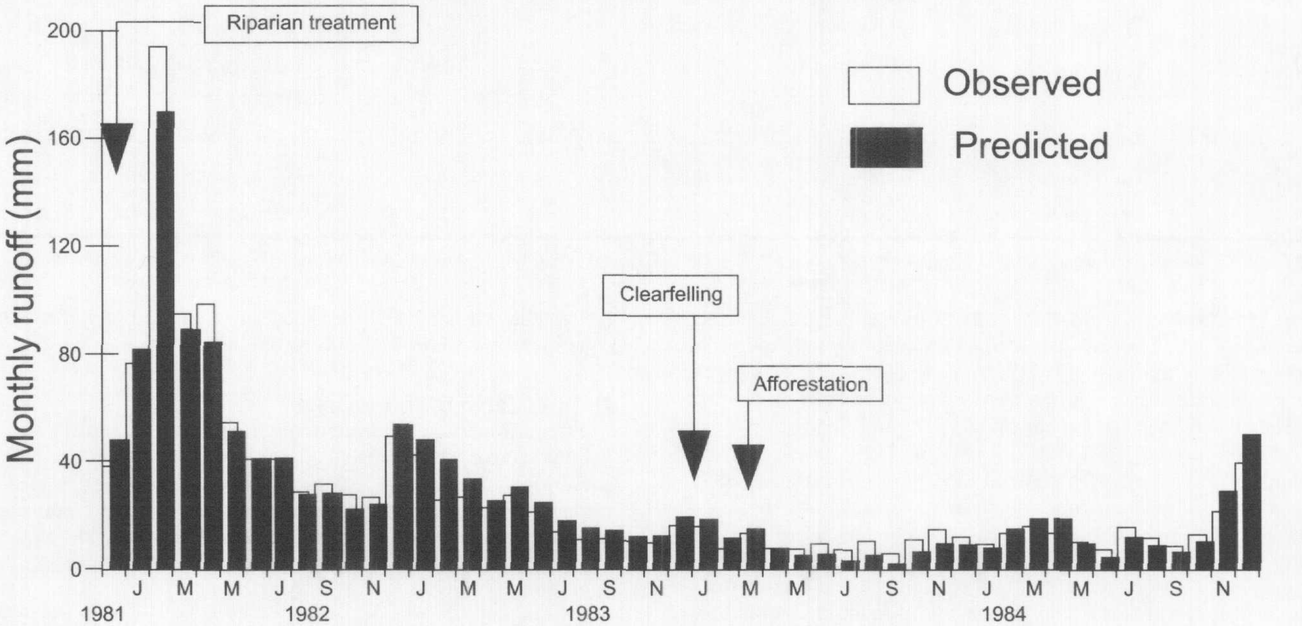

Table 3. Summary table of treatment effects on runoff at Westfalia catchment D, giving the mean weekly runoff (mm) and the calculated change as a result of treatments.

Treatment description	Date of treatment	Post-treatment period	No. of weeks	Observed mean weekly runoff (mm)	Change in runoff (%)*
Calibration			131	13.81	—
Riparian clearing	Jan. 1981	First year	48	14.27	9
		Second year	52	4.53	–19
Clearfell, burn, and afforest	Dec. 1982 –	First year	48	2.16	35
	Mar. 1983	Second year	52	3.39	–6

Note: Positive change indicates an increase. All effects were significant at $P < 0.05$.
*% change = [(observed – predicted)/predicted] × 100.

additional term into the model (Kleinbaum and Kupper 1978). The application of this multiple regression technique for the analysis of paired catchment experiments is described fully in Hewlett and Bosch (1984) and Scott and Van Wyk (1990).

Results

Westfalia: effects of clearfelling indigenous forest

Clearfelling of riparian forest had a small but statistically significant ($P < 0.05$) effect on runoff (Table 3). Total runoff increased in the first year after clearing by 55 mm, 9% greater than predicted but, in the second year, was 56 mm (19%) lower than expected (Table 3). The increases in runoff were most pronounced in the first wet season following the treatment (39 mm between 15 January and the end of April) but tapered off by the onset of the following wet season (Fig. 2). The second-year decrease is thought to be due to the rapid regrowth of vegetation in the cleared riparian zone. The second-year decreases in volume occurred in both the wet and dry seasons.

