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THE CONTRASTING EFFECTS OF WILDFIRE AND CLEARFELLING ON THE HYDROLOGY OF A SMALL CATCHMENT

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ABSTRACT

A wildfire in an afforested research catchment presented the rare opportunity to compare the hydrological effects of wildfire with the effects of clearfelling in the same catchment in the Jonkershoek Valley, in the south-western Western Cape Province of South Africa. The timber plantation, which occupies 57% of the 2 km^2 catchment, had been clearfelled and re-planted to *Pinus radiata* roughly five years before the fire. The effects of the two treatments on total flow, storm-flow and quick-flow volumes, peak discharge and storm response ratio were determined by means of multiple regression analysis, employing the dummy variable method to test for the significance of treatments. Both clearfelling and wildfire caused significant increases in all the stream-flow variables analysed. But the clearfelling effect was dominated by large increases in total flow (96% over three years), of which storm-flow and quick-flow volumes formed only minor parts. After the wildfire, by contrast, increases in total flow were small (12%) but the storm flow increases were three- to four-fold in the first year and roughly double in the second year. The wildfire caused fire-induced water repellency in the soils which led to overland flow on mid-slope sites, where soil infiltrability normally far exceeds local rainfall intensities. It is argued that these results support the hypothesis that stream-flow generation processes were changed by the wildfire in that overland flow made a direct contribution to storm flows, but that clearfelling had no such effect. © 1997 by John Wiley & Sons, Ltd.

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KEY WORDS clearfelling (logging); storm flow analysis; stream flow generation; water repellent soils; wildfire

INTRODUCTION

An accidental fire in an afforested research catchment presented the rare opportunity to compare the effects of wildfire with the effects of clearfelling in the same catchment in the Jonkershoek Valley in the south-western Western Cape Province of South Africa. A wildfire in the Bosboukloof catchment caused marked increases in various storm-flow components. These effects were attributed, in part, to the role of fire-induced water repellent soils in causing overland flow, and the rapid delivery of water to stream channels (Scott and Van Wyk, 1990). As a partial test of this hypothesis the results of clearfelling in the same catchment were quantified and compared with the effects of the wildfire. The total water yield and storm-flow components were compared with pre-treatment baselines and with each other.

Hydrological consequences of fire may be assigned to two causes, namely (i) the reduced evapotranspiration in a burned catchment caused by the removal of most of the vegetation, and (ii) the direct effects of heating of the soil by the fire.

Catchment evapotranspiration (E) is the sum of evaporation from the soil surface (E_s) and open water surfaces (E_o), and of transpiration (E_t) and intercepted precipitation (E_i) (Hewlett, 1982), i.e.

$$E = E_s + E_o + E_t + E_i$$

In a well-wooded catchment E_s and E_o will be very small relative to E_t and E_i, to the extent that they may be neglected under fully afforested conditions (Hewlett, 1982). The understorey vegetation may form a

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significant part of the transpiration and interception losses. After a fire in a wooded catchment, the original major components of the above equation, E_t and are reduced almost to zero. To a minor extent this is compensated for by an increase in E_s as a consequence of increased net solar radiation on the ground through reduced albedo of the ash-blackened soil surface and increased wind movement over it. For instance, immediately after a fire in a tall grassland in Natal, South Africa, albedo decreased from 15% to nearly 3% at noon, and there were associated increases in soil temperature and net radiation (Savage and Vermeulen, 1983). Overall, however, a reduction in evaporation from the burned catchment can be expected after fire.

Fire and clearfelling, for the same reasons and to a similar extent, will reduce evaporative losses which will translate into increased stream flows. The size and magnitude of the changed stream-flow response following clearing of the vegetation will depend on the type, age and biomass of the vegetation supported by the catchment, the proportion of the catchment affected and the precipitation characteristics of the catchment, as indicated in the review of deforestation and afforestation experiments by Bosch and Hewlett (1982).

Reduced evaporative losses can be expected to increase general catchment wetness, resulting in generally higher storm-flow volumes and peak discharge. Examples of a deforestation-linked effect of fire are the increases in total flow recorded after fires in the Wilson River catchment in Oregon (Anderson, 1976), the Burns Watershed in Washington (Helvey *et al.*, 1976) and the Etajima Island catchments in the Hiroshima Prefecture of Japan (Kusaka *et al.*, 1983).

The second source of an altered hydrological response to fire is the direct effect of heating of the soil during the fire. Usually, severe heating of the soil will increase its erodibility (DeBano, 1981; Giovannini and Lucchesi, 1983; Watson and Poulter, 1987). The mechanism for this action seems to be the combustion of organic matter that is incorporated in the soil, where it is important in aiding micro-aggregation of the soil.

Soil heating, such as may occur during fire, has also been found to intensify water repellency in the soil (DeBano and Krammes, 1966; Dyrness, 1976; John, 1978; Scott and Van Wyk, 1990). Fire-induced water repellency in soils has been observed mostly in chaparral areas in southern California (Krammes and DeBano, 1965; DeBano and Krammes, 1966; DeBano *et al.*, 1970), but also in the states of Montana, Arizona, Oregon and Michigan (DeByle, 1973; Salih *et al.*, 1973; Scholl, 1975; Dyrness, 1976; McNabb *et al.*, 1989; Reeder and Jurgensen, 1979) as well as in New Zealand, Australia, Chile and South Africa (John, 1978; Leitch *et al.*, 1983; Ellies, 1983; Scott and Van Wyk, 1990, respectively).

