A model for comparing water yield from fynbos catchments burnt at different intervals*

JM Bosch, BW van Wilgen and DP Bands**
South African Forestry Research Institute, Jonkershoek Forest Research Centre, Private Bag X5011, Stellenbosch 7600, South Africa.

Abstract

The model presented in this paper estimates the differences in water yield resulting from different burning cycles in fynbos (macchia), for long-term broad-scale planning purposes. It is based on the results from two catchment experiments. The model assumes firstly that the magnitude of post-fire increase in streamflow is dependent on pre-fire biomass and secondly that the rate of decrease in streamflow after fire depends on the ratio of re-seeding to re-sprouting plants. The model formalizes these assumptions in simple mathematical terms. As such it provides a basis for formulating hypotheses which, once tested, will lead to further refinement of the model.

Introduction

Mountain catchments in South Africa are managed by the Forestry Branch of the Department of Environment Affairs to maintain a sustained yield of clean water (Garnett, 1973). Several research projects (Plathe and van der Zel, 1969; Van der Zel, 1974; Van der Zel and Kruger, 1975), aimed at determining the effects of different fire regimes on the water yield from natural fynbos covered catchments, are conducted by the Department. The experiments include the application of fire at different intervals and in various seasons.

Fynbos is a sclerophyllous vegetation type occurring in mountain catchments of the Western and Southern Cape and is described in detail by Kruger (1979). The results of experiments designed to test the effects of burning fynbos on water yield, which in many cases appear to be contradictory, have been reported recently (Bosch *et al.*, 1984). The varying climatic and vegetation conditions under which these results were obtained make generalisations difficult. Additional research on hydrological processes has been initiated to enable more accurate modelling of the effects of burning, but results are not yet available.

In the interim, certain rules of thumb based on scant data have been used in decisions regarding burning of fynbos for water yield. The most widely used results are those given by Van der Zel and Kruger (1975). On the basis of results from one catchment experiment in Jonkershoek near Stellenbosch (33°57'S, 18°55'E, mean annual precipitation 1 500 mm) these researchers concluded that water yield decreases at the rate of 1% of post-fire annual flow for every year of fynbos growth after fire. They calculated that a reduction in the average post-fire age of fynbos from 18 to 6 years through burning would result in an average annual increase in yield of 300 mm (mean annual runoff from these areas is approximately 500 mm). This conclusion was incorrect because the authors based their extrapolations on the limited data available at that stage. Recent analysis of the data now available showed that the annual rate of reduction in water yield with aging of the fynbos amounted to about 8 mm a^{-1}, which is 0,5% of post-fire flow; furthermore, streamflow ceased to decline at a post-fire age of about 20 years (van Wyk, 1977 and unpublished data). Results from other experiments (Lindley, 1986) show increases in yield which last for a short period after burning 6 and 12 year-old fynbos at Zachariashoek in the Klein Drakenstein mountains near Paarl (33°48'S, 19°02'E, mean annual precipitation 1 100 mm). The rate at which streamflow declined after an initial increase following the burn was higher than that observed at Jonkershoek by Van der Zel and Kruger (1975). This difference can be attributed to the difference in vegetation structure and composition. The Langrivier catchment at Jonkershoek has a tall closed shrubland formation (*vide* Campbell *et al.*, 1981). The dominant plants, obligate re-seeding shrubs, are killed by fire and regenerate from seed only. Such plants grow relatively slowly initially, but attain a relatively high biomass. The Zachariashoek catchments, on the other hand, have vegetation dominated by sprouters, which are not killed by fire, and sprout from underground buds protected from fire. Such plants recover rapidly after a fire but attain a lower final biomass. These results illustrate that streamflow response to fire can vary considerably, depending on vegetation and other factors.

The aim of this paper is to formulate these findings in simple mathematical terms to provide a procedure for comparing the effects of different burning cycles in different fynbos structural formations on the water yield from catchments and secondly to express hypotheses that can be tested by further research.