The clearfelling (of the whole catchment), burning, and planting with eucalypt seedlings caused a small but statistically significant increase in weekly runoff (Table 3). Runoff increased by 27 mm (35%) in the first year after treatment, of which 19 mm was in the dry season. An increase was to be expected and reflects the savings in transpiration and interception losses caused by the clearing of vegetation. In the second year after the treatment runoff decreased by 12 mm (6%), although there was again an obvious increase in dry season streamflow (Fig. 2). The cause of the overall decrease is thought to be the regrowth of sprouting vegetation in the catchment combined with the rapid establishment of young eucalypts.

Witklip: effects of clearfelling riparian bush and weeds

The first riparian treatment, that of removing all larger woody plants, caused an increase of roughly 57 mm/year (29%) over 2 years (Table 4). This increase was sustained and increased through further riparian treatments to keep the vegetation short (Fig. 3). The actual increases in streamflow were small during the drought years of 1981–1983, but as the calibration regression was particularly tight (Table 2), these small changes were easily discernible. In the two driest seasons (1982 and 1983) the relative flow increases were the

Fig. 3. The predicted and observed streamflow in Witklip catchment 2 for the period starting with a series of riparian clearing operations and ending with the clearfelling of 92% of the plantations in the catchment.

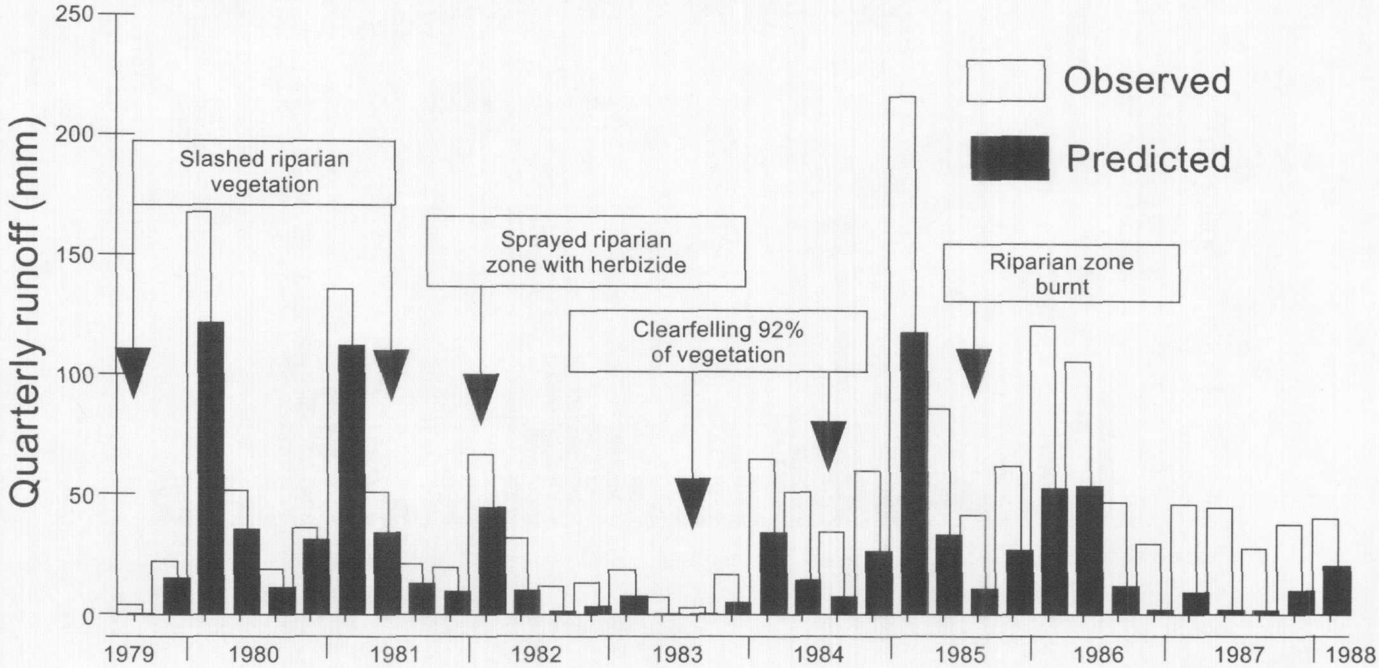

Table 4. Increases in weekly and equivalent annual (total) streamflow at Witklip catchment 2 following a series of riparian zone treatments and clearfelling.