The purpose of this paper is to compare the hydrological effects of clearfelling and a wildfire, specifically on the storm flow response of the catchment. A more marked storm flow response to wildfire would indicate an altered mechanism of stream-flow generation in the catchment.

DESCRIPTION OF THE CATCHMENTS

The treatment catchment, Bosboukloof, and its adjacent control, Lambrechtsbos-B, are in the Jonkershoek State Forest (33°57′S, 18°15′E), in the south-western Western Cape Province of South Africa. Some of the physical features of the catchments are summarized in Table I. The climate is mediterranean, with hot, dry summers and cool, wet winters. By Köppen's (1931) system, the climate may be classified as mesothermal (Csb) with a warm, dry summer (mean temperature of the hottest month $\leqslant 22°C$) and a relatively wet winter. Over 80% of the rain falls in a seven-month wet season between April and October (Wicht *et al.*, 1969) usually in long duration, low intensity, frontal events.

The indigenous vegetation of the area is fynbos, a sclerophyllous scrub dominated by species of Proteaceae, Ericaceae and Restionaceae. Along stream courses there are naturally occurring belts of native riparian forest. Both catchments have been afforested with *Pinus radiata* which is managed as a saw-timber crop on a 35–40-year rotation. Over the periods of comparison used in this study the forest cover in the control catchment has been stable, affording good experimental control. Details of the vegetation cover of the catchments are given in Table II.

The Peninsula Sandstone Formation of the Table Mountain Group underlies most of the two catchments and outcrops as cliffs in the upper elevations. It is highly folded and faulted and contains occasional shale

Table I. Summary of the physical features of the research catchments used in this study

Name	Area (ha)	Elevation of weir (m)	Relief (m)	Mean channel slope (%)	MAP* (mm)	MAR* (mm)
Bosboukloof	200	270	637	13	1296	593
Lambrechtsbos-B	65	292	828	26	1473	531

* MAP = mean annual rainfall, MAR = mean annual runoff (from Van Wyk, 1987)

Table II. Summary of the vegetation characteristics and treatments of the research catchments

Name	Native vegetation	% Afforested	Species afforested	Age at time of fire (years)	Treatment applied
Bosboukloof	tall, mountain fynbos	57	*Pinus radiata*	4–7	Clearfelled in 1979–1982; wildfire, dry season, February 1986
Lambrechtsbos-B	tall, mountain fynbos	82	*Pinus radiata*	22	Control for Bosboukloof

lenses. Beneath the sandstone, and outcropping occasionally in the lower parts of the valleys, is deeply weathered Cape Granite which allows deep penetration of roots and water.

The soils of the Jonkershoek catchments are derived from hard ortho-quartzitic sandstone and coarsely porphyritic granite. Weathering, soil creep and colluviation have resulted in a complex and varied distribution pattern of soil parent materials. The soils are friable and deep, with the main texture class being sandy loam. Their high gravel and rock content, low bulk density and high pore volume result in a high infiltration capacity and percolation rate (Versfeld, 1981).

Both catchments are traversed by roads (*ca*. 1% of catchment area) most of which were built prior to, or at the time of, afforestation, although the uppermost road in Bosboukloof was cut at the time of clearfelling. The initial disturbance caused by road-building is therefore not expected to have had a primary influence on the results of this study, although the road surface and drains may well have contributed to sediment losses.

DESCRIPTION OF TREATMENTS

Clearfelling of Bosboukloof

Bosboukloof catchment was felled using harvesting methods that were standard for the region. Felled trees were de-branched, cut to saw-log lengths, then pulled or rolled to the roadside by mule or hand (for very steep slopes). At the roadside the trees were loaded directly on to trucks for transport to the mill. These practices cause mildly compacted and bare skid-tracks to develop up and down the slopes, and loose sediments on the roads. Logging slash was piled in rows, which ran roughly up and down the slope. A sparse fynbos cover re-established within two years after clearfelling.

Clearfelling of the pine plantation in Bosboukloof was spread over four years, commencing in 1979 and completed in 1982. This meant that, unlike the fire which could be seen as a virtually instantaneous treatment, there was a long period when Bosboukloof was neither cleared nor fully planted. For this reason some storm flow data were omitted from the analysis during the treatment period. The pre-treatment period was taken as the hydrological years (April–March) of 1977 and 1978, and post-treatment as the period after 70% of the plantation was cleared (in effect, the hydrological years of 1981 and 1982). For the analysis of total flow the continuous flow record was used, so as to determine at what stage clearing began to have an effect. Cleared compartments were replanted, on average, within a year. Over the short period of comparison in this study the second rotation crop was not expected to influence streamflow noticeably as Van Wyk (1987) had only detected stream flow reductions in the seventh year after the initial planting of this same catchment.

