Changes in water yield after fire in fynbos catchments

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Abstract

Streamflow records from three subcatchments in the Zachariashoek research area near Paarl in the south-western Cape were analysed to determine the effects of prescribed burning of fynbos vegetation on streamflow. Treatments consisted of late spring (November) burns on six and twelve-year cycles.

Results indicate that burning six-year-old vegetation increased streamflow significantly. The most marked changes occurred in the 12-month periods immediately following two consecutive fires (1971 and 1977) in the same catchment. Streamflow increased by an average of 7,1 mm/month (15 % of the average monthly discharge over the three calibration years) after the 1971 burn, and by an average of 5,7 mm/month (7 % of average monthly discharge over six calibration years) following the 1977 burn. Burning of twelve-year-old vegetation in another catchment did not cause any significant increase in streamflow.

The effects of burning fynbos vegetation on streamflow are comparatively short-lived, and appear to be influenced by the rate of vegetation recovery. Changes in streamflow occur mainly during the rainy season.

Introduction

Approximately 30 % of the high rainfall catchment areas of South Africa are covered with fynbos (macchia) vegetation (Van der Zel, 1981). These areas are managed by the Forestry Branch of the Department of Environment Affairs to ensure a sustained yield of high quality water. Prescribed burning is an important management option to optimise water yield from these mountain catchments.

Catchment experiments throughout the world have demonstrated that water yield can be influenced by manipulation of vegetation (Bosch and Hewlett, 1982; Bosch *et al.*, 1984). Results have generally indicated that changes in water yield are directly related to changes in plant biomass (Wicht, 1971). It is expected that the reduction of plant biomass by burning will increase water yield by reducing transpiration and rainfall interception. The effects of fire in fynbos on streamflow are being investigated at several sites in the Cape Province. Published results to date are limited to one experiment at Langrivier in the Jonkershoek Valley near Stellenbosch (Van der Zel and Kruger, 1975). In this case fynbos was protected from fire for 25 years. Van der Zel and Kruger (1975) concluded from their analysis that growth of the fynbos resulted in a decline in annual streamflow at a rate of 1 % /a. A corollary was drawn that an increase in water yield, equal in magnitude to the progressive decrease due to growth, would follow burning of the protected fynbos. This logical deduction has not been tested. Preliminary analyses from other experiments in the western Cape also indicated possible large variations in streamflow response, depending on site, climate and vegetative factors. As management decisions to date have largely been based on the results from Langrivier, it is important to quantify the response of streamflow to fire in other areas in order to rationalise management decisions. This paper specifically examines the effects of burning on streamflow volumes in the Zachariashoek catchments.

The study area

The Zachariashoek catchments lie between the Klein Drakenstein and Wemmershoek Mountains near Paarl in the south-western Cape at latitude 39° 49'S and longitude 19° 02'E (Fig. 1). Climate is characterised by a relatively dry summer and a winter rainfall maximum. Mean annual rainfall is 1 280 mm calculated over a 10 year period (1969 to 1978).

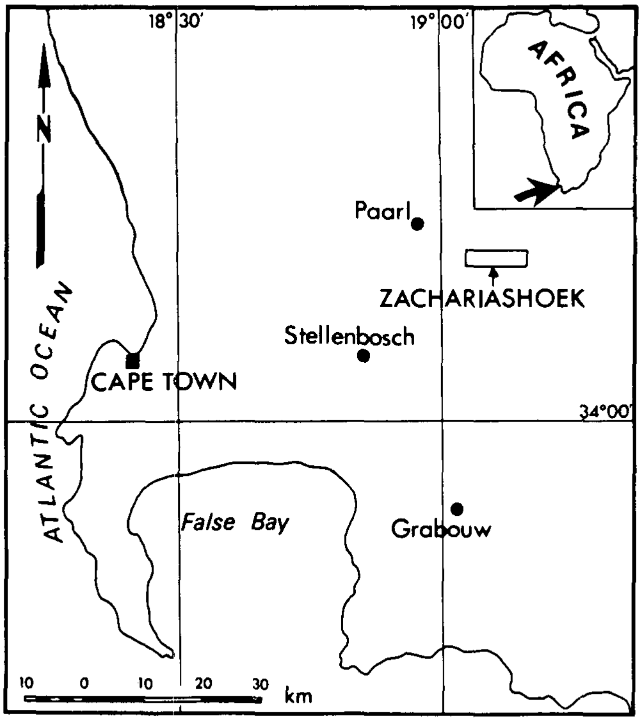

Figure 1
Location of the Zachariashoek research catchments.

