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THE DEVELOPMENT OF GUIDELINES FOR THE DESIGN OF STREAMWATER QUALITY MONITORING STRATEGIES IN THE FORESTRY INDUSTRY

Report to the
WATER RESEARCH COMMISSION
by the
DIVISION OF FOREST SCIENCE AND TECHNOLOGY, CSIR

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Division of Forest Science and Technology, CSIR

Report to the **Water Research Commission** on the project "Development of a rule model for the design of streamwater quality monitoring strategies in the forestry industry"

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EXECUTIVE SUMMARY

BACKGROUND

The increasing awareness of the need to protect the quality of South Africa's water resources from degradation, has resulted in a growing awareness of the need to also control non-point pollution. Legislation controlling non-point pollution may affect the forestry industry and their management of catchment water resources.

This project was undertaken to analyse and synthesise inorganic streamwater quality data collected over 16 years in afforested montane catchment areas in South Africa. The aim of this analysis was to develop rule models or guidelines which the forestry industry could apply in a cost-effective way to monitor impacts of management activities on water quality. This entailed identifying the most important water quality variables, and also where and how to sample to obtain reliable data.

OBJECTIVES

The aims of the project as they were described in the original proposal are as follows:

(a) To investigate the importance of specific water quality variables as indicators of impacts of forestry management practices, by conducting an intensive analysis of stream water quality data currently in place on the Forestek database.

(b) To determine possible correlations between stream water quality variables which would indicate if some variables can be used as indicators for others. The Forestek database will be used in corroboration with internationally published data. The water quality variables include: suspended sediment, pH, conductivity, Na^+, K^+, Ca^{2+}, Mg^{2+}, NH_4^+, Cl^-, SO_4^{2-}, NO_3^-, PO_4^{3-}, HCO_3^-, TP (total phosphate), KN (Kjeldahl/total nitrogen), Si and F.

(c) To provide two rule-based models or sets of guidelines for the forestry industry, giving the most cost-effective methods for water quality monitoring for both short- and long-term goals. One model will be simple, using easily measurable variables, and the other more detailed, including all relevant variables. The rule models will be based on normal forestry management practices, for example clearfelling, site preparation and afforestation.

APPROACH

Water quality data from three different mountain catchment areas were analysed for changes that could be attributed to changes in forestry management practices. These consisted of three catchments under plantations in the south-western Cape, two indigenous forested catchments in north-eastern Transvaal, and one partly afforested catchment in the eastern Transvaal.

The management practices that were considered varied from riparian zone clearings to afforestation of a once indigenous forested catchment with commercial tree species. Of the Cape catchments, one was kept as a control. A second catchment underwent a riparian clearing, followed by the total clearfelling of the plantation (and catchment) and subsequent re-afforestation. Just more than half of the third catchment was under plantation, and this was clearfelled over a period and planted with a second-rotation crop. A few years later the whole of the latter catchment accidentally burnt down, and was planted-up again.. Of the indigenous forested catchments in north-eastern Transvaal, one was bulldozed and burnt, and a plantation established, while the other was maintained as a control. The catchment in the eastern Transvaal underwent several riparian clearings. Before the final burning of the riparian zone, the plantation, which covered 25% of the catchment, was clearfelled.

Samples taken from both high- and low-flow conditions were included in the study. All water quality variables indicated under 'Objectives' were analysed. Statistical analyses applied on all variable concentrations included tests for normality of data, the Wilcoxon Rank Sums tests on concentration ratios, Kendal's Tau trend analyses which included test for seasonality and auto-correlation, and correlation analyses.

MAJOR RESULTS AND CONCLUSIONS

There were no consistent statistically significant changes in the concentrations of the variables in spates (high flow) as a result of the different forest management practices. Suspended sediment was the only variable that changed as a result of a number of different management practices. The most marked increases in sediment, upto five-fold, occurred after a fire burnt a plantation in the south-western Cape. Although the effects were short-lived, the extent of the increases indicated that spate sampling would be needed to monitor such extreme changes in vegetation cover.