The Wildfire in Bosboukloof

On 16 February 1986, towards the end of a particularly long, dry summer (1·4 mm of rain in the previous month and 54·1 mm in the previous three months) and under adverse conditions (maximum temperature for the day of 38°C, minimum relative humidity of 12% and wind speed at 1400 hours of 13 km h^{-1}), a wildfire swept through 80% of the Bosboukloof catchment. Fuel loads were high because logging slash from four to seven years previously had been left on-site. Most of the slash had been concentrated into wind-rows, roughly 1·5 m wide every 10 m, and had been added to by a first pruning of the young second-rotation pine crop. Mean dry fuel loads measured subsequently in adjacent unburnt plantation were 15 kg m^{-2} and 1·1 kg m^{-2} on and between the slash piles, respectively. Actual fuel loads varied considerably as felling and re-planting of the catchment had been spread over four years. Many of the old pine stumps from the previous rotation were also consumed in the fire. The result was a fire characterized by a very high rate and absolute amount of energy release. The treatments are summarized in Table II.

The stream flow variables measured over the three hydrological years (April–March) 1983 to 1985 were used to develop calibration relationships against which the same variables measured in the first two years after the fire (1986 and 1987) were compared.

METHODS

Stream Flow

Data collection. The catchments used in this study are established hydrological research catchments, gauged with compound 90° V-notch weirs. Stream flow stage height through the notches is monitored continuously using Belfort chart recorders. For this study, stream-flow charts were digitized and stream-flow volumes summed over weekly periods. The stream-flow volumes and annual rainfall, summed by the hydrological year of April to March, are presented in Table III.

The effects of fire on storm flow were assessed from an analysis of storm hydrographs which were separated using the method of Hewlett and Hibbert (1967; Figure 1). The separation of hydrographs, despite criticisms of artificiality (Beven, 1987), is none the less a useful tool for the study of the behaviour of small catchments. Hewlett and Hibbert (1967) proposed a standard slope of the separation line which is independent of catchment area (*viz.* 0·002 mm h^{-1} h^{-1}; Figure 1) which allows comparison of storm flows in different catchments. In the smallish, humid catchments used in this study, this slope, although of itself arbitrary,

Table III. The rainfall and stream flow in the two study catchments summed by hydrological year (April to March) over the full study period

Hydrological year*	Lambrechtsbos-B		Bosboukloof	
	Rainfall (mm)	Stream flow (mm)	Rainfall (mm)	Stream flow (mm)
1977	1510	737	1552	940
1978	823	171	947	268
1979	808	132	958	302
1980	943	136	1210	330
1981	986	159	1096	464
1982	1051	112	1098	355
1983	786	243	1191	644
1984	1188	266	1329	510
1985	865	332	1166	536
1986	1026	338	1068	657
1987	901	319	1076	623
1988	1053	257	1087	443

* 1977 denotes, for example, the hydrological year from April 1977 to March 1978

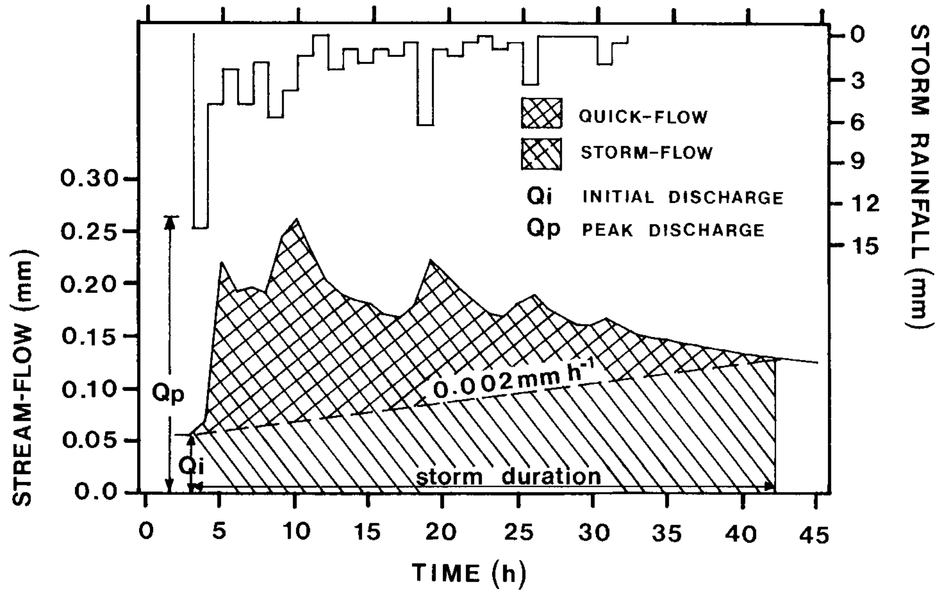

Figure 1. The standardized storm hydrograph classification method of Hewlett and Hibbert (1967) applied to an actual storm event (18 July 1988) in the Bosboukloof catchment

produced intuitively realistic results, i.e. comparable to graphical methods. This method is consistent, objective and allows comparison of storm flow response from disparate areas (Hewlett and Hibbert, 1967; Ward, 1975).

The following variables were measured from each storm hydrograph:

(i) storm-flow volume, i.e. the total volume of runoff over the period of storm flow,

(ii) quick-flow volume, i.e. that portion of storm flow above the fixed-slope separation line of Hewlett and Hibbert (1967),

(iii) peak discharge, i.e. the highest flow rate during the storm,

(iv) initial discharge, and

(v) storm flow duration.