Annual water balance components and streamflow-rainfall ratios for the experimental catchments are given in Table 1. The annual variations in water balance components are large and related to gross annual precipitation, but the pattern in the variations is similar in all three catchments. The streamflow-rainfall ratio in Zachariashoek is smaller than in the other two catchments.

The catchments are underlain by the Table Mountain Group of the Cape Supergroup. This group consists of quartzite, sandstone and narrow bands of shale and of tillite. Sandstone is the dominant parent material. Soils range from shallow to deep sands and are frequently rocky. Clay content is less than 8 % (Van Wilgen and Kruger, 1985).

The vegetation of the area falls within Acocks (1953) veld type 69 (fynbos). The vegetation communities have been described in detail by Van Wilgen and Kruger (1985). The dominant plant

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community is a Tall (up to 1m) Mid-Dense Herbland dominated by Restionaceae and Cyperaceae. Low shrubs (0,2 to 0,5m) are common but taller shrubs (up to 4m) occur only sporadically.

TABLE 1
MEAN ANNUAL WATER BALANCE OF THREE EXPERIMENTAL CATCHMENTS OVER A TEN-YEAR PERIOD (1971-1980)

Catchment	Rainfall (mm)	Streamflow (mm)	Evapotranspiration (mm)	Streamflow/ rainfall ratio (1%)
Zachariashoek	1 003(303*)	379(252)	623(126)	35(13)
Bakkerskloof	1 223(367)	586(299)	637(116)	46(11)
Kasteelkloof	1 443(434)	694(350)	749(182)	46(10)

* Standard deviation in brackets

Methods

The Zachariashoek catchment experiment was initiated in 1965 to establish the relationship between prescribed burning of mountain fynbos and water yield, vegetation composition and erosion (Van der Zel, 1974). The experiment includes 3 main subcatchments namely, Bakkerskloof (356,4 ha), Kasteelkloof (324,5 ha) and Zachariashoek (287 ha) (Fig. 2). Streamflow gauging commenced in October 1969. Treatments consist of late spring (November) burns on six and twelve-year cycles in the Kasteelkloof and Zachariashoek subcatchments respectively, and protection from fire in Bakkerskloof. Kasteelkloof and Zachariashoek were last burnt before commencement of the experiment in 1965, and Bakkerskloof in 1957. The fire history of the area is summarised by Van Wilgen and Kruger (1981).

Paired catchment analysis

The paired catchment experimental approach was used. This is a widely used method for the analysis of treatment effects on the hydrological response of a catchment (Wicht, 1967; Hewlett, 1983). Using this method, a relationship between the streamflows from two physiographically similar catchments is established for a calibration period during which vegetation cover remains unchanged. Deviations from the established relationship between streamflows after vegetation on one catchment has been altered, are then attributed to the vegetal change. Exclusion of climatic influences requires at least two catchments (control and treatment), and two experimental periods (calibration and treatment) (Table 2). The control catchment serves as the climatic standard throughout the experimental period, and is used in regression analysis to predict streamflow from the treated catchment. The deviations of observed streamflow from the expected (calculated) streamflow are assumed to reflect the effect of the treatment on streamflow.

After an initial period of calibration the Kasteelkloof and Zachariashoek subcatchments were burnt on 6 to 12-year cycles respectively while Bakkerskloof remained the control catchment (Table 2).

Dummy variable regression analysis

A multiple regression analysis using dummy variables (attributed in its present form to Gujarati, 1978; and Kleinbaum and Kupper, 1978) was used to determine temporal changes in the relationship between monthly streamflow from Kasteelkloof (6-year burning cycle) and Bakkerskloof catchments. Monthly values of streamflow and precipitation were used as the record was too short to permit accurate analysis of annual data. The dummy variable analysis of data from the Zachariashoek subcatchment showed that burning resulted in a decrease in streamflow. This unexpected result was investigated using a second technique, double mass curve analysis, on annual streamflow as a visual confirmation.