Grab-sample concentrations of suspended sediment, NO_3^--N, PO_4^{3-}-P, K^+ and Ca^{2+} provided good indications of the effects of most forest management practices. Management practices which disturbed the upper soil layers caused sediment concentrations to increase in streamwater. The increased concentrations of NO_3^--N, PO_4^{3-}-P, K^+ and Ca^{2+} is attributed to water percolating through decaying litter, slash, roots and ash and the consequent leaching of these important plant nutrients. NO_3^--N and K^+ were also found to be indicators of long-term change, with concentration levels being elevated for a number of years following disturbance caused by changes in management practices. Intensive site preparation during the conversion of an indigenous forest to plantation caused the most lasting concentration increases of NO_3^--N and K^+ in streamwater.

There were no consistent significant correlations between variables, and none could be used to predict others.

The method of stream ordering was used to indicate a sampling hierarchy in greater catchment areas. A control or untreated catchment provided a highly effective way of separating actual changes in water quality in the treated area from changes caused by variation in climate. Monthly grab samples were found adequate for general monitoring while specific sampling of high-flow conditions will be needed to determine the effects of extreme management practices or events on catchment water quality.

MEETING OF OBJECTIVES

The objectives, as set out in the original proposal were generally met. Suspended sediment, NO_3^--N, PO_4^{3-}-P, K^+ and Ca^{2+} were found to be reliable indicator variables of the impacts of forestry management practices. Correlation analyses involving all the sampled variables in all the catchments showed that

(a) none of the variables were consistently highly correlated and

(b) they could not be used to predict each other.

The third objective was met in that general guidelines for water quality monitoring were compiled. No rule models were determined.

Part B of this report provides guidelines to forest managers for designing a water quality monitoring system for forested catchments, and can be used as a stand-alone section.

RECOMMENDATIONS FOR FURTHER RESEARCH

Sampling frequency determinations still need more attention. The inconsistent results for different variables found in this study points to the need for a more detailed analysis than was possible in this study.

The effects of different site-preparation techniques on streamwater quality have not been specifically researched. Information on these impacts could affect conclusions about the importance of specific variables, and refine the guidelines for monitoring.

Although this study did not include aquatic organisms, it would seem that they can be used complementary to inorganic indicators and are potentially more sensitive indicators of change in montane headwater streams. A combination of both types of monitoring (inorganic and biotic) might give a better indication of the effects of forest management practices on water quality.

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GLOSSARY AND LIST OF ABBREVIATIONS

calibration period	period before application of management practice during which variable concentrations in the treated catchment are correlated with those in an undisturbed (control) catchment
control catchment	catchment in which water quality variable concentrations have stabilised, and where no management practices are applied for the duration of the study
grab sample	streamflow sample taken by hand using a container; streamflow levels can *be low (usually) or high.*
spate	the increase in the volume of streamflow resulting from a substantial rainfall event
spate sample	sample taken during heightened streamflow levels
treated catchment	catchment in which forest management practices have been applied

Ca^+	calcium
Cl^-	chloride
EC	electrical conductivity
F^-	fluoride
HCO_3^-	bicarbonate
K^+	potassium
KN	Kjeldahl/total nitrogen
Mg^{2+}	magnesium
Na^+	sodium
NH_4^+-N	ammonium
NO_3^--N	nitrate
PO_4^{3-}-P	phosphate
Si	silicon
SO_4^{2-}-S	sulphate
TP	total phosphorus
TSS	total suspended sediment

INTRODUCTION

Montane headwater catchments receiving more than 800 mm rainfall per annum are regarded as invaluable water resource areas of South Africa, as the major part of the country is classified as arid or semi-arid (Department of Water Affairs, 1986). The forestry industry, which is concentrated mainly in the higher rainfall regions, is a significant role player in water resource management.