Principles of the model

Results from experimental work (Van der Zel and Kruger, 1975; Versfeld and Bosch, 1982; Bosch *et al.*, 1984) imply that a fire in fynbos will cause an immediate increase of a certain magnitude in water yield and that the initial increase will be reduced at a certain rate as vegetation recovers. The post-fire increase in water yield will last for a certain period depending on vegetation type, recovery rate and climate. Each of these aspects should be quantified when considering the effects of different burning cycles. Changes in water yield following two different burning cycles are presented schematically in Fig. 1(a). This figure, which is based on the results obtained by Bosch *et al.* (1984), Lindley (1986) and van Wyk (1977), will be used in the discussions that follow. The line AB represents annual flow from a fynbos catchment immediately after a fire and the line AC the decline in annual water yield as vegetation recovers. If not burned again, water yield will decline to a point C after which it will remain steady as depicted by the line CD. The triangle EFG represents the streamflow response if the catchment was burned again after y_i years and triangle GNM the subsequent burning cycle of y_i years. Variations in position, size and form of the triangles represent varia-

---

*Revised paper, originally presented at the Second South African National Hydrology Symposium, Pietermaritzburg, 1985.

**To whom all correspondence should be addressed.

Received 10 January 1986.

tions in response to burning different vegetation types at different cycles. Fig. 1(b) gives a schematic representation of water yield pattern as in Figure 1(a) but in a vegetation type where the maximum reduction is relatively small.

The model assumes linear relationships between streamflow response and time after burning. This is admittedly a simplified representation of the real response, which is likely to be sigmoidal, as is the case with plantations (Bosch, 1982). However, this assumption is unlikely to lead to large differenes between simulated and actual streamflow. The model further assumes that the decrease in yield is independent of variations in mean annual rainfall in the post-burn period. It is based on mean rainfall observed in the pre-fire period. Dry years following a fire, for example, will result in lower streamflow. Because the mean fire cycle in fynbos is in excess of 10 years it is unlikely that this assumption will lead to large discrepancies between simulated and actual streamflow over the long term.

Basis of comparison (datum line)

When comparing changes in water yield resulting from different burning regimes one must deal with changes relative to some datum line. For the purpose of this model the datum line is taken to be the stabilized flow from a catchment with mature vegetation of a specific type. This is depicted in Fig. 1(a) as line RD. The increase above the datum line is Qm (the line RA) and was experimentally determined as approximately 180 mm a^{-1} in the case of a tall closed shrubland in a high rainfall catchment (Langrivier). Changes in water yield over a period due to different burning cycles will be gauged against this datum line which is taken to be characteristic of a certain vegetation type. The hypothesis of the authors is that Qm is a function mainly of the biomass (which is related to other factors such as leaf area) of a vegetation type. Structural classes of fynbos, as given by Campbell *et al.* (1981), were therefore assigned an arbitrary biomass ranking and a related expected post-fire maximum increase in water yield. The hypothetical relationship is shown in Fig. 2(a) and the biomass ranking for structural formations given in Table 1. The values of Qm as given in Fig. 2(a), namely 180 mm and 60 mm were obtained from the results of the Langrivier and Zachariashoek catchments, which have Tall Closed Shrubland (Van Wilgen, 1982) and Tall Mid-dense Herbland (Van Wilgen and Kruger, 1985) vegetation respectively.

Certain burning cycles may change the structural characteristics of the vegetation which in turn will affect the magnitude of Qm. For example, short cycle (6 to 8 years) burning changes tall closed shrublands to low closed herbland (Van Wilgen, 1982). Such changes must be borne in mind when assigning values for Qm to short burning cycles. This factor, along with other refinements will be built into the model as the results of further research at other sites, such as Moordkuil in the Southern Cape Province and Swartboskloof in the Western Cape Province, become available.

Rate of reduction in water yield

The recovery rate of the vegetation canopy after a fire will be a major factor in determining the rate of reduction in streamflow. The slope of the line AC and of lines FG and NM in Figure 1(a) therefore depicts the rate of reduction in streamflow, with an assumed flow at level AB immediately after a fire. There are several factors in the composition and structure of the vegetation community that will determine the slope of this line.