Streamflow from Kasteelkloof was expressed as a function of precipitation and streamflow from the control catchment by means of a multiple regression model:

$$Qt = a_0 + b_1Qc + b_2Pg + e \qquad (1)$$

where:

Qt = monthly streamflow from treated catchment

TABLE 2
SCHEDULE OF TREATMENTS FOR THREE EXPERIMENTAL CATCHMENTS IN THE SOUTH-WESTERN CAPE. THE YEARS IN WHICH THE KASTEELKLOOF (BURNT TWICE) AND ZACHARIASHOEK (BURNT ONCE) SUBCATCHMENTS WERE BURNT ARE INDICATED IN THE TABLE. THE CALIBRATION PERIODS AND THE PERIODS OVER WHICH BURNING EFFECTS WERE DETERMINED (TREATMENT PERIODS) ARE INDICATED BY DOTTED LINES

Catchment	Year											
	1969 (APR)	1970	1971 (OCT)	1972	1973	1974 (OCT)	1975	1976	1977 (OCT)	1978	1979	1980
Bakkerskloof (control)	◄ - - -	- - -	- - -	- - -	- - -	- - -	NO BURNING	- - -	- - -	- - -	- - -	- - - ►
Kasteelkloof (6-year cycle)	◄ - - -	Calibration period (T=O)	Burn (1) ►◄	- - -	Treatment period (T=1)	►◄	- - -	Calibration period (T=O)	Burn (2) ►◄	- - -	Treatment period (T=1)	- - - ►
Zachariashoek (12-year cycle)	◄ - - -	- - -	- - -	- - -	Calibration period (T=0)	- - -	- - -	- - -	Burn ►◄	- - -	- - -	Treatment period (T=1) ►

Note: By 1973 and 1979 post-fire streamflow trends in Kasteelkloof had stabilised to prefire levels.

