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The hydrological effects of fire in South African mountain catchments

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Abstract

Streamflow and its storm-flow elements in four catchments were analyzed by the paired catchment method for a response to fire. Prior to burning two of the catchments were vegetated with over-mature fynbos (the indigenous scrub vegetation of the southwestern Cape, South Africa), one was afforested with *Pinus radiata* and the fourth with *Eucalyptus fastigata*. One of the fynbos catchments was burned in a prescribed fire in the late dry season. The other catchments burned in wildfires.

Neither of the fynbos catchments showed a change in storm-flow. Annual total flow increases of around 16% were in agreement with model predictions, being related to the reductions in transpiration and interception. The manner of streamflow generation appeared to have remained unaltered despite the presence of some water repellency in the soils and consequent overland flow on some steep midslope sites.

The two timber plantation catchments experienced large and significant increases in storm-flows and soil losses, while total flow increased by 12% in the pine catchment and decreased marginally in the eucalypt catchment. The pattern of the storm-flow increases was similar in both cases. After fire, storm hydrographs were higher and steeper though their duration was little changed. The respective first year increases in the pine and eucalypt catchments were 290% and 1110% for peak discharge, 201% and 92% for quick-flow volume, and 242% and 319% for storm response ratio. These fire effects are considered to be due to changes in storm-flow generation consistent with an increased delivery of overland flow (surface runoff) to the stream channel. This was caused, in part, by reduced infiltration resulting from water repellency in the soils of the burned catchments. Overall the hydrological effects of fire are related to numerous interactive factors, including the degree of soil heating, the vegetation type and soil properties.

Introduction

South Africa is generally an arid country and water is a limiting factor in its further economic development. The mountain catchment areas which receive higher rainfall are important as the source of the country's rivers. All the catchments still carrying indigenous vegetation are subject to management by regular burning. In the past century large parts of the humid regions

have been afforested to timber species (*Pinus*, *Eucalyptus* and *Acacia* spp.). In the plantations the short, dense indigenous vegetation is entirely suppressed and a deep litter mat develops giving a continuous cover with good soil protection characteristics. The timber plantations are at risk of burning as they are surrounded by fire-maintained vegetation. The response of these afforested catchments to fire may be different from that of the naturally vegetated catchments. It is, therefore, important for managers to understand the causes of different hydrological responses to fire in all these catchments.

Wildfire can cause accelerated soil erosion and marked changes in the hydrological behaviour of forest and scrub catchments. Such fire effects have been reported from the chaparral mountains of California (Colman, 1951; Wells, 1981), from coniferous forests in Washington, Oregon and Arizona (Anderson, 1976; Helvey et al., 1976; Campbell et al., 1977), from eucalypt forests in Australia (Brown, 1972; Leitch et al., 1983), and from fynbos (macchia-type scrub of the southwestern Cape) and pine-afforested catchments in South Africa (Rycroft, 1947; Scott and Van Wyk, 1990). The reported effects can be very large, for example, a thousandfold increase in peak sediment discharge (Brown, 1972), 306 t ha^{-1} soil loss in a single postfire storm (Colman, 1951), a 900% increase in peak discharge (MacKay and Cornish, 1982), and total streamflow increases of up to 700% (Campbell et al., 1977). Thus, the consequences may have serious environmental and economic costs, both on the burned site and downstream.

Part of the explanation for these marked hydrological effects of fire is the development of fire-induced water repellency in the soil. Soil heating, such as may occur during fire, has been found to intensify water repellency in the soil (DeBano and Krammes, 1966; Scott and Van Wyk, 1990). Water repellent soils impede infiltration and percolation, which may result in the generation of overland flow (DeBano, 1971) and the restriction of percolation to preferred pathways in the soil profile (Burch et al., 1989; Van Dam et al., 1990). Hydraulic conductivity of the soil will also be reduced (DeBano, 1971; Van Dam et al., 1990).

Overland flow on sites where soils have been left more erodible by an intense fire will result in even greater erosion losses. This seems to be the sequence of events which has led to striking examples of fire–flood–erosion events in eucalypt forests in Australia (Brown, 1972; Leitch et al., 1983) as well as in chaparral and coniferous forest in the USA (e.g. Colman, 1951; Campbell et al., 1977).

This paper brings together the results of four catchment studies on the hydrological effects of fire in mountainous regions of South Africa. The studies tested the hypothesis that marked hydrological responses to fire are caused by fire-induced water repellency in the soils, and the consequent

delivery of overland flow to the stream channel. The variation in hydrological response which was recorded in these studies is related to differences in hillslope and streamflow generation processes, resulting from differences in vegetation type and fire characteristics.

Description of the research catchments and treatments

The catchments studied are all small, mountainous and with a high rainfall, each forming part of long-term experimental catchment networks and having been monitored for at least 3 years before burning. Selection of the catchments was by chance: they were all the gauged catchments that burned during the period of study. The physical features, vegetation and treatments of the four burned catchments and their respective control catchments are summarized in Tables 1 and 2. Three of the burned catchments are in the Jonkershoek Valley in the southwestern Cape (Fig. 1), where two catchments (namely, Swartbosk-loof and Langrivier) were vegetated with over-mature fynbos, and the third (Bosboukloof) supported a second rotation *Pinus radiata* plantation. The

Table 1
Summary of physical features of the catchments used in this study

Name and location	Area	Elevation of weir	Relief	Mean channel slope	MAP[a]	MAR[a]
	(ha)	(m)	(m)	(%)	(mm)	(mm)
Swartboskloof, Jonkershoek	180.0	362	833	46	2270	1060
Tierkloof, Jonkershoek	157.2	277	1230	39	1810	1128
Langrivier, Jonkershoek	245.8	369	1492	59	2261	1603
Bosboukloof, Jonkershoek	200.9	270	637	13	1296	593
Lambrechtsbos B, Jonkershoek	65.5	292	828	26	1473	531
V1H020[b], Ntabamhlope	132	1424	121	7.5	838	140
V1H028[b], Ntabamhlope	41	1460	85	11.1	838	140

[a] MAP, mean annual rainfall; MAR, mean annual runoff (from Van Wyk, 1987).
[b] Data from Schmidt and Schulze (1989); catchment V1H028 is nested within V1H020 (Fig. 2).