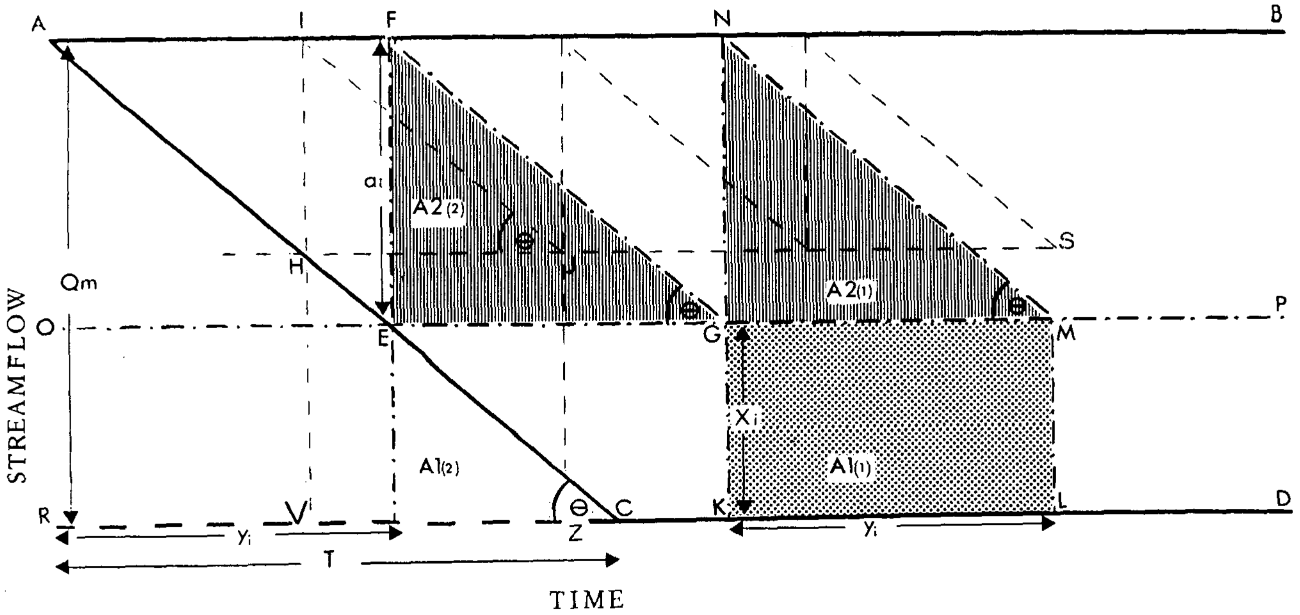

Figure 1(a)
Schematic representation of changes in water yield following two different burning cycles in fynbos. The line AB represents streamflow immediately after a burn; line CD represents the flow after maximum reduction (Qm) for a particular vegetation type has been reached. Depending on the annual rate of reduction (slope of line AC) maximum reduction will occur after T years. The areas of the triangles and rectangles represent streamflow above a datum line RD.

TABLE 1
HYPOTHETICAL VALUES OF EXPECTED POST-FIRE MAXIMUM INCREASE (Qm) AND SUBSEQUENT RATE OF ANNUAL DECREASE (k) IN WATER YIELD AS RELATED TO STRUCTURAL FORMATIONS IN FYNBOS

Structural formation	Biomass rank†	Expected max. post-fire increase in streamflow/year (Qm) (in mm)	Sprouter :* seeder ratio	Expected rate of post-fire decrease in water yield/year (k) (in mm a^{-1})
Tall closed shrubland	1	180	0:100	4
Tall mid-dense shrubland	2	130	0:100	4
Mid-high closed shrubland	2	130	0:100	4
Tall open shrubland	3	90	25:75	8
Mid-high mid-dense shrubland	3	90	0:100	4
Low closed shrubland	3	90	50:50	19
Closed graminoid shrubland	3	90	75:25	37
Tall closed herbland	3	90	100:0	60
Tall sparse shrubland	4	60	50:50	19
Mid-high open shrubland	4	60	25:75	8
Low mid-dense shrubland	4	60	50:50	19
Dwarf closed shrubland	4	60	50:50	19
Mid-dense graminoid shrubland	4	60	75:25	37
Tall mid-dense herbland	4	60	100:0	60
Closed herbland	4	60	100:0	60
Mid-high sparse shrubland	5	35	50:50	35
Low open shrubland	5	35	75:25	35
Dwarf mid-dense shrubland	5	35	50:50	35
Open graminoid shrubland	5	35	75:25	35
Tall open herbland	5	35	100:0	35
Mid-dense herbland	5	35	100:0	35
Low sparse shrubland	6	18	75:25	18
Dwarf open shrubland	6	18	75:25	18
Sparse graminoid shrubland	6	18	100:0	18
Tall sparse herbland	6	18	100:0	18
Open herbland	6	18	100:0	18
Dwarf sparse shrubland	7	0	75:25	0
Sparse herbland	7	0	100:0	0