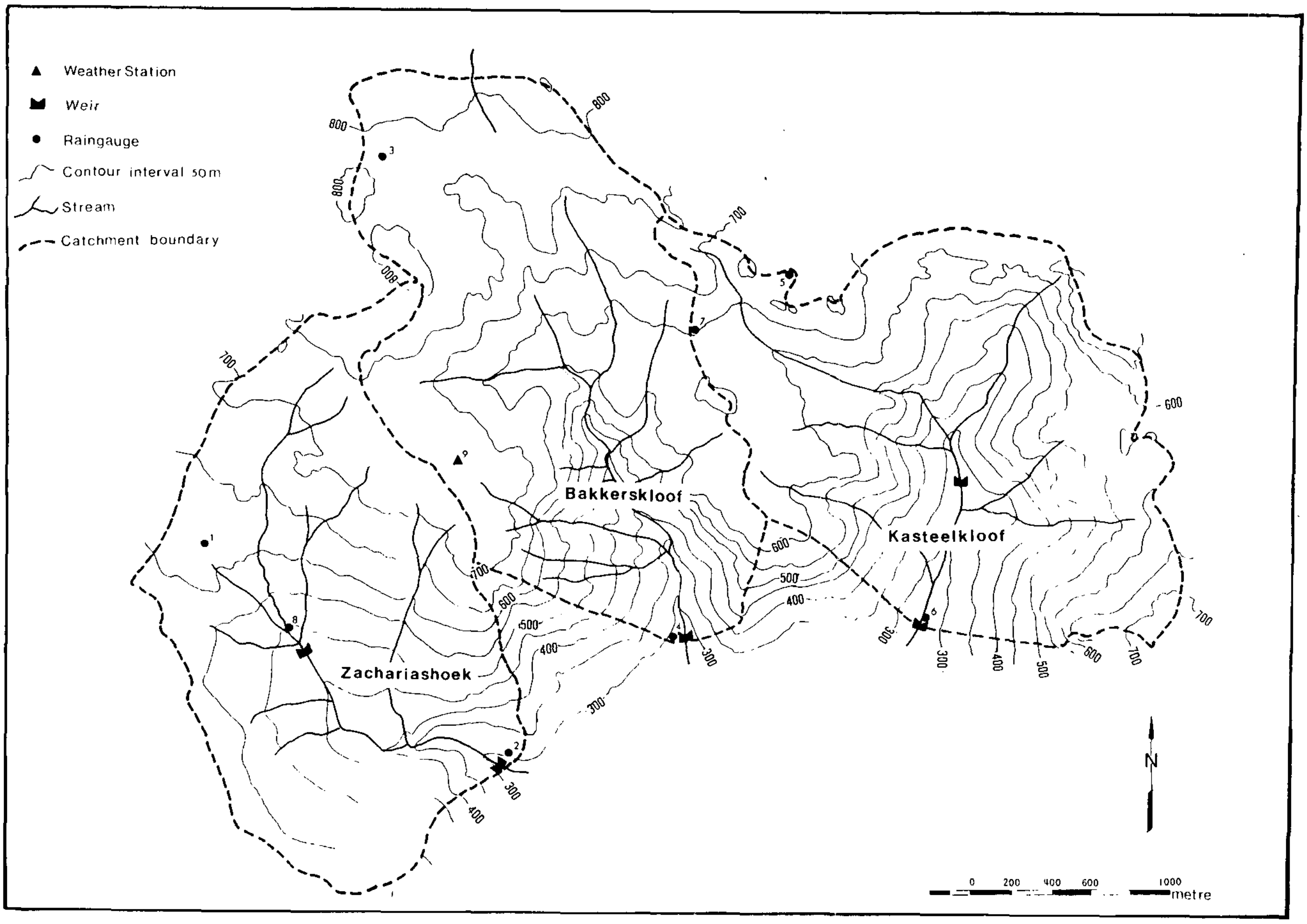

Figure 2
Map of the Zachariashoek catchments showing the three subcatchments, topographical features, catchment boundaries, and the position of weirs and rain gauges. Rain gauges 7, 9 and 8 were erected in 1976.

Qc = monthly streamflow from the control catchment
Pg = monthly precipitation (average of rain gauge 6 and 7 at the bottom and top of Kasteelkloof)
e = additive error term

This linear regression equation was extended to include a dummy variable T which was assigned a value of 0 for the calibration period and a value of 1 for the period after the burn (Table 2). The model was of the general form

$$Qt = a_0 + a_1T + b_1Qc + b_2TQc + b_3Pg + b_4TPg + e \qquad (2)$$

where:
a_1T = the differential intercept coefficient
b_2TQc and b_4TPg = differential slope coefficients

In order to test whether treatment had a significant effect on streamflow, the full and a reduced model (2 and 1 respectively) were compared. The full model (2) includes the effects of burning through the dummy variable T, while the reduced model where T = 0 does not contain T as a variable (1).

The following F-test was used to determine whether the full model(2) accounted for a significantly larger portion of the total sum of squares than the reduced model (1).

$$\text{Computed F} = \frac{(SS2 - SS1) / (df2 - df1)}{EMS2} \qquad (3)$$

where SS2 and SS1 are the sums of squares due to regression for the full and reduced models, and df2 and df1 are the degrees of freedom for the full and reduced models respectively. EMS2 is the error mean square computed for the full model (2). Variables in which the F-test was non-significant at the 0,05 level were excluded from further computations.

Changes in monthly streamflow were quantified by substituting overall mean values of the independent variables (streamflow and rainfall) in the full model (2).

Double mass curve analysis

The double mass curve technique was used to evaluate changes in streamflow in Zachariashoek (12-year cycle) relative to the control catchment. Double mass curve analysis tests the consistency of observations by comparing the accumulated values of the observations, such as annual precipitation or streamflow, with the corresponding accumulated values for a nearby representative catchment (Linsley *et al.*, 1982). A comparison is achieved by separate multiple regression analyses on the accumulative calibration and treatment data sets respectively. Any significant change in the slope of the curve (verified by a minimum of five points on a regression line) indicates a change at one measuring point relative to the other (Figs. 5 and 6). In this analysis the control catchment

(Bakkerskloof) was used as the baseline for comparison with the burnt catchment (Zachariashoek).

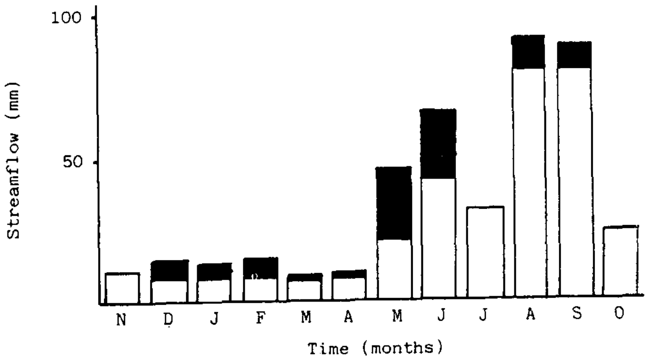

Figure 3
The bars (unshaded plus shaded) depict observed monthly streamflow in a fynbos catchment (Kasteelkloof) burnt in 1971 when the post-fire age of the vegetation was 6 years. The unshaded areas depict model predictions and the shaded areas increases in streamflow during the 12 months immediately following treatment.