Table 2
Summary of the vegetation and treatments of the research catchments

Name and location	Native vegetation	Percentage afforested	Species afforested	Age at time of fire (years)	Treatment applied
Swartboskloof, Jonkershoek	Tall, mountain fynbos	0	—	29	Prescribed burn, dry season March 1987
Tierkloof, Jonkershoek	Tall, mountain fynbos	36	*Pinus radiata*	31	Control for Swartboskloof and Langrivier
Langrivier, Jonkershoek	Tall, mountain fynbos	0	—	40	Wildfire, wet season October 1987
Bosboukloof, Jonkershoek	Tall, mountain fynbos	57	*Pinus radiata*	5	Wildfire, dry season February 1986
Lambrechtsbos B, Jonkershoek	Tall, mountain fynbos	82	*Pinus radiata*	22	Control for Bosboukloof
V1H020, Ntabamhlope	Short, dense grassland	26.5	*Eucalyptus fastigata*	7	Wildfire, dry season August 1989
V1H028, Ntabamhlope	Short, dense grassland	0	—	—	Control for V1H020

fourth catchment is in the summer rainfall region, at Ntabamhlope in the Natal Drakensberg foothills (Fig. 2), and was afforested with young *Eucalyptus fastigata*. One of the fynbos catchments (Swartboskloof) was burned in a prescribed fire while the other catchments burned in wildfires.

Jonkershoek catchments

Three research catchments are in Jonkershoek State Forest, in the south-western Cape region of South Africa (33°57'S, 18°15'E; Fig. 1). The climate is mediterranean, with hot, dry summers and cool, wet winters. Approximately 80% of the rain falls in a 7 month wet season between April and October in long-duration, low-intensity, frontal storm events (Wicht et al., 1969). The indigenous vegetation of the area is fynbos, a sclerophyllous scrub dominated by species of the Proteaceae, Ericaceae and Restionaceae. Along stream courses there are naturally occurring belts of native riparian forest.
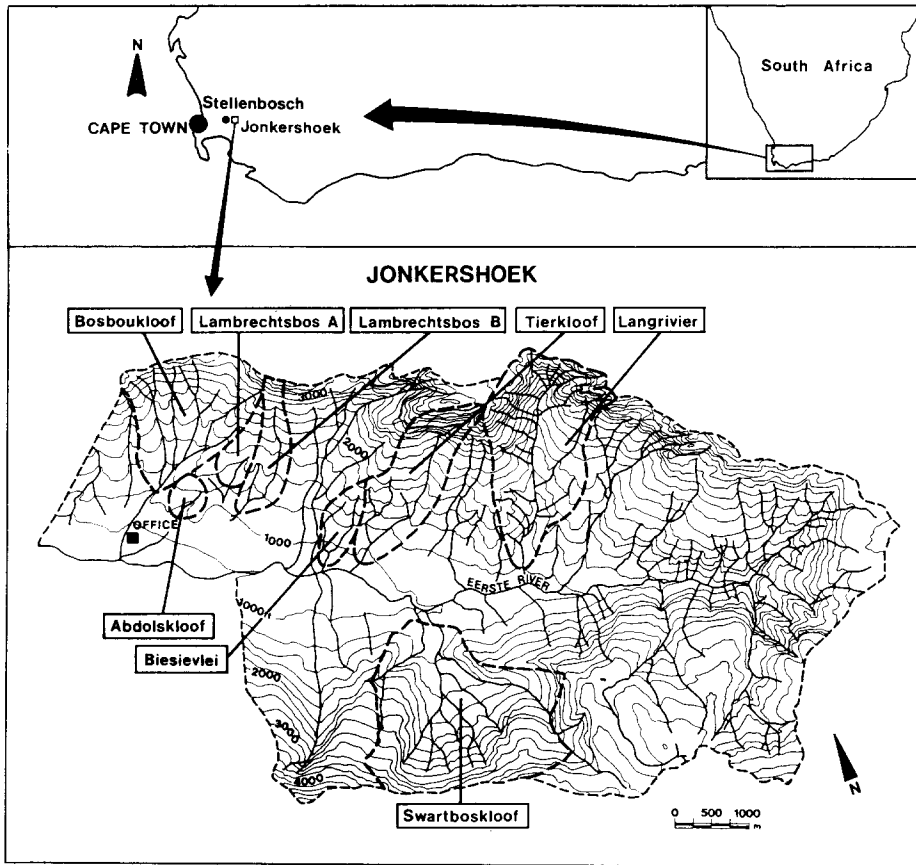
Fig. 1. Map showing the location and topography of the Jonkershoek Valley and the gauged research catchments (contours in feet).

One of the treatment catchments, Bosboukloof, and both the Jonkershoek control catchments, Lambrechtsbos-B and Tierkloof, are afforested with *Pinus radiata* which is managed as a saw-timber crop on a 35–40 year rotation (Table 2). Over the periods of comparison used in this study the forest cover in the control catchments has been stable, affording good experimental control.