*The sprouter : seeder ratio given is only a rough guide; it should rather be estimated in the field and Fig. 2(b) used to derive a related k value.
†Tall closed shrubland (biomass rank 1) at Jonkershoek had a biomass of approximately 5 000 gm^{-2} (Van Wilgen, 1982); Tall open shrublands (biomass rank 3) had a biomass of approximately 3 000 gm^{-2} (Van Wilgen et al., 1985); Tall mid-dense herbland (biomass rank 4) had a biomass of approximately 500 gm^{-2} (Van Wilgen and Kruger, 1985).

The hypothesis of the authors is that communities with a large proportion of obligate re-seeding tall shrubs will recover relatively slowly and that the gradient of streamflow reduction with aging will be less steep. A community with a large proportion of sprouters will cause a sharper decline in water yield after burning, as the vegetation will recover more rapidly. For example, sprouting individuals of *Jacksonia floribunda* attain 80 times the biomass of seedlings of the same species 4 years after fire in Western Australian heathland, which is analogous to fynbos (Bell *et al.*, 1984). These authors indicated that species regenerating from seeds have a long phase of seedling establishment before a phase of vigorous growth as opposed to the rapid and vigorous regrowth of sprouters.

Research projects currently under way to determine relationships between vegetation recovery and streamflow for different vegetation types within the fynbos can be used to test this hypothesis. In Langrivier, with its large component of seeding plants, a rate of reduction in streamflow of 8 mm a^{-1} was observed, but this reduction rate was 60 mm a^{-1} at Zachariashoek, where the vegetation consists largely of sprouters. Results from afforestation experiments at Cathedral Peak gave average reduction rates of the order of 15 mm a^{-1} of plantation development (Bosch, 1979).

A hypothetical relationship between expected annual rate of change in water yield (k) and the sprouter : seeder ratio of vegetation is expressed in Fig. 2(b). Results from Langrivier and Zachariashoek were used as the basis for the relationship.

An attempt was made to assign constants (k values) to different structural formations of fynbos in Table 1. These should however be used only as a rough guide. The sprouter : seeder ratio should rather be estimated in the field and Fig. 2(b) used to derive the k value. Thus Langrivier, a Tall Closed Shrubland, was assigned a value of 8 as about 25% of the dominant shrubs are re-sprouters (*Brunia nodiflora*). Five broad categories based on the ratio of sprouters versus seeders have been used for Fig. 2(b):

- those that have mainly seeders;
- those with 75% seeders;
- those with 50% seeders;
- those with 75% sprouters; and
- those that have mainly sprouters.

The sprouter : seeder ratio of a particular vegetation community will be changed by reducing the burning cycle and will be drastically affected when burning cycles are shortened to below eight years (Van Wilgen, 1982). This should be kept in mind when selecting k values for the modelling purposes described below.

Stabilization of flow

The hypothesis of the authors, supported by available results, as given above, is that streamflow declines with ageing of fynbos until climax or induced climax conditions in the vegetation are attained. Thereafter water yield reductions are likely to stabilize. The point in time (point C in Fig. 1(a)) at which this occurs is determined by the slope of line AC combined with the magnitude of Qm; in other words, by the rate of recovery and the maximum reduction in streamflow for a specific vegetation type. These two factors have been discussed above. Point C is the time (T in Figure 1(a)) beyond which further lengthening of the period between burns will not result in any *further* decreases in water yield induced by vegetation. For the purpose of this model the period T is called the stabilization period.

Comparison of different burning cycles

When comparing different burning cycles with respect to water yield, the different components as depicted in Fig. 1(a) need to be calculated relative to the datum-line conditions described in the section above for each burning cycle (y_i). The resultant increase of each burning cycle above the datum-line is used to compare the two burning cycles.