The forestry industry has emphasised water yield in its water resource management, allowing for sufficient flow from planted-up areas. Due, in part, to pressure from external environmental groups the emphasis has now shifted to include the quality of the water emanating from afforested lands. Legislative standards for non-point pollution, to which afforested areas are typical contributors, are now being considered to complement those for point pollution control (Department of Water Affairs, 1986; van der Merwe and Grobler, 1990). Despite two decades of pollution control of point sources, the quality of water in South Africa has continued to deteriorate steadily. This situation has lead to a new approach which specifies the water quality requirements of receiving waters. Pollution control will be applied to ensure that these requirements are met (van der Merwe and Grobler, 1990). Implementation of the new receiving water quality objectives (RWQO) approach requires the control of both point- and non-point sources of pollution. The forestry industry will be required to devise a water quality monitoring strategy for plantation areas to meet the RWQO. The water quality database at Forestek can be used to assist forestry management to develop a water quality management strategy by supplying information on sampling methods and the importance of certain water quality variables for monitoring.

The effects of the afforestation of grassland, fynbos and forested mountain catchment areas in South Africa on water yield have been studied extensively (Wicht, 1967a; Nänni, 1970; Bosch, 1979; van Lill *et al.*, 1980; van Wyk, 1987; Bosch and Smith, 1989; Smith 1991; van Wyk and Scott, 1993a & b). Monitoring of the quality of the water from these catchments commenced in 1974 (van Wyk, 1981). The main aim of the water quality research has been to determine the effects of different forest management practices in upper mountain catchment areas on water quality and budgets of inorganic constituents (imports and exports). This was done in part to quantify whether there was non-point pollution of inorganic water quality variables due to different forest management practices.

Mountain catchment areas with undisturbed indigenous vegetation are generally regarded as sources of pristine quality water (Likens *et al.*, 1977; Swank and Waide, 1988; Lynch and Corbett, 1990; van Wyk and Lesch, 1992). Natural ecological disturbances in these areas, for example the burning of fynbos in the south-western Cape and grasslands in the Natal highlands, do not have any detrimental effects on the quality of the water (van Wyk, 1981; van Wyk, 1986; van Wyk and Lesch, 1992; van Wyk *et al.*, 1992). Recent studies on the effects of clearfelling of plantations on aspects of water quality have shown that some variables are affected by the change of vegetation (Lesch and van Wyk, in prep.; van Wyk and Scott, 1993a & b).

The objectives of this study were to determine:

(i) which inorganic water quality variables were most affected by normal forest management practices,

(ii) why these were affected and

(iii) which of these, if any, could be used as good indicators of management effects in both high- and low flow conditions.

The study was carried out in a number of successive steps: The first step was to analyse the existing data base at Forestek statistically in order to achieve the above-mentioned objectives. The next step was to use the data to determine sampling frequency and to devise procedures for selecting appropriate sampling sites to obtain reliable data on the impact of forest management practices on water quality. Existing recommendations in the literature for sampling sites were incorporated in this section. Finally, guidelines for cost-effective monitoring of streamwater quality in afforested areas were compiled using the information obtained from the above objectives. Practical, cost-effective monitoring strategies and procedures for decision makers to use for interpreting water quality data in South Africa are given by Harris *et al.* (1992). Their study incorporated many of the ideas proposed by Sanders *et al.* (1987). This study followed much the same route.

The report consists of two major sections. Part A contains descriptions of the catchment areas used in the study and the experimental techniques and management practices applied. This is followed by a discussion of the results of the statistical analyses; firstly the spateflow data, then the grab-sample data (mainly low flow). Seasonal trends in grab-sample concentration levels were investigated before the effects of management practices were analysed. The next section discusses the results of a correlation analysis of the relationship between different water quality variables. The final section of Part A addresses the analysis of information on sampling site selection and sampling frequency. Part B contains guidelines for water quality monitoring of afforested areas, using information from the results obtained in Part A, and can stand on its own.