The associated storm rainfall depth, duration and maximum one- and two-hour rainfall depths were derived from a single recording Casella rain gauge located at the foot of each catchment. As the rain gauges do not provide accurate areal assessments of rainfall over the whole catchments, the response ratio is overestimated as storm rainfall has a low bias. The same criteria applied by Hewlett and Bosch (1984) for the inclusion of storms were followed, i.e. at least 20 mm of rainfall without an interruption of more than six hours. This cut-off level excluded few storms that produced distinct hydrographs, i.e. hydrographs that could reasonably be separated. The mean pre-fire values of the variables used in the storm-flow analysis are shown in Table IV. The low storm response ratio of the Bosboukloof catchment is apparent, with quick-flow representing only 2·4% of storm rainfall in the three-year calibration period.

Data analysis. The paired catchment approach was used on the stream-flow data to test for possible effects of clearfelling and fire. This method requires the pre-treatment calibration of the stream flow in the catchment to be treated against observations from a similar, control catchment. The calibration relationship, expressed as a multiple regression model, was then used as a baseline against which possible treatment effects could be measured.

Table IV. The mean and standard deviations of the storm-flow variables measured in the research catchments over the pre-fire calibration period

Catchment		Bosboukloof (burned)	Lambrechtsbos-B (control)
n		34	31
Storm rainfall (P) (mm)		47.6 ± 27.6	40.4 ± 23.8*
Storm duration (h)		24.6 ± 14.3	23.8 ± 14.4
Maximum rainfall intensities	(mm in 1 h)	10.3 ± 4.2	9.9 ± 3.9*
	(mm in 2 h)	15.0 ± 5.6	14.7 ± 5.0*
Initial discharge (mm day^{-1})		1.56 ± 5.04	0.98 ± 0.75
Peak discharge (mm day^{-1})		6.62 ± 5.04	4.46 ± 4.46
Storm flow (mm)		3.69 ± 3.81	3.07 ± 3.77
Quick flow (Q) (mm)		1.40 ± 1.74	1.45 ± 2.10
Response ratio (Q/P) (%)		2.4 ± 1.8	1.9 ± 2.0*

n = Number of storms in the sample
* = Rainfall data for 11 larger storms during the earlier period of record were missing owing to instrument malfunction

The statistical test for treatment effects was the dummy variable method, attributed to Gujarati (1978) and its application to similar hydrological data outlined by Hewlett and Bosch (1984) and Hewlett and Doss (1984). For individual storm events the multiplicative regression model of the general form

$$T = \exp^{\beta_0} C^{\beta_1} P^{\beta_2} I_{60}^{\beta_3} I_{120}^{\beta_4} Q_i^{\beta_5} D^{\beta_6} \varepsilon$$

was developed for each of the dependent (treatment catchment) storm-flow variables, using the REG and STEPWISE procedures of the SAS statistical package (SAS Institute, 1985) where

T and C = the corresponding treatment and control catchment variables
P = storm rainfall (mm)
I_{60} and I_{120} = maximum 1 h and 2 h rainfall depths (mm), respectively
Q_i = initial discharge (mm day^{-1})
D = storm duration (h)
ε = the model error term and
β_0–β_6 = fitted regression coefficients

By taking the logarithm of each variable and introducing a dummy variable, F, which assumes the value 0 for the pre-treatment condition and 1 for the post-treatment condition, the following intrinsically linear, full model accounts for the treatment results:

$$T' = \beta_0 + \alpha_0 F + \beta_1 C' + \alpha_1 FC' + \beta_2 P' + \alpha_2 FP' + \beta_3 I'_{60} + \alpha_3 FI'_{60} + \beta_4 I'_{120} + \alpha_4 FI'_{120} + \beta_5 Q'_\mathrm{i} + \alpha_5 FQ'_\mathrm{i} + \beta_6 D' + \alpha_6 FD' + \varepsilon'$$

where the prime (′) indicates the logarithm of the variable in each case, and α_0–α_6 are the additional fitted regression coefficients for the full model.

The coefficients β_0 and β_1–β_6, respectively, give the intercept and 'slope' of the calibration relationship (i.e. pre-treatment state) between the catchments, i.e. when $F = 0$. The coefficients α_0–α_6 adjust the relationship for a post-fire state, i.e. when $F = 1$. The rejection of the null hypothesis ($H_0 : \alpha_i = 0$) for any coefficient, i, indicates that the fire term explains a significant part of the variation in the dependent storm-flow variable. The test of the null hypothesis, $H_0 : \alpha_i = 0$, is performed with the t-test for entry of the associated term into the model. This t-statistic can be shown to be the equivalent of an F-test for the extra sum of squares owing to entry of an additional term to the model (Kleinbaum and Kupper, 1978).