Hard quartzitic sandstones of the Table Mountain Group cover most of the catchments and outcrop as cliffs in the upper elevations. Underlying the sandstone and outcropping occasionally, particularly in the lower parts of the valleys, is deeply weathered Cape Granite (Söhnge, 1988). Weathering, soil creep and colluviation have resulted in a complex and varied distribution pattern of soil parent materials. The soils are friable and deep, and mainly sandy loams. Their high gravel and rock content, low bulk density and high
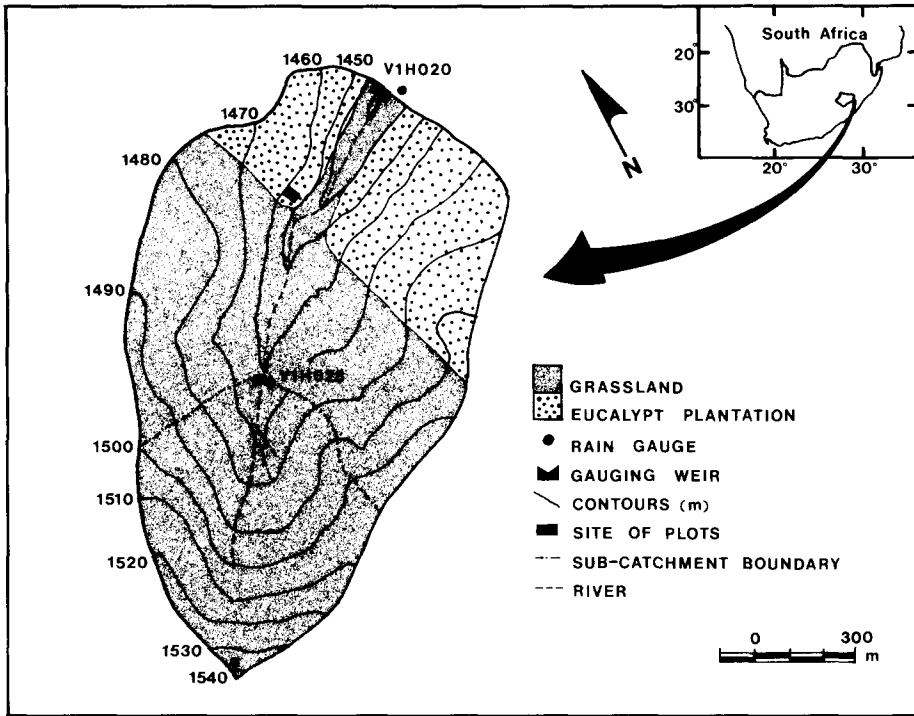
Fig. 2. Map of the Ntabamhlope nested catchments V1H020 and the V1H028 (control), showing the gentle topography and the location of the weirs, raingauges, plantation and overland flow plots.

pore volume favour the ready infiltration of rainwater (Versfeld, 1981). Further descriptions of the catchments are given in Van Wyk (1987), Scott and Van Wyk (1990), and Van Wilgen et al. (1992).

The fires in Jonkershoek

On 18 February 1986, towards the end of a particularly long, dry summer, and under hot, dry and windy conditions, a wildfire swept through 80% of the Bosboukloof catchment. Fuel loads were high because slash from logging activity some 5-8 years previously had been left in rows on the site. The result was a fire characterized by a very high absolute energy release and a high rate of energy release, i.e. a high intensity.

At the time of the prescribed fire in Swartboskloof the fynbos vegetation was 29 years old, which would make it over-mature, with large areas of the dominant shrubs (2-4 m tall) in a state of early senescence. By contrast to the

wildfire in Bosboukloof, the fire in Swartboskloof was a carefully planned and executed prescribed burn over 18 h on 17 March 1987. Although it was expected to be a hot, late summer burn, unseasonably good rains fell in February (70 mm) and in the week before the fire (40 + mm). The fuels, surface litter and soils gained considerable moisture during these rains which undoubtedly reduced the eventual intensity of the burn.

The Langrivier catchment is a protected fynbos catchment with a mesic mountain fynbos vegetation much like that in Swartboskloof but tending to be taller and moister, with larger areas of riparian forest. On 5 October 1987, fire escaped from a fire-break burning operation, and burned the 245 ha Langrivier catchment in a high-intensity fire within a matter of hours. At the time of the fire the vegetation was 45 years old, and contained a large proportion of dead, down, woody plant material.

Ntabamhlope catchments

The two, nested catchments, V1H020 and V1H028, are at the Ntambamhlope Agricultural Research Station in the Drakensberg foothills, near Estcourt in Natal (29°50′S, 29°50′E; Fig. 2). The catchments are situated on gently sloping terrain in alternating sandstones and mudstones. The soils are shallow, highly leached and apedal, with low erodibility characteristics. The soil depth varies between 0.25 m and over 2 m, draining well to greater depths. Their texture is fine silty clay to clay loam and infiltration rates are generally moderate to high (Schmidt and Schulze, 1989).

The climate at Ntabamhlope is typical of the high-altitude summer rainfall areas of South Africa. Summers are wet and hot while winters are dry and sunny with frequent night frosts and mild day temperatures. Around 82% of the annual rainfall of 838 mm falls between October and March; most of this in high-intensity convectional rainstorms.

The native vegetation of the catchments is a dense upland grassland of medium height which still covers most of the catchment. It is a fire-maintained dominant, burned every second year in early spring. The slopes of the lower catchment were planted to *Eucalyptus fastigata* (Fig. 2) in 1976–1977 for production of pulp wood on a roughly 10 year cycle. This plantation covers 35 ha, which is 26.5% of the whole catchment. The trees were felled in 1986–1987 and regenerated from coppice. A broad riparian buffer strip was left unplanted along the channel where slopes steepen towards the stream. This strip is maintained with a healthy grass cover by burning it along with the rest of the grassland catchment.

The wildfire in Ntabamhlope V1H020

The fuel load in the eucalypt plantation was high as slash from felling and thinning operations had been left on site in piles roughly 10 m apart running up and down the slope. Between the slash piles fuel was a lighter and more evenly spread load of leaves, twigs and bark. The lower third of the catchment (roughly the plantation area and the intervening riparian zone, Fig. 2) was burned in a high-intensity wildfire on 25 August 1989. The wildfire was driven by a warm, dry northwesterly wind and occurred after a prolonged dry season, at a time when soils and fuels had very low moisture contents. All fuels were consumed and the soil surface was left completely exposed beneath dying trees. The soil surface was heated to an ashed condition in those places where fuel loads had been high, and these slash pile sites consequently had a higher soil erodibility after the fire.

Methods and analyses

Streamflow and storm-flow

The primary variables of interest in this study were total streamflow volume, some storm-flow characteristics and the sediment yields of the catchments. Streamflow stage height is monitored continuously using chart recorders (Belfort in the case of the Jonkershoek catchments, and Ott at Ntabamhlope) on compound V-notch weirs. Stage heights were digitized from the charts and streamflow volumes calculated and totalled over weekly periods.