Treatment description	Date of treatment	No. of weeks	Observed mean weekly runoff (mm)	Change in runoff* Weekly runoff (mm; %)	Change in runoff* Equivalent annual (mm/year)
Calibration	Nov. 1976 – July 1979	143	6.2	—	—
Slashed riparian vegetation >10 cm DBH	Aug. 1979	100	4.8	1.1; 29	56.5
Slashed remaining riparian vegetation	June 1981	34	2.5	0.5; 26	26.3
Sprayed riparian zone with herbicide	Feb. 1982	53	1.7	0.6; 57	32.4
Sprayed riparian zone with herbicide	Feb. 1983	21	0.6	0.2; 63	12.7
Clearfelling 92% of plantation	Aug. 1983 – July 1984	105	5.2	2.4; 90	124.6
Riparian zone burned	July 1985	309	5.5	2.0; 56	102.5

Note: All treatment effects were highly significant ($P < 0.01$).
*% change = [(observed – predicted)/predicted] × 100.

highest. It is not known, however, whether this is because of a higher relative impact by riparian vegetation during droughts or simply a direct effect of the herbicide treatment that killed all streamside vegetation.

Clearfelling of the mature sawlog crop covering 42.6 ha (31% of Witklip 2, and 92% of the afforested part of the catchment) caused a immediate and large runoff increase of 125 mm/year over the first 2 years. The large increase caused by clearfelling dominates any additional effect that might have been obtained from burning the riparian zone in July 1985. In the first 4 years after clearfelling (from August 1984), annual runoff increased by 151 mm (129% greater than predicted). Streamflows were still greater than expected in 1991, 8 years after clearfelling had started.

Biesievlei: effects of clearfelling of riparian pines

The calibration relationship for total flow, using as control the much larger Langrivier catchment, is poor (adjusted R^2 = 0.74; Table 2). But the effect of riparian clearing is nonetheless obvious and statistically significant (Table 5), despite the fact that this treatment was applied progressively through the year (April to November).

During the year of the riparian treatment in Biesievlei, annual runoff increased significantly by 123 mm or 48% (Table 5; Fig. 4). In the next hydrological year, when the remaining plantation was being clearfelled the yield increase was 225 mm or 89%. Part of this increase could be attributed to the riparian clearing in the previous year, but it is not possible to separate the effects of the two treatments. In the two subsequent years, runoff was more than double that which would have been expected prior to clearfelling, increasing by an average of 345 mm/year or 139%.

The riparian clearfelling had a more marked effect on the dry season flows than on the total flows (89% as opposed to

Fig. 4. The predicted and observed monthly streamflow in Biesievlei catchment for the period after the riparian clearing (1984) and subsequent clearfelling of the whole catchment (1985).