PART A: ANALYSIS

1 EXPERIMENTAL SITES AND METHODS

1.1 Physiographic description of the sites

In this study we concentrated on three areas in South Africa, all part of a network of catchment experiments established to determine the hydrological character of upper mountain catchments (Wicht, 1976b).

The catchments studied at Jonkershoek in the south-western Cape comprised two treated catchments, Bosboukloof and Biesievlei, and an afforested control catchment, Lambrechtsbos-B (Figure 1). Streams from these catchments flow into the Eerste River that supplies water to farming and industrial areas. Jonkershoek has a mediterranean-type climate, with hot summers and cold winters, with more than 70% of rainfall occurring during the winter (April to September) (Wicht *et al.* 1969). The underlying bedrock of most of the afforested area is deeply weathered Cape Granite. A lens of shales from the Malmesbury Group, lying on top of the granites, cuts across all three catchments. The granite and the overlying sandstone from the Table Mountain Group (Cape Supergroup), give rise to the coarse colluvial soils, which have excellent infiltrability (Versfeld, 1981). Major soils are loams to sandy-loams and of the forms Hutton, Magwa and Nomanci (terminology: MacVicar *et al.* 1977). The natural vegetation of the area is fynbos, mainly with Protea species, and evergreen tall forests in protected sites, such as along rivers and on screes (van Wilgen, 1982). Additional features are summarised in Table 1.

Two catchments were studied at Westfalia in the north-eastern Transvaal. Catchment B was used as the control and D was subjected to treatments (Figure 1). Streams from the Westfalia Estate are part of the upper reaches of the Great Letaba River which flows through one of the major agricultural and industrial growth areas of South Africa, and finally the Kruger National Park. In contrast to Jonkershoek, Westfalia lies in the