Storm hydrographs were separated using the standard method of Hewlett and Hibbert (1967) which gives an arbitrary but repeatable approach to storm-flow analysis on catchments of varying size and location. The variables of storm-flow (the total volume of runoff over the period of storm-flow), quick-flow (that portion of storm-flow above the fixed-slope separation line of Hewlett and Hibbert (1967)), peak discharge (the highest flow rate during the storm), initial discharge and storm-flow duration were determined from each storm hydrograph. Storms generated by rainfall of at least 20 mm without an interruption of more than 6 h were analyzed. For the Ntabamhlope study the minimum storm rainfall was lowered to 15 mm to increase the sample size.

The associated storm rainfall depth, duration and maximum 1 and 2 h intensities were derived from recording Casella rain gauges at the foot of each catchment. These variables were tested as means of predicting storm-

flows. The response ratio for individual storms was derived by dividing quick-flow by storm rainfall. The mean prefire values of the variables generated for the storm-flow analyses are shown in Table 3.

To test for the effect of fire the streamflow and storm-flow data were analyzed by the paired catchment approach. The dummy variable method (Kleinbaum and Kupper, 1978) was used to test for a postfire change in each of the multiple regression relationships established for the calibration (prefire) period. The details of this approach are given in Scott and Van Wyk (1990).

The calibration regression models were used to predict values of each of the dependent variables for the postfire period. The differences between these predicted values and the actual measured values (i.e. the deviations about the calibration relationship) were generated to indicate the nature and extent of any response in the dependent variables to the fire.

Sediment yields

To estimate the amount of soil loss in each catchment following fire, the suspended and bedload sediment loads were measured. Suspended sediment was sampled at the weirs of each burned catchment by weekly grab sampling and by automatic rising and falling stage samplers. From these samples and associated streamflow data monthly suspended sediment yields were determined. In Bosboukloof and Swartboskloof, the wet volume of bedload trapped in the weir stilling ponds was measured and its dry mass estimated by sampling, as described by Van Wyk (1983). At Ntabamhlope no measurement of bedload was made.

Water repellent soils

It was hypothesized that the major effect of fire on hydrology was through fire-induced water repellency in the soils. The water repellency of soils was determined in the field by the water drop penetration time (WDPT) and critical surface tension (CST) tests as described by DeBano (1981). WDPT is simply the time taken for a drop of water to be absorbed by the soil. The values obtained from these tests were combined into a simple water repellency index, $RI = \mathrm{WDPT/CST}$ (DeBano, 1981). According to the value of RI the soils were classed as repellent (> 1000), somewhat repellent ($1000 > RI > 100$) or wettable (< 100).

In Bosboukloof and Swartboskloof, respectively, 12 and 15 sample soil profiles in each of the major vegetation types were studied to assess the influence of the fire on soil wettability. In the Langrivier and Ntabamhlope

Table 3
The mean and standard deviations (s.d.) of the variables used in the storm-flow study measured over the prefire (calibration) periods

Catchment	n		Storm rainfall (P) (mm)	Storm duration (h)	Maximum rainfall intensities (mm in 1 h)	(mm in 2 h)	Initial discharge (mm day⁻¹)	Peak discharge (mm day⁻¹)	Storm-flow (mm)	Quickflow (Q) (mm)	Response ratio (Q/P) (%)
Swartboskloof (burned)	51	Mean	44.9	39.4	9.4	n.m.	3.5	19.0	15.8	7.4	12.6
		s.d.	34.4	33.3	4.0	n.m.	2.7	21.8	23.2	14.1	14.2
Tierkloof (control)	50	Mean	44.7	35.2	9.1	n.m.	2.2	27.5	16.4	11.5	18.6
		s.d.	30.7	18.8	4.2	n.m.	1.2	34.3	31.8	29.3	21.8
Langrivier (burned)	65	Mean	55.4	56.6	10.3	14.7	2.3	34.7	36.6	24.5	38.6
		s.d.	36.8	32.9	4.0	5.3	1.6	27.1	39.7	31.6	30.2
Bosboukloof (burned)	34	Mean	47.6	24.6	10.3	15.0	1.56	6.62	3.69	1.40	2.4
		s.d.	27.6	14.3	4.2	5.6	5.04	5.04	3.81	1.74	1.8
Lambrechtsbos-B (control)	31	Mean	40.4ᵃ	23.8	9.9ᵃ	14.7ᵃ	0.98	4.46	3.07	1.45	1.9ᵃ
		s.d.	23.8	14.4	3.9	5.0	0.75	4.46	3.77	2.10	2.0
V1H020, Ntbamhlope (burned)	31	Mean	35.5	24.4	22.7ᵇ	n.m.	n.m.	43.4	n.m.	4.69	3.4
		s.d.	20.4	17.1	17.0			76.4		7.36	2.6
V1H028, Ntabamhlope (control)	31	Mean	34.0	29.4	22.7ᵇ	n.m.	n.m.	69.3	n.m.	8.11	4.8
		s.d.	24.9	25.3	17.0			12.1		14.28	2.4

n, number of storms in the sample.

n.m., not measured.

ᵃRainfall data for 11 larger storms during the earlier period of record were missing owing to instrument malfunction.

ᵇMaximum of 30 min. intensities (mm h⁻¹).

catchments brief field surveys were carried out after the fires to determine the extent of water repellency in the soils, yielding a qualitative description of repellency at each site.

It was assumed that the pattern of repellency under the unburnt vegetation was normal and the pattern after fire was compared with this, by using the Chi-squared test, to determine whether fire had changed the situation. In the case of Swartboskloof where the fire was planned, the same sites were visited before and after the fire. For the wildfire sites, nearby unburnt areas were tested to obtain an index of the unburnt condition of the soils.

Plot studies

The real significance of water repellent soils, according to the hypothesis being tested, is that they can lead to overland flow during rainstorms. To test this idea, standard overland flow plots (3 × 22 m and closed on the sides and top) were established after the fires in both Swartboskloof (six plots) and Langrivier (three plots) to act as large infiltrometers. The plots were located on steep midslope sites where any overland flow was expected to reflect likely delivery of surface runoff to the stream channel. At each plot rainfall, depth of overland flow, and total sediment yield were measured after each major storm. Results from these plots were compared with an unburned control site on a comparable slope situated between the catchments. All plots had a slope gradient of roughly 53%. A multiple regression approach similar to that for the catchment analysis, was used on these plot data, using the dummy variable method to test for fire effects.