Table V. Significant ($\alpha < 0{\cdot}05$) predictor terms in the multiple regression models for the Bosboukloof catchment developed over the pre-clearing and full periods (pre- and post-clearfelling) of stream-flow data. The presence of the clearfell dummy variable (F) in the full models indicates a significant effect of felling

Dependent variable	Calibration period (before clearing)			Full measurement period		
	Significant predictor terms	Error d.f.	Adjusted R^2	Significant predictor terms	Error d.f.	Adjusted R^2
Weekly stream flow	C, S	108	0·98	C, S, F	470	0·89
Storm-flow volume	C, P, Qi	24	0·98	C, P, Q_i, F	53	0·98
Quick-flow volume	C	24	0·97	C, P, Q_i, F	53	0·97
Peak discharge	C	24	0·89	C, Q_i, F	54	0·91
Response ratio	C	24	0·94	C, Q_i, F	53	0·91

C = the corresponding control catchment variable; S, F = dummy variables for season and clearfelling respectively; P = storm precipitation; Q_i = initial discharge.
d.f. = degrees of freedom.

Table VI. Significant ($\alpha < 0{\cdot}05$) predictor terms in the multiple regression models developed for the pre-fire and full periods of stream-flow data in the Bosboukloof catchment. The presence of the fire dummy variable (F) in the full period models indicates a significant effect of fire

Dependent variable	Calibration period			Full measurement period		
	Significant predictor terms	Error d.f.	Adjusted R^2	Significant predictor terms	Error d.f.	Adjusted R^2
Weekly stream flow	C, R, S	94	0·89	C, S, F	198	0·97
Storm-flow volume	C, Q_i, D	28	0·98	C, I_{60}, Q_i, D, F	62	0·98
Quick-flow volume	C, P	30	0·96	C, I_{60}, P, D, F	62	0·98
Peak discharge	C, I_{120}	30	0·96	C, I_{60}, I_{120}, F	63	0·97
Response ratio	Pd, I_{60}	31	0·94	$Pd, I_{60}, I_{120}, D, F$	62	0·94

R = weekly rainfall (mm); C = the corresponding control catchment variable; F, S = dummy variables for fire and season, respectively; D = storm duration (h); P = storm precipitation (mm); $I_{60,120}$ = maximum rainfall (mm) over 1 h and 2 h periods; Q_i = initial discharge (mm day^{-1}); Pd = peak discharge (mm day^{-1}) in control catchment; used to predict response ratio because of missing rainfall data in the control catchment

The total flow (summed by weekly flow volume) was analysed by the same procedure, except that the model contained fewer predictor terms. The independent variables in the best reduced model were chosen from control catchment stream flow, weekly rainfall and dummy variable terms to account for a seasonally changing relationship between control and treatment catchments. The full model had, in addition, the necessary treatment dummy variable terms.

As with most hydrological data there is some relationship between adjacent data points (sequential storm events and weekly flow volumes) relating to such things as seasonal changes, but statistically these data points can be treated as independent observations because of the independent control that is available.

The calibration regression models were used to predict values of each of the dependent variables of interest for the post-treatment periods. Where a significant effect was found, the difference between these predicted values and the actual measured values (i.e. the deviations from the calibration relationship) were generated to indicate the nature and extent of any response in the dependent variables to the clearfelling or fire.

RESULTS

The fit and predictor terms of the reduced (calibration) and full regression models for the clearfelling and wildfire treatments are given in Tables V and VI, respectively. In all cases the fit of the calibration regression