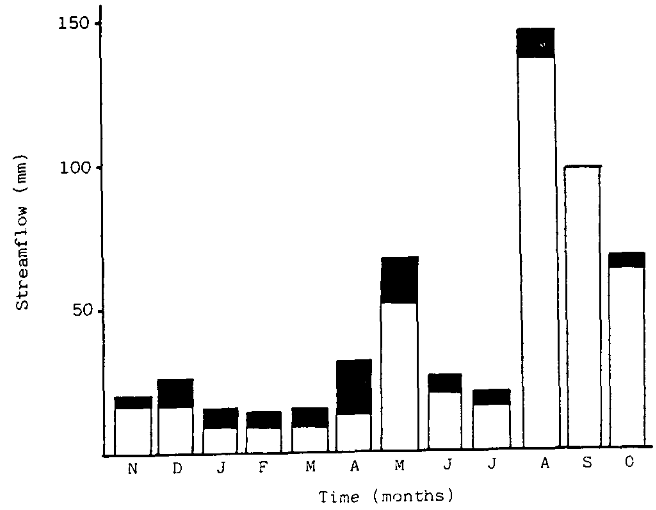

Figure 4
The bars (unshaded plus shaded) depict observed monthly streamflow in a fynbos catchment (Kasteelkloof) burnt in 1977 when the post-fire age of the vegetation was 6 years. The unshaded areas depict model predictions and the shaded areas increases in streamflow during the 12 months immediately following treatment.

Results

Burning on a six-year cycle (Kasteelkloof)

The results from the dummy variable regression analysis are presented in Table 3. Figs. 3 and 4 illustrate the increases in streamflow for the 12 months immediately following treatment (calculated from Equation 2) relative to the flow recorded during the calibration period (Equation 1).

TABLE 3
RELEVANT STATISTICS OF THE DUMMY VARIABLE METHOD (SEE TEXT), AND MEAN MONTHLY INCREASES IN STREAMFLOW FOR CONSECUTIVE YEARS FOLLOWING TWO DIFFERENT FIRES IN SIX-YEAR-OLD FYNBOS (KASTEELKLOOF)

Year of burn	Time after burn years	r^2 Full model	Computed F-value	Significance level	Mean monthly increase (mm)	% of mean monthly streamflow for two different calibration periods
1971	1	,98	18,7	0,001	7,1	15,6
	2	,98	5,0	0,05	0,9	2,6
	3	,98	5,5	0,05	2,6	4
	4	,98	2,1	NS	0	–
1977	1	,98	3,6	0,05	5,7	7
	2	,98	0,5	NS	0	–
	3	,98	0,2	NS	0	–

Burning produced a significant (P=0,001) increase in streamflow during the 12-month period immediately following the treatment in 1971 (Table 3). The mean monthly increase in streamflow was 7,1 mm (85 mm/a). This increase occurred mainly during the rainy season (Fig. 3).

Although the increases in streamflow during the second and third years following treatment were measurable (being significant at the 0,05 level), their low order of magnitude made it difficult to assign much practical importance to them. (Table 3). These results were therefore excluded from any further analysis. Discussion of the results below refers only to the first year following the burn.

The second burning operation in 1977 yielded a significant (p=0,05) increase in mean monthly streamflow of 5,7 mm (68,4 mm/a). By the second year following treatment streamflow had stabilised to pre-burn levels. The increments to flow were distributed fairly evenly throughout the year (Fig. 4).

Burning on a twelve-year cycle (Zachariashoek)

Analysis using the dummy variable approach outlined above indicated an insignificant increase of 2 mm in the mean monthly streamflow in the first year following treatment. A reduction of 7,4 mm in mean monthly streamflow was calculated in the treated catchment relative to the control catchment during the second year following treatment. Calculated mean monthly changes in streamflow, up to three years after the burn, are presented in Table 4.