In Bosboukloof and Ntabamhlope similar overland flow plots were established, but only the total sediment yield was measured. In Bosboukloof, three plots measured erosion off slopes of 29, 35 and 62%, and at Ntabamhlope three adjacent plots on a slope of 30% were contrasted against a single unburnt plot in a nearby eucalypt plantation. Two of the three burned plots were on the lines of slash piles while the third was on the interrow between them.

Results

The fynbos catchments: Swartboskloof and Langrivier

Total streamflow volume increased following fire in both the fynbos catchments and by an amount that was anticipated. In Swartboskloof increases were 79 mm (15% up on an expected runoff of 1080 mm) and 77 mm (17% up

Table 4
Summary table of fire effects on streamflow characteristics: post fire values and percentage change over expected (predicted) values in the first post fire year

Characteristic	Swartboskloof	Langrivier	Bosboukloof	Ntabamhlope
Annual flow (mm)	1246	1389	733	109
	15.3%	9.4%	12%	−6%
Storm-flow (mm)	16.1	30.3	6.4	n.m.
	(−2.4%)	(3.8%)	62%	
Quick-flow (mm)	7.2	20.6	3.6	2.1
	(22%)	(0.5%)	201%	92%
Peak discharge	15.4	42.2	32.3	78.5
(mm day^{-1})	(19%)	(8.4%)	290%	1100%
Response ratio (%)	11.9	36.0	7.5	6.5
	(6.7%)	(11%)	242%	319%

n.m., not measured.
Percentage change figures in parentheses are not significant. Negative percentage change indicates a decrease.

on an expected runoff of 912 mm) in the first and second years, respectively. In Langrivier, streamflow increased by 119 mm (9.4% more than the expected 1265 mm) in the first year after fire (Table 4).

These increases are ascribed to reductions in rainfall interception and transpiration following the removal of vegetation. Increases of this magnitude are expected and confirm the findings in the southwestern Cape and elsewhere regarding water use by shrub vegetation (Bosch and Hewlett, 1982; Lindley et al., 1988). Bosch et al. (1986) proposed a model for predicting increases in streamflow following fire, based on prefire biomass and the expected rate of recovery of the vegetation. The model predicts increases in streamflow of around 120 mm and 93 mm in the first and second years after fire, respectively; these estimates are slightly higher than those recorded at Swartboskloof.

In neither of the fynbos catchments did fire result in significant changes in any of the storm-flow variables (Tables 4 and 5). In Swartboskloof this may, in part, have been due to the weak calibration models, but it is clear that there was no marked response to fire of the order seen in the afforested catchments (Table 4). The volume and height of spates and the proportion of rainfall they represented was not sufficiently altered by the fires to be detected by the techniques applied. The multiple regression models fitted to the storm-flow data are little different in the postfire period (Table 5), with the same predictor

Table 5

Significant ($P < 0.05$) predictor terms in the multiple regression models developed for the prefire and full periods of storm-flow data for each of the burned catchments

Independent variable		Swartboskloof	Langrivier	Bosboukloof	Ntabamhlope V1H020
Storm-flow (mm)	Prefire	D, P, Q_i, I_{60}, S	C, D, Q_i	C, P, Q_i	n.m.
	R^2	0.97	0.91	0.98	
	Error df	22	60	28	
	Postfire	D, Q_i, I_{60}	C, D, Q_i	C, D, Q_i, I_{60}, F	n.m.
	R^2	0.97	0.88	0.96	
	Error df	66	107	44	
Quick-flow (mm)	Prefire	D, C, P, Q_i, I_{60}, S	C, D	C, D	C, D
	R^2	0.98	0.85	0.96	0.97
	Error df	18	61	29	28
	Postfire	D, C	C, D, Q_i	C, D, I_{60}, F	C, D, Q_i, I_{30}, F
	R^2	0.94	0.88	0.94	0.95
	Error df	63	107	44	36
Peak discharge ($m^3 s^{-1}$)	Prefire	I_{60}, D, P, S	C, D, Q_i	C, Q_i, P, I_{60}	C, P
	R^2	0.90	0.83	0.85	0.92
	Error df	22	60	27	28
	Postfire	C, D, P, I_{60}, S	C, D, Q_i	C, I_{120}, I_{60}, F	C, Q_i, I_{30}, F
	R^2	0.96	0.78	0.89	0.90
	Error df	64	107	45	35
Response ratio (%)	Prefire	D, I_{60}, Q_i	C, D	Q_i, D, I_{60}, P	C, D
	R^2	0.80	0.83	0.76	0.95
	Error df	19	61	29	28
	Postfire	D, I_{60}, Q_i	C, D	P, D, I_{60}, F	C, D, Q_i, I_{30}, F
	R^2	0.83	0.76	0.86	0.93
	Error df	65	108	48	35

The presence of the fire dummy variable (F) in the postfire models indicates a significant effect of fire.

C, the corresponding control catchment variable; S, dummy variable for season; D, storm duration (h); P, storm precipitation (mm); $I_{30,60,120}$, maximum rainfall over 0.5, 1 and 2 h periods; Q_i, initial discharge (mm day^{-1}) or antecedent precipitation index (mm); F, dummy variable for fire effect.

variables being useful both before and after the fire. There is more variability in the models for Swartboskloof because here the available control catchments did not provide very useful predictor variables and the models were generally poorer.