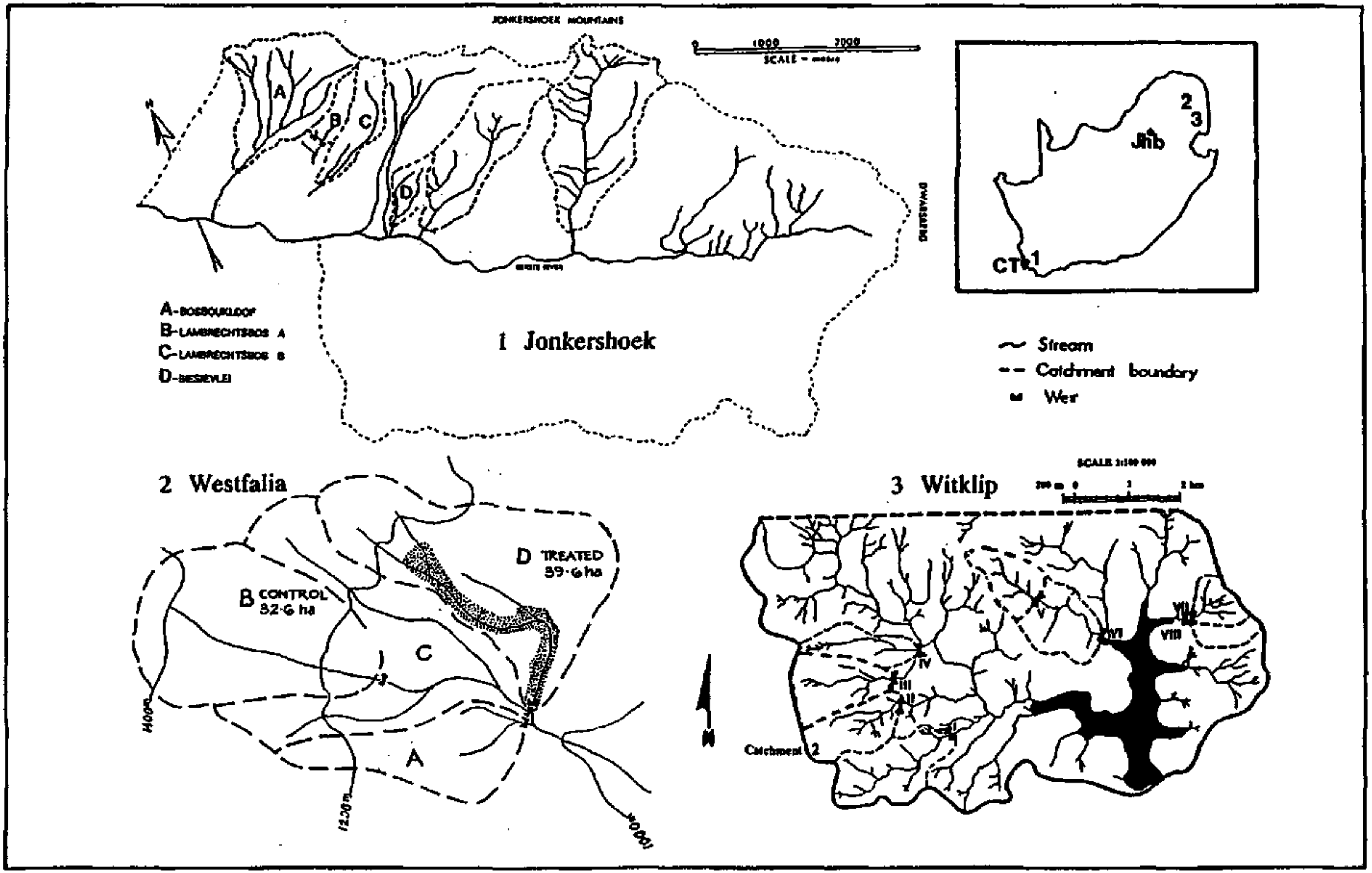


Figure 1 Position and lay-out of the experimental research areas used in this study.

Table 1 Selected physical features of the catchments used in this study (from van Wyk,1987; Smith and Bosch 1989)

Catchment name	Area(ha)	Percentage Afforestation	Elevation(m)	Mean Slope(%)	MAP[1] (mm)	MAR[2] (mm)
South-western Cape:						
Bosboukloof	200.9	57	270 - 780	26	1296	593
Biesievlei	27.2	98	280 - 300	23	1427	663
Lambrechtsbos-B	65.5	82	290 - 840	46	1473	531
North-eastern Transvaal:						
Westfalia B	32.4	0	1050 - 1430	42	1597	543
Westfalia D	39.6	83	1050 - 1320	33	1611	548
Eastern Transvaal:						
Witklip 2	136	34	1100 - 1470	30	1400	220

[1] mean annual precipitation

[2] mean annual runoff

subtropical summer rainfall area, with 84% of the rainfall occurring from October to March. Here the bedrock is a biotite-bearing granite gneiss (called the Turfloop granite) with dykes and sills of diabase criss-crossing the catchment area. The soils on the slopes are well-drained, changing to hydromorphic soils in the riparian zone. The soils are friable and well-aerated with low cation exchange capacity (Döhne, 1984) and the dominant form Hutton. The indigenous vegetation in the area is transitional between evergreen high forest and deciduous woodland. More information on the catchments is given by Smith and Bosch (1989).

The third experimental site is that in the eastern Transvaal at Witklip, north of Nelspruit (Figure 1), where only one treated catchment (no. 2) was analysed (Table 1). These catchments supply the Witklip dam and eventually flow into the Crocodile River. The climate of this area is similar to Westfalia, being subtropical with most of the rain falling from October to March. Again the underlying bedrock is a biotite-bearing gneissose granite (of the Nelspruit type), while alluvial material is found in the valley-bottoms. The indigenous vegetation is classified as North Eastern Mountain sourveld (Acocks, 1953), comprising short grassland with high forests in the riparian and other protected zones. Wicht and Kluge (1976) give additional details.