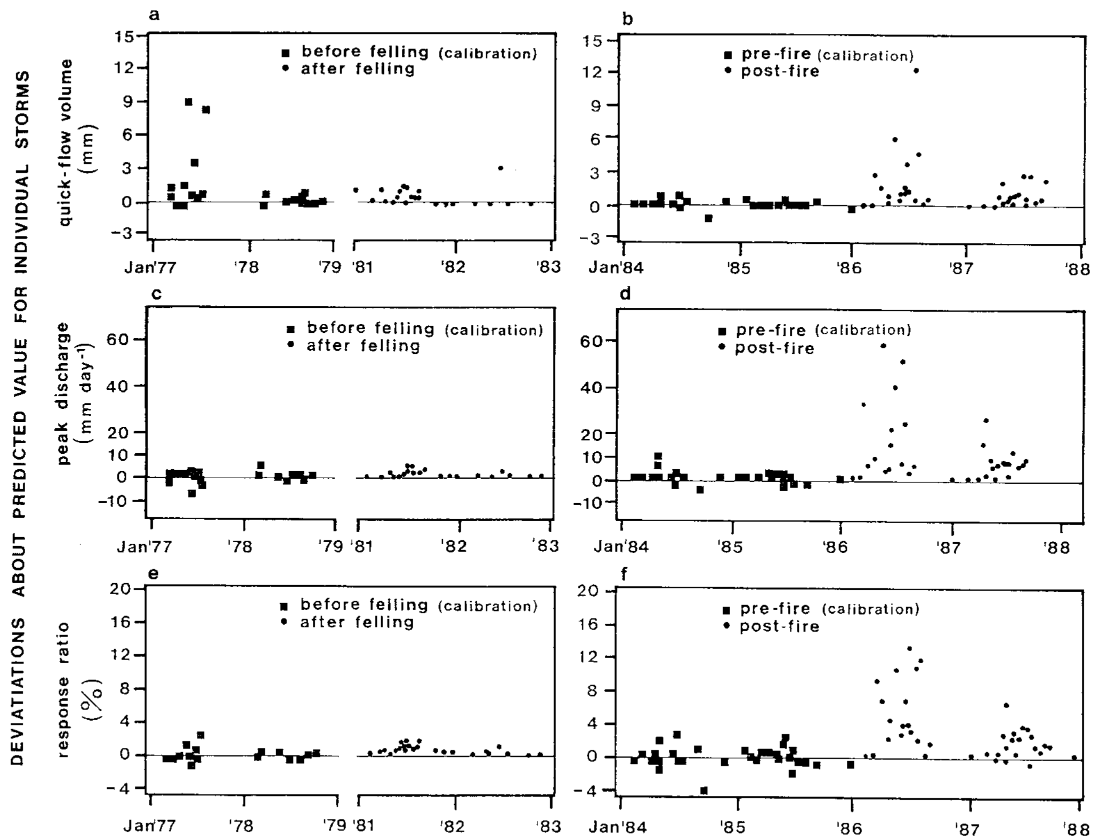

Figure 2. Time plots of the differences between the observed and expected values (deviations about regression) of quick-flow volume (a, b), peak discharge (c, d) and response ratio (e, f) in Bosboukloof over the calibration periods and after clearfelling and wildfire

models is good (the weakest being the pre-felling calibration model for peak discharge, which has an adjusted R^2 of 0·89 with 24 degrees of freedom) and improved for the full models. The significant entry of the treatment dummy variable (F in Tables V and VI) into the full models indicates a significant treatment effect. For both treatments and every stream-flow variable tested the null hypothesis of no change (in the relationship between the treatment and control catchments) could be rejected at, at least, the 95% confidence level.

The nature and extent of the treatment effects on the storm flows is clearly visible in the time trend plots of deviations in individual storm events about the regression models (Figure 2). The pattern of deviations in storm-flow volumes was much the same as for quick-flow volume, and hence these have not been plotted. It can be seen that deviations are greatest during the winter season (mid-year) when stream flows and storm flows are highest. Deviations are greater and consistently positive following treatments, indicating increases resulting from the treatments. The deviations (increases) following the wildfire are much greater than those following clearfelling, although the size of deviations in the second post-fire year are noticeably smaller than those immediately after the wildfire.

Effects of Clearfelling

Clearfelling caused significant increases in all the measured storm-flow variables: storm-flow and quick-flow volumes, peak discharge and response ratio (Tables V and VII; Figure 2a, 2c and 2e). In the two post-felling hydrological years (1981 and 1982) storm-flow volumes increased by a mean of 0·45 mm per storm

Table VII. Increases in stream-flow variables as a result of clearfelling of timber plantations in the Bosboukloof catchment

Stream-flow variables	Recorded pre-felling (1977, 1978)		Recorded in 1981		Change over expected value*	Recorded in 1982		Change over expected value*
	mean	*n*	mean	*n*		mean	*n*	
Weekly stream flow (mm)	11·1	112	8·9	52	97% increase	6·8	52	102% increase
Storm flow (mm)	6·9	29	2·7	20	25% increase	1·8	13	18% increase
Quick-flow volume (mm)	1·8	29	0·9	20	62% increase	0·6	13	37% increase
Peak discharge (mm/day)	6·8	29	5·8	20	53% increase	3·1	13	30% increase
Response ratio (%)	2·5	29	2·3	20	70% increase	1·2	13	36% increase

* Change is calculated as {(Observed − Predicted)/Predicted} × 100%

(23%) which was composed largely of quick-flow volume increases of 0·30 mm (53%); while peak discharge and response ratio increased by means of 46 and 60% per storm respectively.

Actual means of the storm-flow variables shown in Table VII declined in the two post-clearing years, which had drier wet seasons than the calibration period. Relative to the expected values after felling, however, (based on the calibration relationships) there were clear, significant increases in all the variables measured. By the wet season of 1982 all the timber plantations had been clearfelled but some re-planted timber stands were well established by this time, and the increase in storm-flow variables is consequently smaller in this second year (Table VII; Figure 2).

Table V shows the significant predictor terms and the fit of the models for the calibration and full periods of data. The pre-clearing models, except for storm-flow volume, are simple, containing only the control catchment equivalent of the independent variable as predictor. After clearfelling, initial discharge (an indicator of catchment wetness) and precipitation became significant predictors in the models for the storm-flow variables. This indicates that following felling the catchment was more responsive to antecedent wetness and rainfall.

As would be expected, weekly stream flow was also significantly increased by clearfelling (Table V). Clearfelling caused a significant increase in total flow as early as 1979 when less than half the plantation had been felled (Figure 3). In this year the increase over the expected flows was 94 mm (19%) and the increase became steadily larger, peaking over the three years 1981 to 1983, when the annual increase averaged 237 mm (a 96% increase). By 1985 water yield was still significantly greater than expected, but clearly approaching the pre-treatment condition. The magnitude of the total flow increases following clearfelling agree closely with the yield decreases measured following initial afforestation. The water yield decline in Bosboukloof between the 16th and 39th years after afforestation was estimated to average 201 mm per year (Van Wyk, 1987).

Effects of Wildfire

The fire caused a marked increase in stream flow and, particularly, in the various storm-flow components (Tables VI and VIII, Figure 2b, 2d and 2f).