Each burning cycle will result in a new base-line flow relative to the datum-line flow as given by the line RD. This hypothesis is represented by the line OP for a certain burning cycle in Figure 1(a) and line HS for an even shorter burning cycle. The increase in the amount of water over the datum-line flow for the period of one cycle, which is due to this component, is reflected by the area of the rectangle KGML for burning cycle 1 or rectangle VHJZ for burning cycle 2.

The immediate increase in water yield after burning and the subsequent decline in yield with regrowth of the vegetation are also factors which influence yield increases over one burning cycle (above the climax vegetation datum line). This is represented by the triangle GNM in Figure 1(a) for burning cycle 1 or triangle HIJ for burning cycle 2. The areas of the rectangle and the triangle (shaded) will give the increase in water yield above the datum line RD for burning cycle 1 for the *period* (y_i) *of the burning cycle* only.

A third component to be considered is the number of cycles, each with a peak (represented by triangles EFG, GNM, etc. in Figure 1(a)) over a long period.

Development of equations

As discussed above, direct comparison of different burning cycles involves comparing different components. Two of these components, represented by the rectangle KGML and triangle GNM in Figure 1(a), relate to the period of one cycle. The frequency of cycles over the long term also plays a role. These three components are expressed mathematically as follows (using Figure 1(a) as reference).

Base-line flow increase above datum-line:

The increase (Qm) in base-line flow above the datum-line flow is represented by the rectangle KGML. The area of KGML for a given burning cycle i is given by:

$$A1_i = x_i\, y_i \quad \ldots\ldots \quad (1)$$

where

$x_i = Qm - a_i$

$a_i = y_i \tan\theta$ (increase in water yield immediately after a burn at y_i year intervals)

y_i = number of years in cycle i.

Therefore:

$$A1_i = y_i\,[Qm - (y_i \tan\theta)] \quad \ldots\ldots \quad (2)$$

where

Qm = maximum yield increase in mm for specific vegetation type (from Table 1)

θ = calculated as $\tan^{-1}$ (k), expressed in degrees

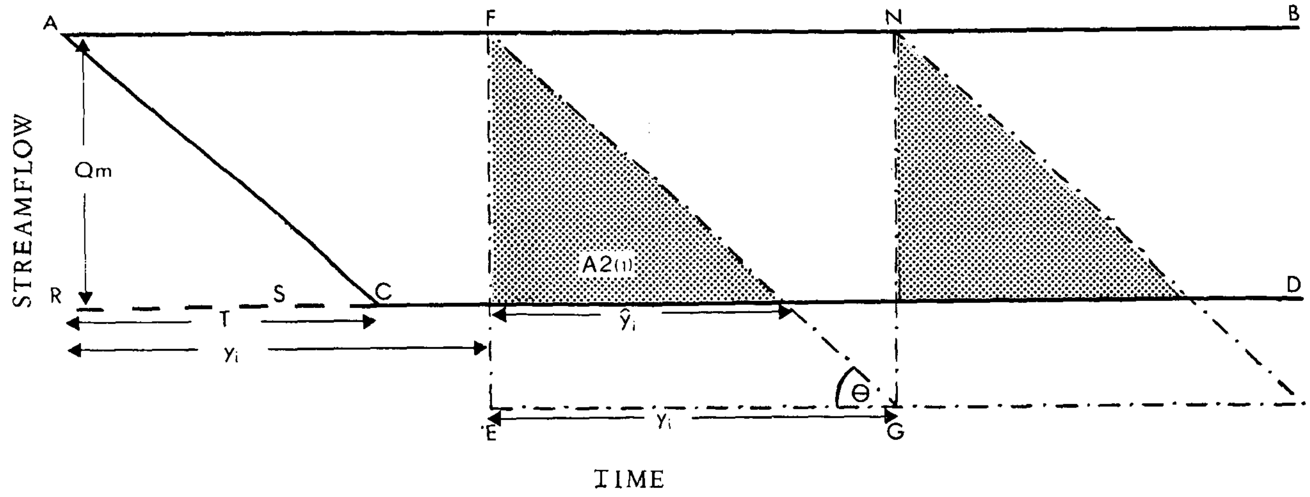

Figure 1(b)
Schematic representation of water yield pattern as in Figure 1(a), but in a vegetation type where the maximum reduction (Qm) is relatively small, which will cause a short stabilization period (T) with one burning cycle being longer than the period T.