The double mass curve technique was subsequently used (with an additional two years of data) as a visual display of the trends and to determine whether this apparent decline was the result of differences in precipitation on the two catchments, or whether the records differed on the basis of streamflow alone.

A comparison of accumulated annual precipitation data for the two catchments shows a fairly consistent record (Fig. 5). Although there is a shift in slope (albeit small) during the post-treatment period, this is insufficient to establish a significant difference between the two data sets.

Similar analysis of accumulated annual streamflow totals for both catchments shows a more definite change in slope during the five years following treatment, indicating a decrease in streamflow from the treated catchment relative to the control catchment.

TABLE 4
RELEVANT STATISTICS OF THE DUMMY VARIABLE METHOD (SEE TEXT) AND MEAN MONTHLY INCREASES IN STREAMFLOW DURING THREE CONSECUTIVE YEARS FOLLOWING A BURN IN 12-YEAR-OLD FYNBOS (ZACHARIASHOEK)

Year of burn	Time after burn (a)	r^2 Full model	Computed F-value	Significance level	Mean monthly increase (mm)	% of mean monthly streamflow over calibration periods
	1	,85	0,54	NS	+2	7
1977	2	,85	3,18	0,05	−7,35	–
	3	,85	1,69	NS	0	–

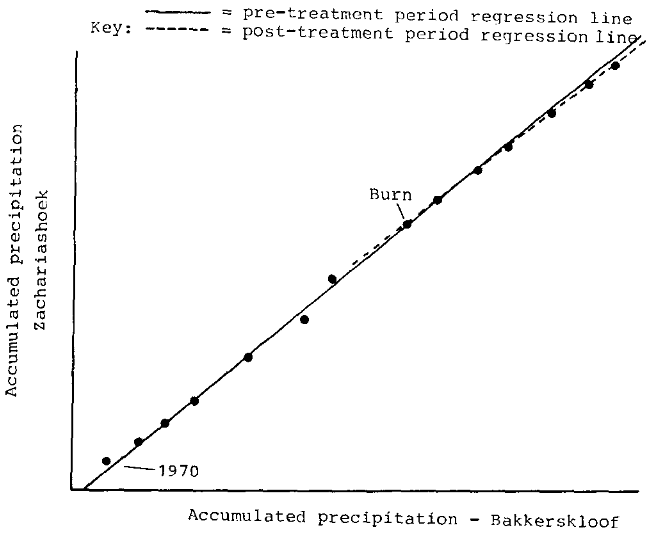

Figure 5
Double mass curve analysis for annual precipitation (1970 to 1983) in the Zachariashoek and Bakkerskloof catchments, showing consistency in their relationship. The mean of two rain gauges in each catchment was used to calculate catchment precipitation.

Discussion

The vegetation of the Zachariashoek catchments

Although the vegetation in the experimental catchments is potentially a Tall Open Shrubland, historical management resulted in a degradation of the vegetation and a resultant lower growth form. The history of these catchments is discussed in detail by Van Wilgen and Kruger (1985). They point out that the area was possibly used for grazing which required frequent burning with consequent depletion of the tall reseeding plant communities. Recent encroachment of the area by an exotic shrub *Hakea sericea*, required clearing and subsequent burning with high fuel loads. The resultant vegetation is a Tall Mid-Dense Herbland which differs markedly in growth form from that of relatively less affected mountain fynbos found in the nearby Wemmershoek Mountains. Van Wilgen and Kruger (1985) pointed out that the pre-experimental history of the catchments would have a bearing on the results of the experimental treatments and extrapolation of results obtained from them to more pristine areas with higher densities of large seed-producing shrubs.

Six-year burning cycles

Increments to streamflow are small and comparatively short-lived. This finding is apparently in contradiction to those of Van der Zel and Kruger (1975), who showed a gradual long-term decrease in streamflow with increasing post-fire age of the vegetation. The contradiction can be explained by the difference in vegetation types between Langrivier and the Zachariashoek group of catchments. Fynbos in the Langrivier catchment is a Tall Closed Shrubland formation, consisting predominantly of tall obligated reseeding shrubs. The canopy develops relatively slowly, but eventually becomes tall and dense. Evapotranspiration is expected to increase by following this trend. Assuming a direct but opposite effect of evapotranspiration on streamflow, one can expect a similar trend in streamflow reduction with canopy development. Fynbos vegetation in the Zachariashoek and Kasteelkloof subcatchments, on the other hand, consists of a high proportion of species that regenerate by sprouting. Regeneration of all or most of these species occurs within the first 2 weeks after a fire and recovery of the canopy (transpiring and intercepting surface) to pre-burn levels may occur within 12 months (Kruger and Bigalke, 1984). Secondly, while the recovery of vegetation at Zachariashoek is relatively rapid, the final biomass is low compared to that at Langrivier.