Total and storm-flow sediment yields in Swartboskloof for the 21 months following fire were no different from prefire levels (Scott and Van Wyk, 1992). A minor increase in sediment loss during storms was recorded in the first 6 months after the fire in Langrivier (Van Wyk and Lesch, 1989) but annual soil loss (0.15 t ha^{-1} year^{-1}) was nonetheless below that in the previous year. In

Table 6
The mean soil loss from small (22 × 3 m) plots (rows 2 and 3) and from the whole catchment (rows 4 and 5), and overland flow from the plots in the burned catchments during the first postfire year

	Swartboskloof[a]	Control[b]	Langrivier[c]	Bosboukloof[d]	Ntabamhlope[e] V1H020
Number of plots	6	1	3	3	3
Soil loss (t ha^{-1})	2.42 (2.5)	0.013	1.15 (0.92)	16	60.0 (13.6)
Per unit of rainfall (kg per 100 mm)	1.00 (3.61)	0.005	0.48 (1.21)	34.23 (42.89)	49.0 (11.1)
Suspended sediment (t ha^{-1})	0.41	n.m.	0.148	6	5.2
Total sediment yield (t ha^{-1})	0.42	n.m.	n.m.	7.8	n.m.
Approximate delivery ratio[f] (%)	8	n.m.	8[g]	50	12[g]
Overland flow (mm) mean per storm	1.87 (0.71)	0.49	1.11 (0.08)	n.m.	n.m.
As % of rainfall	4.9 (2.04)	0.81	2.18 (0.13)	n.m.	n.m.

Standard deviations where available are given in parentheses below.
n.m., not measured.
[a] From Scott and Van Wyk (1992).
[b] Single unburnt control plot for both Swartboskloof and Langrivier.
[c] From Scott (1989), Van Wyk and Lesch (1989).
[d] From Scott and Van Wyk (1990).
[e] From Scott and Schulze (1992).
[f] See text for definition.
[g] Assumes bedload is 20% of suspended sediment.

both catchments total sediment yield is strongly dominated by sediment yield during storm-flows (in Swartboskloof, this proportion averaged 95% over the 3 years of measurement). The lack of notable increases in sediment yields after the fire, these being dependent on available energy in the streamflow, is therefore linked to the absence of a storm-flow response to fire.

There was greater overland flow and soil erosion on steep slopes, as measured in the plots, at Swartboskloof and Langrivier (Table 6) than would have been expected from a consideration of the soil properties (texture, porosity, bulk density), rainfall intensities and previous studies. Mean overland flow on burned plots, in the first postfire year, ranged between means of 2.5 and 7.9% of rainfall for individual storms while on the unburned plot the mean was 0.8%. Soil loss off the plots ranged from 0.1 to 7.4 t ha^{-1}, with the greater losses off more intensely burned Swartboskloof plots, while the yield from the unburned plot was at least one order of magnitude lower at 0.01 t ha^{-1}. The
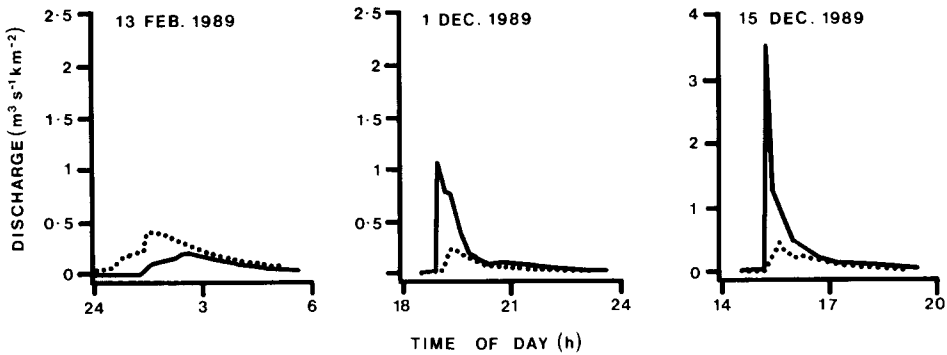
Fig. 3. Three sample pairs of hydrographs from the two nested Ntabamhlope catchments, one from before the fire (a) and two after the fire (b), (c), which clearly illustrate the enlarged hydrographs after the fire in catchment V1H020 (solid line).

recorded overland flows were positively related to the depth of rainfall, rainfall intensity, and the antecedent wetness of the plot. Sediment yields were similarly related to these factors, but increased exponentially with increasing runoff from the plots. The high levels of runoff indicate that infiltration and/or percolation on steep slopes was inhibited.

The CST and WDPT tests of the wettability of soils in these catchments indicated that the fire had induced, in patches, a measure of water repellency in the soils, relative to the unburned state (Scott, 1989; Scott and Van Wyk, 1992). The impeded infiltration caused by water repellent soils could have contributed to the generation of overland flow and hence soil loss on the overland flow plots. But at the catchment level the effects of the fire were not detectable, so it must be assumed that surface runoff on the steep mid-slopes was able to infiltrate lower down on the slopes, and little was available, therefore, to augment storm-flows directly. The soil borne by surface flow would, therefore, also have been deposited on these lower slopes.

The afforested catchments

In contrast to the two fynbos catchments the two afforested catchments showed marked increases in storm-flows (Table 4) which were associated with high soil losses and suspended sediment exports. The pattern of the storm-flow increases, which is most easily described by reference to the storm hydrographs (Fig. 3), was similar in both cases. After fire, storm hydrographs were higher and steeper though their duration was little changed. The respective first year increases in the pine and eucalypt catchments were 290% and 1110% for peak discharge, 201% and 92% for quick-flow volume, and 242% and 319% for storm response ratio. After the fires, rainfall intensity becomes a

significant predictor term in the regression models for storm-flows in both catchments. This indicates a greater role of rainfall intensity in the generation of storm-flows in the burned catchments, which is consistent with the hypothesis of a greater contribution by overland flow to streamflow generation.

Annual flow in Bosboukloof increased by 70 mm (12%) which can be attributed to the expected water use for the area of young pine vegetation which was burned. In the Ntabamhlope catchment, total flow was in fact reduced by 7 mm (6%) in the first 10 months after the fire. This result is difficult to explain, but it may be due, at least partly, to the unusually low rainfall season which followed the fire.

In Bosboukloof soil losses off the overland flow plots ranged from 10 to 26 t ha^{-1} (Scott and Van Wyk, 1990) during the first wet season after the fire, while suspended sediment and bedload losses in the first year were 6 t ha^{-1} and 1.8 t ha^{-1}, respectively. Thus, the proportion of the soil eroded from the slopes and which actually left the catchment in the streams (the delivery ratio) was roughly 50%. The soil loss from the catchment was very much greater than those recorded in the otherwise similar fynbos catchments in the same valley (0.42 t ha^{-1} year^{-1} in Swartboskloof and 0.148 t ha^{-1} year^{-1} in Langrivier).