1.2 Forest management practices applied

In the experiments used for this study the clearing of riparian vegetation and replacement of indigenous forest by a commercial plantation was only for experimental purposes, as both vegetation types are legally protected in South Africa. The planting of trees within 20 m of a perennial stream or water source area has not been permitted since 1972 (van der Zel, 1982). Conservation guidelines accepted by the industry recommend that neither riparian areas nor areas close to indigenous forests "be cultivated or planted up" (Bigalke, 1990). The Afforestation Permit System prescribes planting at a minimum of 30 m from the edge of indigenous forests.

The management practices included in this study are summarised in Table 2. The following different practices potentially had major effects on water quality variable concentrations:

i) At Bosboukloof, Jonkershoek, the first-rotation plantation was 40 years old when clearfelled, and that at Biesievlei 35 years old (Table 2). A standard method of harvesting was followed, with felled trees being de-branched, cut to sawlog lengths and rolled (by hand or tractor) to the nearest road. Slash from the harvesting was piled mostly in rows vertically down (Bosboukloof) or along contours (Biesievlei) in the catchment (van Wyk and Scott 1993a). The standard replanting procedure was pitting and planting at an espacement of 2.7 m by 2.7 m (1372 stems ha^{-1}), reducing disturbance to a minimum.

ii) The wildfire that burnt Bosboukloof in 1986 was of a high intensity, because fuel loads were high and fuel moisture low (Scott and van Wyk 1990). This was an ideal opportunity to study first-hand the effects of an event that is, though undesirable, a significant risk in any plantation area.

iii) Catchment D at Westfalia and catchment 2 at Witklip both underwent a number of riparian treatments and were also clearfelled to varying degrees (Table 2). High fuelloads and low moisture, resulted in a hot fire during the burning of the riparian zone in Witklip 2. Similar afforestation techniques to that at Jonkershoek, were applied in both these catchments.

1.3 Experimental design

The paired catchment experimental approach was followed for Jonkershoek and Westfalia. Water quality variable concentrations for a treated catchment were compared with those of an adjacent protected, or control, catchment. This method assumes that relationships between the values of variables from the two adjacent catchments would remain constant if the vegetation was not changed (Hewlett and Pienaar, 1973). In this way natural fluctuations in water quality and, for example, the effects of major climatic changes can be distinguished from those due to treatment. Where possible, the ratio of the values for the treated and control catchments during a pre-treatment period was

Table 2 Summary of treatments applied to all the experimental catchments used in this study. Adjacent protected treatments were used as controls.

Catchment	Date	Treatment
Bosboukloof	1980 - 1982	Clearfelling of *Pinus radiata* plantation which comprised 54% of the catchment; no riparian treatment; re-afforestation within a year of felling
	18 Feb 1986	Wildfire that burnt 80% of the catchment, also seriously affecting parts of the riparian zone.
Biesievlei	Feb-Apr 1984	Felling of trees in a 20 m belt (riparian zone) either side of the lower 2/3 of the stream; catchment had been afforested (*P. radiata*) up to stream.
	Aug-Nov 1984	Remaining upper third of riparian zone felled.
	May 1985 - Mar 1986	Clearfelled *P. radiata* plantation, in all 98% of the catchment; re-afforestation within a year of felling, again up to the river.
Westfalia D	Jan 1981	Riparian zone, 20 m either side of the stream, slashed, material being left *in situ*; 4 ha affected (10% of catchment).
	Nov 1981	Riparian zone regrowth slashed and left.
	Dec 1982 - Jan 1983	Felling and bulldozing of 83% of the indigenous forest; vegetation stacked in the catchment and burnt.
	Mar - Apr 1983	Afforestation of entire catchment, including riparian zone, with *Eucalyptus grandis*.
Witklip 2	Aug 1979	Riparian zone vegetation of > 100 mm diameter at breast height (dbh) felled.
	June 1981	Remainder riparian vegetation felled.
	Feb 1982	Riparian zone sprayed with Roundup to suppress woody growth.
	Feb 1983	Riparian zone sprayed with Roundup.
	Aug 1983 - Jul 1984	Clearfelling of the pine-afforested area (25%) of the catchment, slash left *in situ*; Re-afforestation within a year after felling.
	30/1 Jul 1985	Burning of the riparian zone

compared with that of a post-treatment period. Since there were no suitable control catchments at Witklip, trend analyses of the changes in values with time were used.