The observed means of the stream-flow variables and the estimated increases following fire are given in Table VIII. Storm-flow volume increased by means of 2·4 mm (62%) and 0·9 mm (20%) per storm in the first and second post-fire years, respectively. These increases were composed mainly of observed mean quick-flow volume increases of 2·2 mm (201%) and 0·8 mm (47%) in the first and second post-fire years, respectively. Peak discharge increased by means of 17·3 (290%) and 6·8 mm day^{-1} (108%) over the two post-fire years, and response ratio increased from a pre-fire mean of 2·4% to means of 7·5% (242% increase) and 4·1% (88% increase) over the two post-fire years.

Annual stream-flow volume (total flow) showed small but significant ($\alpha < 0{\cdot}01$) increases of 70 (12%) and 61 mm (11%) in the first and second years, respectively. The first year increase in total flow was

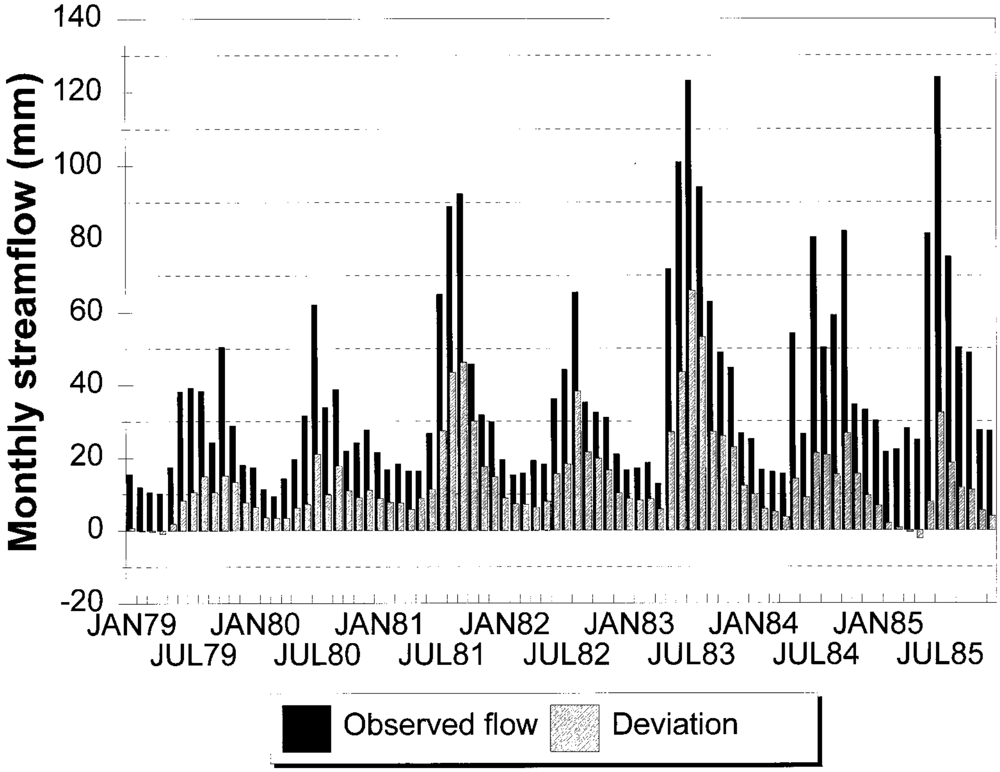

Figure 3. A time plot of the observed, and deviations about expected, monthly stream flow in Bosboukloof over the clearfelling and post-felling periods

composed largely (57%) of increased quick-flow. This implies that only 30 mm in the year could be attributed to an increase in baseflows, and hence the overall wetness of the catchment. In the second year quick-flows composed only 25% of the total flow increase. This indicates a rapid return to pre-fire stream-flow generation in the burned catchment.

Table VIII. Increases in stream-flow variables as a result of the wildfire in the Bosboukloof catchment

Stream-flow variables	Recorded pre-fire		Recorded in first post-fire year (1986)		Change over expected value*	Recorded in second post-fire year (1987)		Change over expected value*
	mean	*n*	mean	*n*		mean	*n*	
Weekly stream flow (mm)	9·9	11 2	14·1	4 4	12% increase	11·4	5 3	11% increase
Storm-flow (mm)	3·7	34	6·4	1 8	62% increase	5·1	1 9	20% increase
Quick-flow volume (mm)	1·4	34	3·6	1 8	201% increase	2·2	1 9	47% increase
Peak discharge (mm day^{-1}) {m^3 s^{-1}}	6·6 {0·2}	34	22·5 {0·75}	1 8	290% increase	12·0 {0·40}	1 9	108% increase
Response ratio (%)	2·4	23	7·5	1 8	242% increase	4·1	1 9	88% increase

Change is calculated as {(Observed − Predicted)/Predicted} × 100%

DISCUSSION

Wildfire Effects

Scott and Van Wyk (1990) hypothesized that the hydrological effects of the wildfire in Bosboukloof were a result of overland flows on mid-slope sites caused by the presence of water repellency in the soils. Their survey of soil wettability showed an increased frequency and degree of repellency below the surface of soils in the burned pine plantation that was positively related to fire intensity. The layered appearance of water repellency in the soils of Bosboukloof after fire was quite marked, and agreed with descriptions of fire-induced repellency reported in Oregon and California (Dyrness, 1976; DeBano, 1976).