k = rate of annual reduction in streamflow in mm after a burn (from Table 1)

Additional increase in yield due to burning and subsequent decline in water yield over period of y_i years:

This quantity is represented by the area of the triangle GNM ($A2_i$)

$$A2_i = \frac{(a_i\, y_i)}{2}$$

$$A2_i = \frac{(y_i^2 \tan\theta)}{2} \quad \ldots\ldots (3)$$

Comparing two cycles:

Two burning cycles can only be compared by calculating their respective increased flow relative to the datum-line flow over a specific period. A convenient period to use is the lowest common denominator (LCD) of the two cycles.

The general equation is:

$$Qi = \frac{\mathrm{LCD}}{y_i}(A1_i + A2_i) \quad \ldots\ldots (4)$$

Where

Q_i = total water yield in cm above datum-line yield for burning cycle y_i over the LCD period,
y_i = number of years in burning cycle i,
$A1_i$, $A2_i$ as determined in equations 2 and 3 respectively

An average *annual* increase above datum-line flow is obtained by dividing the total Q_i by LCD. This value can be used to make relative comparisons over shorter periods.

The above equations change slightly when one or both of the burning cycles are longer than the period required for streamflow to stabilize after a fire (T = stabilization period). Consider Figure 1(b) where the maximum increase Qm is relatively small with a correspondingly short stabilization period (T). The period T is calculated as:

$$T = \frac{Qm}{\tan\theta} \quad \ldots\ldots (5)$$

Water yield (Q_i) above the datum line for the burning cycle is calculated using equations 2 and 3. A burning cycle longer than period T will not result in a base-line flow higher than RD. Therefore A1 need not be calculated. Only peaks (triangles) with a base shorter than the cycle period y_i will be used in calculating yield increase above datum line. A new ŷ must be calculated. In this case a_i = Qm (Fig. 1(b)) therefore

$$\hat{y}_i = \frac{Qm}{\tan\theta} \quad \ldots\ldots (6)$$

The flow increase (shaded area of triangle EFG in Fig. 1(b)) is:

$$A2_i = \frac{(a_i\, \hat{y}_i)}{2}$$

$$= \frac{Qm^2}{\tan\theta . 2} \quad \ldots\ldots (7)$$

Total yield increase (Q_i) is calculated as in equation 4.

When both cycles are longer than the stabilization period T, Q_i is determined by calculating $A2_i$, using equation 7, for both burning cycles and comparing increases over the period of the lowest common denominator.

Procedure and worked example

The above procedure will be illustrated by working through an example step by step. Suppose one wishes to calculate difference in water yield from fynbos of the tall closed shrubland formation fynbos which had been burned on a 15 year cycle, but will now be burnt on a 9 year cycle.

STEP 1: Determine the maximum expected increase (Qm) for tall, closed shrubland from Table 1: in this case 180 mm.

STEP 2: Determine the slope angle (θ) for post-fire reduction rate : $\theta = \tan^{-1}$ (k) where k is read from Table 1 (4 for Tall Closed Shrubland). Preferably the ratio of sprouters to seeders should be determined in the field and Fig. 2(b) used to derive a k value. In our example, the tall closed shrubland in Langrivier had a sprouter : seeder ratio of 25 : 75, which, gives a k value of 8 mm a^{-1}. Thus $\theta = \tan^{-1}(8) = 82{,}8$ (degrees).

STEP 3: Determine the streamflow stabilization period (T) from equation 5 : $T = \frac{180}{\tan 82{,}8} = 22{,}7$ (23 years)

This means that protection for longer than 23 years will not result in any further progressive decrease in water yield, and cycles longer than 23 years will have to be compared by using equations 6 and 7.