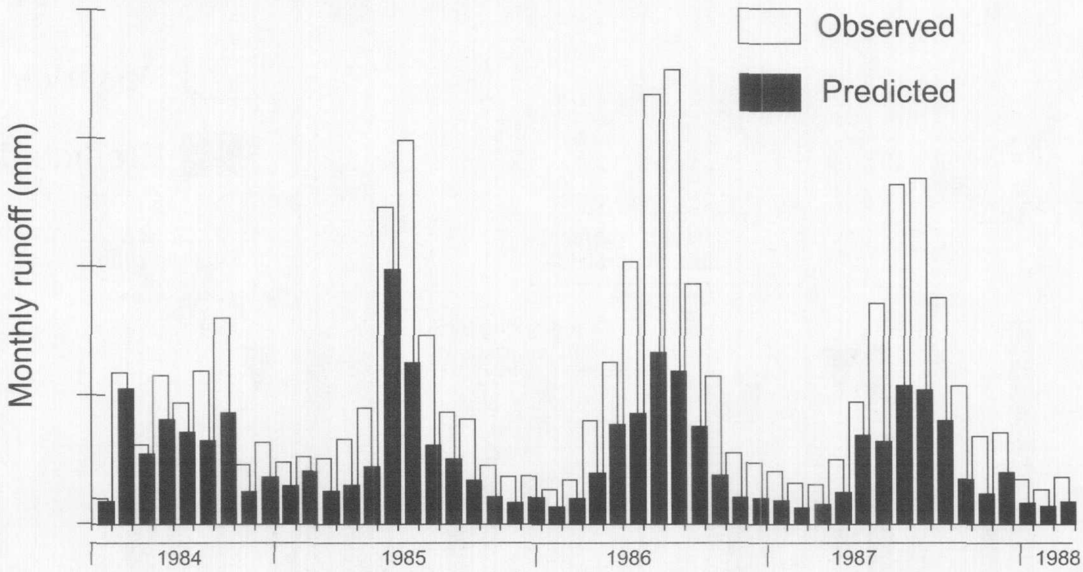

Table 5. Increases in weekly and equivalent annual (total) or dry season streamflow at Biesievlei, following riparian and upslope clearfelling.

Description of treatment or period	Period of analysis	No. of weeks	Observed mean weekly runoff (mm)	Change in weekly runoff relative to model prediction (mm; %)	Change in runoff (mm/year)*
Total flow					
Calibration	Apr. 1980 – Mar. 1984	209	4.2		
Riparian clearing	Apr. 1984 – Mar. 1985	52	7.2	2.4; 48	123.4
Clearfelling	Apr. 1985 – Mar. 1986	52	9.2	4.3; 89	224.6
First post-felling year	Apr. 1986 – Mar. 1987	52	12.3	7.3; 147	380.6
Second post-felling year	Apr. 1987 – Mar. 1988	52	10.3	5.8; 131	309.8
Dry season					
Calibration	Nov. 1981 – Mar. 1984	65	1.9		
Riparian clearing	Nov. 1984 – Mar. 1985	20	4.9	2.2; 81	43.2
Clearfelling	Nov. 1985 – Mar. 1986	21	3.4	1.6; 94	34.4
First post-felling year	Nov. 1986 – Mar. 1987	21	3.9	2.2; 135	46.8
Second post-felling year	Nov. 1987 – Mar. 1988	21	4.3	2.3; 130	49.1

*% change = [(observed – predicted)/predicted] × 100.

48%; Table 5). This provides some evidence to support the theory that a large part of the impact of trees in the riparian zone is through transpiration, which would dominate water use in the summer dry season. In subsequent dry seasons, once clearfelling commenced, there was little difference between the relative increases in the dry season and total runoff (Table 5).

Discussion

Witklip: sustained water yield gains

The water yield gains produced at Witklip by clearfelling and subsequent control measures in the riparian zone (44% per 10% cleared in the first year; 47% per 10% over 4 years; Table 6) are important from a water supply point of view. This is particularly the case as relative gains were greatest over the drought period (Table 4). The cost of followup treatments in the riparian zone may well be justified by the value of the additional water that is available to irrigators. However, the challenge is to economically maintain a short but healthy vegetation cover in the riparian zone. It is significant that the riparian zone at Witklip was safely burned, as fire is the most practical means of maintaining a healthy grass sward.

Biesievlei: wetting up of the soil profile

Some insights on the process by which the clearing of trees actually affects streamflow generation are available from a study of soil wetness across a single hill-slope profile in Biesievlei during the riparian and clearfelling operations (Steinhauer 1989). This study showed that before and after clearing, soil wetness at the bottom of a transect of neutron

Table 6. Summary table of the effect of riparian and upslope clearfelling on streamflow.