In the burned Ntabamhlope catchment (V1H020) the mean soil loss from the two slash pile plots was 75 t ha^{-1} and from the between-pile plot was 46 t ha^{-1}, averaging around 52 t ha^{-1} for the whole plantation site in the first 10 months after the fire. Soil losses off the unburned eucalypt plot were around two orders of magnitude lower (0.1 t ha^{-1}) than those off the burned site. The suspended sediment yield if attributed solely to the burned area of the catchment was 5.22 t ha^{-1} which was also much lower than erosion off the plots (Scott and Schulze, 1992). Field observations in this catchment showed that large amounts of the eroded material (soil and ash) had been trapped in a well-grassed riparian buffer strip of 30 m width on either side of the stream. Delivery ratios of eroded sediment were much higher in Bosboukloof than at Ntabamhlope (roughly 50% as opposed to 10%). Within the burnt area in Bosboukloof, a large part of the riparian zone of tall shrubs and forest was also burned, and consequently was less effective at trapping and retarding movement of soil than was the grassed buffer strip at Ntabamhlope. There was also more water in the Bosboukloof channel and it has a steeper slope.

In Bosboukloof a balanced testing of soil wettability in burned and unburned pine and fynbos areas showed that fire had greatly increased the incidence of water repellency of the burned soils, and that the degree of repellency was positively related to the intensity of the fire (Scott and Van Wyk, 1990). By comparison with the fynbos catchments (Swartboskloof and Langrivier) the occurrence of repellency was much more obvious and general in Bosboukloof. The pattern of water repellency in the soils was consistent with the postulations

of fire-induced water repellency of DeBano and others in the USA (DeBano, 1981). The source of the hydrophobic substances is plant litter, and these substances may form a weak repellent layer in the surface soil in the unburnt condition. Following fire, adequate heating of the surface soil will denature or vaporize repellent substances in this surface layer leaving it completely wettable. Beneath the surface less heating can intensify incipient repellency (DeBano, 1966) and vaporized hydrophobic substances moving down the profile along a temperature gradient can condense on to soil particles, thereby creating a broader band of repellency in the soil (DeBano, 1966). Deeper in the soil profile heating may not be sufficient to affect the wettability of the soil.

At Ntabamhlope, the soils beneath eucalypts, whether burnt or unburnt, were highly repellent. In this case the fire had the effect of burning off some repellency at the soil surface (between 5 and 30 mm depending on the amount of surface heating), though it was not certain from field testing that fire had intensified repellency deeper in the profile. The crucial role of fire in this case was to remove surface litter and hence storage opportunities and obstacles to surface flow, and to increase the erodibility of soil on the surface. The inherent repellency of the soils, which has been found to be a common feature in South African eucalypt plantations (Scott, 1991), was an important factor reducing infiltration and leading to overland flow.

In both these afforested catchments the presence of water repellent soils is thought to have led to overland flow. The increased delivery of overland flow (surface runoff) to the stream channel is probably the cause of the observed change in the shape of the hydrographs. Surface runoff on the soils left highly vulnerable by the fire, increased soil erosion in these catchments. Other factors in the afforested catchments which contributed to surface runoff were the removal of surface storage by the consumption of litter by the high-intensity fires and the presence of roads and skid paths which aided the rapid and efficient delivery of surface runoff to the streams.

Clearfelling of the Bosboukloof catchment from 1980 to 1982 resulted in an immediate increase in water yield but storm-flows increased only minimally (Scott, unpublished results, 1989). It is assumed from this contrast with the fire effects that the saturation zones in the catchment play little role, or a role little affected by fire or clearfelling, in the generation of storm-flows.

Discussion

Contrasting the results from the four catchments

The observed hydrological responses to fire in the different catchments can be related to the level of soil heating. In the fynbos catchments the fuel loads

were generally lower and more dispersed than in the timber plantations, though fuel loads themselves were not low in absolute terms. More significant, probably, were the fuel and soil wetness at the time of the fynbos fires. Soil heating in a fire will not be severe until the insulating mat of litter has been consumed and the water in the soil has been driven off (Chandler et al., 1983). While a fuel is moist more of the energy of combustion is released in a latent form. Soil wetness, because of its effect on the thermal capacity and conductivity of the soil, is the most important factor controlling soil heating. When a soil is dry, as before the Bosboukloof and Ntabamhlope fires, it has a relatively low thermal capacity and conductivity, so that the same amount of energy can raise its temperature to a much greater extent.

The Langrivier fire, though a high-intensity wildfire, occurred at the end of the wet season when the soils were thoroughly wetted and when fuels would also have had high wetness levels. The Swartboskloof fire, although applied at the end of summer (dry season), occurred after an unseasonably wet February and early March (> 100 mm in preceding 6 weeks). Consequently, it was not a high-intensity fire and the potential for severe soil heating was, therefore, greatly reduced. Both afforested catchments burned at the end of prolonged dry seasons under hot and dry conditions. These weather conditions are also those under which wildfires are most likely to occur. The high fuel loads, clustering of fuels, dry fuel and dry soil all contributed to maximal soil heating, with the greatest potential for fire effects on the hydrology.

In these catchments it appears that the heating of the soil had two important effects. First, was its potential to induce water repellency in the soil as was shown in Bosboukloof (Scott and Van Wyk, 1990), where the severity of repellency was positively related to the fuel loads. Second, was the ability of severe heating to increase the erodibility of the soil. Sustained high temperatures may cause organic matter, which is incorporated in the soil fabric and is important in soil aggregation, to be consumed, thereby leaving the soil more erodible (DeBano, 1981; Giovannini and Lucchesi, 1983). This latter effect was particularly obvious beneath slash piles in the afforested catchments where large fuel loads close to the ground caused the greatest heating of the soil.