STEP 4: Determine base-line flow increase for the two cycles using equation 2:

Fifteen year cycle	Nine year cycle
$A1_i = y_i\,[Qm - (y_i \tan\theta)]$	$A1_i = y_i\,[Qm - (y_i \tan\theta)]$
$A1_{(15)} = 15\,[180 - (15 \tan 82{,}8)]$	$A1_{(9)} = 9\,[180 - (9 \tan 82{,}8)]$
$A1_{(15)} = 918$ mm	$A1_{(9)} = 978$ mm

STEP 5: Determine increase over y_i years due to direct effect of burning by using equation 3:

Fifteen year cycle	Nine year cycle
$A2_i = y_i^2 \tan\theta$	$A2_i = y_i^2 \tan\theta$
$A2_{(15)} = \frac{15^2 \tan 82{,}8}{2}$	$A2_{(9)} = \frac{9^2 \tan 82{,}8}{2}$
$A2_{(15)} = 890$ mm	$A2_{(9)} = 320$ mm

STEP 6: Determine lowest common denominator of y_{15} (15) and y_9 (9) and then calculate Q_i, using equation 4:

Total flow increase above datum-line:

$$Q_{15} = \frac{\mathrm{LCD}}{15} \cdot (A1_{(15)} + A2_{(15)})$$

$$Q_{15} = \frac{45}{15} \cdot (918 + 890) = 5\,424 \text{ mm}$$

$$Q_9 = \frac{\mathrm{LCD}}{9} \cdot (A1_{(9)} + A2_{(9)})$$

$$Q_9 = \frac{45}{9} \cdot (978 + 320) = 6\,490 \text{ mm}$$

STEP 7: The difference in water yield between two cycles over 45 years is 6 490 − 5 424 mm = 1 066 mm. On average over the long term this amounts to 23,6 mm a^{-1}.

Conclusions

The model described in this paper is a simplification of the effects

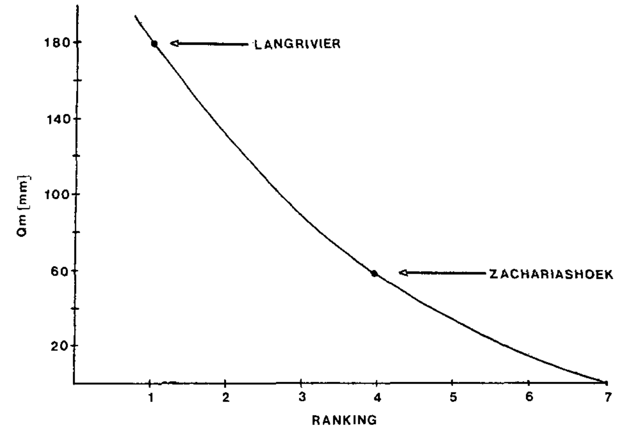

Figure 2(a)
Hypothetical relationship between maximum streamflow reduction (Qm) and structural formations in fynbos according to ranking in Table 1.

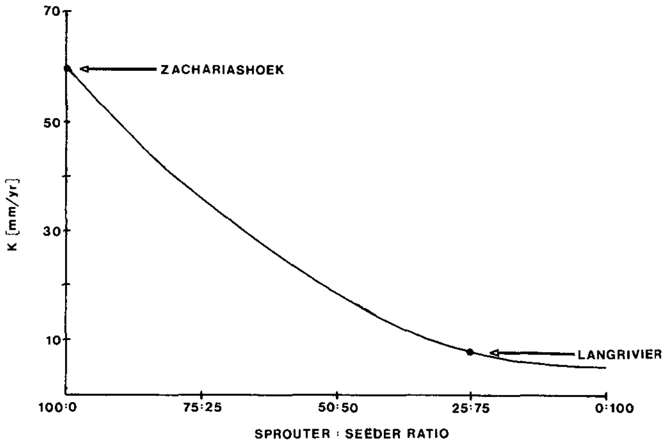

Figure 2(b)
Hypothetical relationship between annual rate of reduction (k) in water yield and the sprouter : seeder ratio of the vegetation in fynbos catchments.

of the real response in water yield to different burning cycles. It does however incorporate the principal empirical information available for fynbos catchments to date. It provides a means for comparing burning cycles in the long term but its real value lies in the fact that it formulates and expresses certain hypotheses in simple mathematical terms. More data will lead to further refinement of the curves presented in Figure 2. The values given in Table 1 are estimates based on scant data, but are reference points which will also undergo further refinement. The values offer a means of relating streamflow response to vegetation structure in terms of biomass, and composition in terms of regeneration modes after fire. As the model is based on empirical data from two catchments, it may be site specific to some degree. However, fynbos mountain catchments are similar in geology and most have relatively high (>1 000 mm) rainfall. The response of vegetation to fire is similar in broad terms. Extrapolation of the model to other catchment areas within the fynbos biome should therefore be possible.