Catchment	Experimental treatment	Clearfelled Area (ha)	Clearfelled (%)[a]	First-year flow increases per area cleared ($m^3 \cdot ha^{-1}$)	(mm/10%)	(%/10%)
Westfalia D	Clearfelling indigenous riparian forest	4	10	5 445	55	9
	Clearfelling indigenous forest outside riparian zone	35.6[b]	100	2 700	27	3.5
Witklip 2	Selective cutting of larger riparian trees	11.2	8.2	7 966	80	44
	Clearfelling of pines outside riparian zone	42.6[b]	39.6	4 044	41	37
Biesievlei	Clearfelling of riparian pines	3	11	11 503	110	44
	Clearfelling of pines outside riparian zone	24.2[b]	98	3 430	35	14

[a]Total clearfelled area, as a percentage of catchment.
[b]Additional (upslope) area clearfelled.

probe access tubes (at depths below 2 m, and probably below most pine root systems) remained relatively constant, presumably indicating saturation. Above this, at between 1 and 2 m depth, clearfelling caused a 20% increase in soil wetness, whilst in the upper metre of the soil profile there was a roughly 30% increase in soil wetness. The overall increase in soil wetness would lead to a greater flow of water from the unsaturated storage (soil water) into the groundwater store, from where it would sustain baseflow in the stream.

The influence of vegetation type

The results of the three experiments are summarised in Table 6. Different measures of the water yield increases resulting from clearfelling are used in an attempt to make the results comparable. The absolute flow increases are similar at Witklip and Biesievlei (7966 and 11 503 $m^3 \cdot ha^{-1}$, respectively) and are roughly double the increase measured in the first year at Westfalia. Expressed as a percent increase per 10% of the catchment cleared, the flow increases at Witklip and Biesievlei are still the highest and of a similar size to each other (44% increase per 10% of catchment cleared), but the gains at Westfalia become relatively smaller (a 9% increase per 10% cleared, which was 20% of those recorded at Witklip and Biesievlei).

It is not immediately obvious why the response to riparian clearfelling was so much greater at Witklip than at Westfalia. Westfalia had indigenous high forest along the stream course, while that at Witklip was generally shorter, with a more broken canopy composed of trees of mixed heights. One possible explanation is that the riparian bush at Witklip with emergent tall trees, including pine and eucalypt invaders, was generally more productive (more vigorous growth) and had much higher transpiration rates relative to the mature forest at Westfalia. This is feasible, as single trees growing outside of a uniform canopy where they have a high advected energy supply, have been recorded as having particularly high individual water use rates (P.J. Dye, personal communication).

Previous work has shown that pine plantations in the Mpumalanga province have a higher water consumption than those in the Western Cape, where growth rates and evaporative demand are lower (Van Wyk 1987; Smith 1991; Scott and Smith 1997). It is therefore reasonable to deduce that the similar water use by riparian vegetation at Witklip and Biesievlei reflects a generally higher water use by pine plantation than indigenous riparian scrub forest. This is as would be expected too; relative to pine plantation the indigenous forest is slow growing and has a lower, thinner canopy.

The importance of riparian position

These experiments confirm that trees in the riparian zone use relatively more water than similar trees over the rest of the catchment. Reviewing afforestation and clearfelling experiments from around the world, Bosch and Hewlett (1982) concluded that clearfelling pine and eucalypt forest caused an additional flow of 30–40 mm for every 10% of the catchment cleared. Clearfelling of pine plantation in South Africa has resulted in measured flow increases of 52 mm per 10% at Witklip catchment 5 (Smith 1991) and 42 mm per 10% in Bosboukloof, Jonkershoek (Scott 1994). At Westfalia the initial flow increase after clearfelling of indigenous riparian forest was 55 mm (9%) per 10% cleared (although soon reversed), while the increase after clearfelling of all vegetation in the catchment in a dry year was a mere 27 mm (3.5%) increase per 10% clearfelled (Table 3). In Biesievlei, the first-year flow increase following the removal of mature pines in the riparian strip was 110 mm (44%) per 10% cleared (Table 6). Clearfelling of the remainder of the pines in this catchment, an estimated 89% of the plantation area, only increased flow by a further 25 mm for each 10% of the catchment cleared, or if gains in runoff are averaged equally over the whole clearfelled area, the increase is 35 mm (14%) increase per 10% (Table 6).