Another difference between the afforested and fynbos catchments is the presence of low-growing vegetation. In the highly productive and dense timber plantations the ground covers tend to be shaded out leaving the site bare of vegetation which can respond rapidly after a fire. The fynbos vegetation is adapted to fire, and there are numerous plant groups which respond rapidly to the conditions created by fire, ensuring a swift return of short, ground covers. The role of this factor was also demonstrated by the grassed riparian zone in the Ntabamhlope catchment. Here the grassland is maintained by regular

burning which results in a high ground and basal cover. Following the fire the grassland showed no signs of erosion, but acted rather as a sediment trap.

In these highly impacted catchments the riparian zones played an important role in intercepting eroded soil and reducing the levels of sediment in the streams. In Bosboukloof much of the riparian zone of indigenous forest or scrub was burned and the sediment delivery ratio was around 50%. But at Ntabamhlope a much broader band of short but dense grassland with a high basal cover provided an especially efficient buffer zone, despite it having been burned in the same wildfire. Here sediment delivery was reduced to around 12% of the soil moved off the midslopes. In the fynbos catchments, most of the riparian zones survived the fires, but with much less eroded soil reaching these areas, their role in filtering out the effects of fire is thought to have been relatively small.

Earlier findings on fire effects

The hydrological effects of fire reported here are largely in agreement with earlier studies of fire effects in South Africa. In the only other inspection of a plantation fire, Van Wyk (1986) found very large increases in soil loss following a dry season wildfire through a *Pinus patula* plantation at Cathedral Peak. Sediment yield in the first postfire year was at least $37 \text{ t ha}^{-1} \text{ year}^{-1}$, and though the changes in streamflow were obvious they could not be quantified largely because of the damage caused by excessive sedimentation after the fire. The striking effects of this fire are put down to the high-intensity fire, high postfire erodibility of the surface soil, and the destruction of the riparian zone in the fire. Judging from the afforested catchments in the present study, it seems likely that water repellent soils were also involved in the remarkable response of this Cathedral Peak catchment to fire.

The naturally grassed catchments at Cathedral Peak showed no response in total streamflow to fire (Nänni, 1960) and only a minor change in storm-flows (Bosch et al., 1984). These grasslands are burned on average every second year, usually in prescribed burns; their basal cover is very high and their recovery of canopy after fire is extremely rapid.

Most studies in fynbos catchments have focused on the additional total water yield following fire, leading to the predictive model of Bosch et al. (1986). One other study of storm-flows in a fynbos catchment, the 11.7 ha Abdolskloof in Jonkershoek, found sharp, though short-lived, increases in storm-flow, peak discharge and total streamflow in the first 3 months of the wet season following a high-intensity wildfire during a dry February (Rycroft, 1947; Banks, 1964). The fire effects in Abdolskloof catchment may have been different from Swartboskloof and Langrivier in that the wildfire occurred during dry conditions.

The response to wildfire in timber plantations recorded here, is comparable with the larger responses reported after fire in forests elsewhere. Cases of large postfire increases in flooding and sedimentation from eucalypt forests have been reported from Australia (Brown, 1972; Leitch et al., 1983). After a severe fire in a *Pinus ponderosa* forest in Arizona, streamflow increased by 800% and catchment response by 450% (Campbell et al., 1977). These results are also similar to the now well-established fire–flood–erosion sequence in mountainous chaparral areas (Anderson et al., 1976). Several reports of increased flooding and erosion after fire have linked these effects to the presence of water repellency in the soils of the burned catchment; in the USA (DeBano and Conrad, 1976; Campbell et al., 1977; Wells, 1981), and in Australia (Leitch et al., 1983).

Conclusions

The results of the catchment studies reported here support the hypothesis that water repellent soils play a part in the hydrological effects of fire through the generation of overland flow. Overland flow is seen as the main agent because of the large amounts of soil eroded off midslope plots and the shape of the hydrographs which were of much the same duration before and after the fires. In the case of the fynbos catchments the occurrence of fire-induced water repellent soils was patchy, but contributed to significant increases in overland flow and soil loss from midslope sites (relative to the unburned condition). On the catchment scale though, to judge by storm-flows, little of the surface runoff appears to have reached the streams, with the result that the mode of streamflow generation may have remained unchanged. In the afforested catchments the overland flow did reach the stream channels, probably aided to some extent by the roads and skid paths, and led to steeper, larger storm hydrographs.

This study highlights the fact that the hydrological response of catchments to fire is governed by numerous factors interacting with each other. Because of this interaction it is not easy to predict the consequences of any particular fire, but the role of some of these factors is now clearer. Forest managers may be in a better situation to understand the effects of fire and to manage it. It is concluded that the following conditions predispose a catchment to a marked hydrological response to fire.

(1) A high level of soil heating, which itself is a function of fuel load, fuel and soil wetness, site and weather conditions. High soil temperatures were positively related to levels of induced water repellency (in the case of the pine and fynbos catchments) and to postfire soil erodibility. Prescribed burns,

which are only likely to be applied after rains, are unlikely to fully combust all fuels or litter, and cause widespread, serious soil heating.

(2) The loss of ground covers owing to shading out of low-growing forbs and shrubs as happens in a plantation cause the site to be bare for longer after fire.

(3) The roads, tracks or skid paths, that are normally found within a managed forest or plantation, may become extensions of the channel system after a fire, increasing the probability of surface runoff reaching the stream and contributing to storm-flow. With surface runoff there is a greater likelihood of erosion and sediment pulses.

(4) Vegetation types which lead to the development of water repellent soils improve the chances of a sharp hydrological response to fire. In the two afforested research catchments the soils beneath the eucalypts and pines showed a high level of repellency which played a part in generating surface runoff in the postfire situation. The eucalypt soils had high inherent levels of repellency, while the pine soils had high levels of repellency only after fire. In the fynbos, fire caused only a minor increase in water repellency.

(5) Wildfires are more likely to occur in hot, dry weather conditions and when soil and fuel moisture are low. These, therefore, pose the greatest risk and wildfires can thus be expected to cause a hydrological response. The Langrivier wildfire was an exception as it burned in fairly moist conditions: it was an accidental fire which occurred under conditions considered safe for the burning of fire-breaks.

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