It was observed that rain-water readily infiltrated the wettable surface soil, but further percolation was impeded by the repellent layer. When the net water entry rate was lower than the rainfall intensity, the surface soil layer eventually became saturated, and, under such conditions, saturation overland flow was observed in Bosboukloof. This is the mechanism by which overland flow arose on soils that would otherwise appear to have an infiltration capacity well in excess of local rainfall intensities. A short spate of rainfall, of as little as 3 mm, in the middle of an average rainstorm of *ca*. 20 mm was enough to initiate overland flow.

Additional evidence for the occurrence of overland flow after the wildfire is the increased soil loss and erosion that was observed. Clearfelling alone had little observable impact on sediment yield from Bosboukloof catchment (D. B. Van Wyk, unpublished data), but the fire caused a marked increase in erosion was attributed to the occurrence of overland flow, an increased erodibility of the severely heated soils and the loss of ground cover.

Part of the effect of fire is the removal (by combustion) of plant litter from the soil surface in higher intensity fires. This effect is clearly important in reducing surface storage capacity (retention and detention) on the site, and in removing obstacles to the flow of water and the transport of eroded soil particles. Given a reduced infiltration capacity in the soils, as a result of water repellency shallowly below the surface, the absence of surface litter was important in reducing the amount of rainfall needed to generate overland flow.

Overland flow was observed to concentrate on the compacted logging paths which had resulted from the clearfelling operation, and on the road system where drains and culverts soon became blocked with sediment and organic debris. This concentration of flow probably exacerbated the erosion problem.

The stream-flow results show that the wildfire caused a marked deterioration of the catchment's 'control' of rainfall. The increase in peak discharge was greater than the increase in quick-flow, indicating a steepening of the hydrograph. This inference is supported by an analysis of storm duration, which showed that storm-flow duration was no longer after the fire than before. The increase in total stream-flow volume was composed largely (92%) of increased quick-flow volumes; in short, a change to a more responsive catchment behaviour. Further evidence of this change is the appearance of rainfall depth and rainfall intensity as predictor terms in the post-fire regression models for storm-flow variables (Table VI).

Comparison of Clearfelling and Fire Effects

The total flow increases following clearfelling were larger than those measured following the wildfire. This resulted from the fact that the fire burned a young plantation, which did not have the full water consumption of the mature plantation that had been logged. It can be seen from Figure 3 that stream flow in Bosboukloof over the period 1984 and 1985 was above that expected from a mature plantation. Yet this was the period used as calibration for the fire treatment, and hence stream-flow increases, as a result of fire were being measured against a fairly high base level. This contention is also supported by the presence of catchment wetness (initial discharge), rainfall depth or rainfall intensity in the pre-fire storm-flow prediction models (Table VI).

It is postulated that the significant increases in storm-flow variables following clearfelling relate to the generally higher wetness of the catchment during and following clearing (Figure 3), and the consequently larger saturated zone or variable source area during rainstorms. As a result, catchment wetness and rainfall depth became significant predictors of storm flows after felling (Tables V and VI; calibration period). In comparison to the effect of fire, however, clearfelling caused only small increases in the storm-flow variables. After fire the storm flows were both larger and showed larger increases: three- to four-fold in the first post-fire year, and roughly double in the second year (Table VIII). After clearfelling the equivalent increases were of the order of a half and a third larger than expected (Table VII).

These results support the hypothesis that stream-flow generation changed after the wildfire and that surface runoff became an important component of storm flow. The much larger storm-flow increases after fire indicate the change in the stream-flow generating mechanism in the catchment. The first year increase in total flow after fire was 70 mm, of which 40 mm was an increase in quick-flow volume. Following clearfelling the overall increase in stream flow was greater, but quick-flow volume formed a minor part of the increase.

CONCLUSIONS

Both clearfelling and wildfire caused significant increases in total flow volume, storm-flow and quick-flow volume, peak discharge and response ratio, but the size and composition of these increases were quite different. The increases in total flow were much larger following clearfelling than fire (96% over three years as opposed to 12% over two years). These increases were much as expected and relate to the greater size and age of the pines that were removed by the clearfelling. Fire through older pine would be expected to result in greater total flow increases.

The increases in storm-flow variables after the clearfelling were relatively small, of the order of a third to a half larger than expected, and can be explained by the greater responsiveness of the generally wetter catchment. The savings in evaporation during and following clearfelling would have enlarged the saturation zone or variable source area. There is no firm evidence that clearfelling changed the mode of stream-flow generation in the catchment.

The increases in the storm-flow variables after the wildfire were much higher than those caused by clearfelling, roughly triple and double the size expected in the first and second post-fire years, respectively. The marked increase in responsiveness indicates a change in stream-flow generation in the catchments. Water repellent soils, the absence of ground cover (plant litter) and the network of skid-paths and roads combined to deliver overland flow to the channel system.

This study gives clear evidence of two distinct causes of increased flooding following wildfire. The first cause is simply the reduction of evaporation owing to the loss of a tree canopy, leading to greater catchment wetness and responsiveness. The second relates to direct effects of the fire: induced water repellency in the soil and removal (by combustion) of ground cover and surface water storage capacity.

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