The situation at Witklip was somewhat different in that the riparian vegetation was shorter than the timber plantation that was clearfelled. But even here, the water use of the riparian zone vegetation, on a per unit area basis, was higher than that of taller vegetation outside of the riparian zone. Here, water yield gains after riparian clearfelling were 80 mm (44%) per 10% in the first year. Clearfelling of the plantation led to average flow gains over the whole catchment (August 1984 – July 1987) of 160 mm/year (145%), which equates to 41 mm (37%) per 10% cleared if attributed to both the plantation (42.6 ha) and riparian zone (11.2 ha).

Erosion and water quality

Throughout the world, it is accepted practice in forestry to minimise disturbance in streamside areas and to leave riparian strips as buffers against water-quality degradation and negative impacts on the aquatic communities. Results from limited studies of inorganic water-quality variables (suspended sediment, nitrogen, phosphate, potassium and silicon) in

Westfalia, Witklip, and Biesievlei could only show a weak or nonsignificant response to the riparian clearing in these experiments (Van Wyk and Scott 1993*a*, 1993*b*; Scott and Lesch 1996). However, neither stream temperature nor stream biota were monitored. Research in the Drakensberg mountain range has shown that regularly burned grasslands maintain the sound hydrological function of these watersheds (Van Wyk 1986; Scott and Schulze 1992). Hence, from a hydrological point of view, regular burning of riparian zones to maintain a healthy and dense grassland cover is a practical management option in Southern Africa. But the full ecological implications of this or other riparian clearing practices are uncertain and ought to be investigated prior to the adoption of such management options.

Conclusions

These experiments show conclusively for South African conditions that riparian forest, and in particular disturbed forest or plantation, is a more liberal user of water than vegetation in other parts of a catchment. The clearing of indigenous forest or timber plantations in the riparian zone of the catchment will result in gains in water yield disproportionately greater than the area affected. Clearing of trees in a riparian zone is likely to increase water yield by around three times as much as would the clearing of the same area of similar trees from an upslope position in that catchment. The South African policy of not afforesting these zones is therefore fully justified in terms of water yield.

The first-year gains in water yield estimated from these experiments represent the maximum possible savings resulting from riparian clearing as they are associated with a very large change in vegetation cover from a tall, dense canopy to a clean riparian zone. The gains in water yield that might be obtained from converting from timber plantations or indigenous forest to indigenous scrub or a weed infestation would be considerably less than measured in these experiments.

The water-use characteristics of indigenous forest are poorly understood and deserve further investigation. Despite their apparent similarities, the riparian vegetation at Westfalia and Witklip, which have a similar climate, responded quite differently in these experiments. At Witklip the riparian bush had a higher water use and water use recovered more slowly after the first clearfelling.

The clearing of a large riparian zone of indigenous forest at Westfalia led to increases in runoff in the first year, which were reversed in the second year. This suggests that short but vigorously growing vegetation can have water-use rates in excess of those of older taller vegetation and that clearing mature indigenous riparian forest in a riparian zone to increase streamflows is not worthwhile unless an alternative short vegetation can be practically maintained in its place. A riparian zone that is not planted to timber plantations must nonetheless be vegetated, and the results at Westfalia suggest that indigenous high forest is a good plant cover from a water-use point of view, as well as from ecological and aesthetic perspectives.

These conclusions are based on short periods of observation in individual experiments on quite different kinds of streams. It is desirable that such experiments are repeated over a wider geographical and vegetation range, and with longer post-treatment observation periods, so that estimates of water use by riparian vegetation can be made with greater confidence. These experiments share the advantages and disadvantages that are common to isolated catchment experiments: while all hydrological processes within the catchment are integrated in the results, the results in turn offer little explanation of the processes contributing to the effect. In retrospect, therefore, it is also apparent that these experiments would have benefited from simultaneous process studies within the catchments, designed to explain the mechanisms by which the clearing of riparian vegetation results in increased streamflows.

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