The differences in streamflow response in the two areas could thus be ascribed to the differences in the dynamics of the canopies. Because biomass is relatively low at Zachariashoek, removal of the canopy by fire will result in relatively smaller decreases in evapotranspiration and increases in streamflow. Streamflow will return to pre-fire levels more rapidly at Zachariashoek because of the higher proportion of sprouters. These arguments were used to develop a conceptual model to estimate streamflow increases when switching from one burning cycle to another (Bosch *et al.*, 1986).

Twelve-year burning cycles

Burning of 12-year-old vegetation was not expected to cause a reduction in streamflow. Streamflow on the treated catchment is calculated relative to the streamflow recorded during the calibration period and in relation to the streamflow in the control

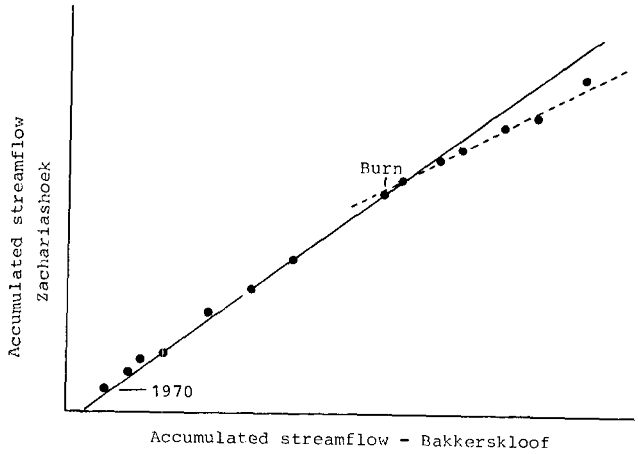

Figure 6
Double mass curve analysis for annual streamflow (1970 to 1983) in the Zachariashoek and Bakkerskloof catchments, showing a reduction in Zachariashoek relative to Bakkerskloof.

catchment (i.e. the decline is comparative). A possible explanation for the observed decrease in streamflow is that the rainfall in the catchments had changed relative to one another. Double mass analysis showed this not to be the case. Other factors may have influenced the data; an unobserved leak in the weir of the treatment catchment, for example, could have coincided with the treatment. This is regarded as unlikely. The observed reduction is thus inexplicable at this stage.

Conclusions

Results from the prescribed burns applied in fynbos vegetation at Zachariashoek suggest that streamflow response to burning is relatively small and short-lived. This is ascribed primarily to the nature of the vegetation in the catchments. Pre-experimental grazing, burning and weed eradication in the catchments have resulted in a relatively degraded fynbos vegetation which is not representative of pristine mountain fynbos. The conditions under which these experiments were carried out were conducive to reduced effects of fire on streamflow. Larger effects are expected in well managed fynbos areas and annual increases of more than 180 mm are expected in the first year after burning of old (more than 30 a) vegetation (Bosch *et al.*, 1986). Burning could therefore still be a useful tool for increasing water yield, especially in relatively pristine areas of higher biomass.

A major change in streamflow is easy to detect, but smaller changes are more difficult to measure with any degree of confidence. Where the change is small and the relative variability of runoff is high, as in the Zachariashoek catchments, it is difficult to separate treatment effects from normal random variations within the period of time over which the treatments become effective. For this reason these results, particularly those of the 12-year burning cycle, are of less practical significance in determining fire cycles in fynbos than would have been the case had the treatments been applied to pristine vegetation.

Six-year burning cycles have detrimental effects on fynbos vegetation in that the majority of seed-reproducing shrubs cannot mature and produce seed between fires. As a result, areas with short fire cycles are depleted of tall shrubs (Van Wilgen, 1981; 1982). In areas managed for nature conservation, such short fire cycles are unacceptable. This is certainly the case with most of the mountain catchment areas of the fynbos biome. For this reason, even if six-year fire cycles did increase water yield significantly, they would probably be unacceptable ecologically.

Acknowledgements

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