Acknowledgements

This work forms part of the conservation research programme of the Forestry Branch of the Department of Environment Affairs and is published by permission of the Director General. Johan Breytenbach and Danie van Wyk provided valuable comment.

References

BELL, D.T., HOPKINS, A.J.M. and PATE, J.S. (1984) Fire in Kwongan. In: Pate, J.S. and Beard, J.S. (Eds.). *Kwongan plant life of the sandplain.* University of Western Australia Press, Nedlands. pp. 178-204.

BOSCH, J.M., SCHULZE, R.E. and KRUGER, F.J. (1984) The effects of fire on water yield. In: Booysen, P. de V. and Tainton, N.M. (Eds.). *Ecological effects of fire in South African ecosystems.* Springer - Verlag, Berlin. pp. 328-348.

BOSCH, J.M. (1982) Streamflow response to catchment management in South Africa: *Proceedings Int. Symp. on Hydrology Research Basins and their Use in Water Resource Planning.* Landeshydrologie, Bern.

BOSCH, J.M. (1979) Treatment effects on annual and dry period streamflow at Cathedral Peak. *SA For. J.* **108** 29-38.

CAMPBELL, B.M., COWLING, R.M., BOND, W. and KRUGER, F.J. (1981) Structural characterization of vegetation in the Fynbos Biome. *S. Afr. NSP report* **52** 18.

GARNETT, T.F.F. (1973) The Department of Forestry and its functions. *Dept. of Forestry Pamphlet* **107** 39.

KRUGER, F.J. (1979) South African heathlands. In: Specht R.L. (Ed.) *Heathlands and related shrublands of the world. A. Description studies.* Elsevier, Amsterdam. pp. 19-80.

LINDLEY, A. (1986) Effects of veld burning on water yield. *Proceedings of SANCIAHS 2nd S. Afr. Nat. Hydrol. Symp.*, Natal University. pp. 384-395

PLATHE, D.J.R. and VAN DER ZEL, D.W. (1969) 'n Veldbrand eksperiment op meervoudige opvanggebiede in Jakkalsrivier, Lebanon. *For. in S. Afr.* **10** 63-69.

VAN DER ZEL, D.W. (1974) Catchment research at Zachariashoek. *For. in S. Afr.* **15** 23-30.

VAN DER ZEL, D.W. and KRUGER, F.J. (1975) Results of the multiple catchment experiments at the Jonkershoek Research Station, South Africa. 2. Influence of protection of fynbos on stream discharge in Langrivier *For. in S. Afr.* **16** 13-18.

VAN WILGEN, B.W. (1982) Some effects of post-fire age on the above-ground plant biomass of the fynbos (macchia) vegetation in South Africa. *J. Ecol.* **70** 217-225.

VAN WILGEN, B.W. and KRUGER, F.J. (1985) The physiography and fynbos vegetation communities of the Zachariashoek Catchments, south-western Cape Province. *S. Afr. J. Bot.* **51** 379-399.

VAN WILGEN, B.W., LE MAITRE, D.C. and KRUGER, F.J. (1985) Fire behaviour in South African fynbos (macchia) vegetation and predictions from Rothermnel's fire model. *J. Appl. Ecol.* **22** 207-216.

VAN WYK, D.B. (1977) Die invloed van bebossing met *Pinus radiata* op die totale jaarlikse afvoer van die Jonkershoek strome. M.Sc. Thesis, University of Stellenbosch.

VERSFELD, D.B. and BOSCH, J.M. (1982) The options for catchments - how to make the right decisions : another view. *Proc.-Jubilee Symp. Forestry Faculty, University of Stellenbosch,* Stellenbosch. pp. 427-446.