1.4 Water sample collection and analysis

At the lower-end of all the experimental catchments, weirs with sharp crested compound 90° V-notches were constructed and fitted with Belfort water level recorders which measured streamflow continuously. Weekly grab samples were taken at these gauging stations from a well mixed, free-flowing spot where the stream entered the stilling pond. The samples were then stored at 4°C. Event-linked spate samples were also taken using a rising stage sampler fixed at the weir (Van Wyk, 1983) which sampled successive stages of the rising limb of the hygrograph. The spate samples were collected either after the event, or during weekly rounds and stored at 4°C. Samples were stored for less than one week before being either analysed, or preserved to be sent to the laboratory for full analyses. Starting dates for the different types of sampling at all the research catchments are summarised in Table 3.

Half of each sample was analysed for suspended sediment, by vacuum filtration (Whatman GF/C filters) in local laboratories at each research centre. Electrical conductivity (EC) and pH measurements were also performed on these samples, taken to constant room temperature (25°C). Measurement of pH was only done on grab samples, as spate samples sometimes remained in the field for a number of days. On either a weekly (Westfalia), fortnightly (Witklip) or monthly (Jonkershoek) basis, the remaining half of each sample was preserved with mercuric chloride and sent to an analytical laboratory. In the Transvaal catchments all sampled spates were analysed while only one spate per month was analysed in the Jonkershoek catchments. From 1974 to 1982 analyses were performed by the CSIR in Bellville, and after that by the Hydrological Research Institute (HRI) in Pretoria according to standard analytical procedures described by the Department of Water Affairs and Forestry (1992). Samples were analysed for: sodium (Na^+), potassium (K^+), calcium (Ca^+), magnesium (Mg^{2+}), ammonium (NH_4^+-N), chloride (Cl^-), sulphate (SO_4^{2-}-S), nitrate (NO_3^--N), phosphate

(PO_4^{3-}-P), bicarbonate (HCO_3^-), fluoride (F^-), total phosphorus (TP), Kjeldahl/total nitrogen (KN) and silicon (Si) and also the pH and electrical conductivity (EC).

Table 3 Dates when water quality sampling began in the experimental catchments used in this study.

Variable	Jonkershoek		Westfalia		Witklip
Group	spates	grab samples	spates	grab samples	grab samples
TSS[1]	June 1981	March 1982	January 1981	January 1981	April 1983
pH and EC[2]	October 1982	July 1974	November 1981	August 1985	August 1985
All other (A[3]+B[4])	October 1982		November 1981	October 1981	May 1983
A		July 1974[5]			
B		July 1983			

[1] TSS = total suspended sediment
[2] EC = electrical conductivity
[3] A = Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}-S and HCO_3^-
[4] B = NO_3^--N, PO_4^--P, NH_4^+-N, F^-, Si, KN and TP
[5] SO_4^{2-}-S only analysed from March 1977

1.5 Data handling

In some of the catchments sampling only commenced a few months prior to the application of management practices. In these cases the data from consecutive years were tested to determine whether they could be combined for further analysis. As indicated in Table 3, spate sampling for all water quality variables at Jonkershoek commenced at the end of the Bosboukloof clearfelling and before the onset of the Biesievlei treatments, giving a calibration period of over a year for Biesievlei. For Bosboukloof the three months of 1982 were lumped with 1983 and compared against 1984 and 1985 respectively. Where there were no significant differences for a specific variable, the concentrations for all three periods were combined to determine the effects the fire of 18 February 1986 had on Bosboukloof water quality.

Grab-sample concentrations of NO_3^--N, PO_4^{3-}-P, NH_4^+-N, F^-, Si, KN and TP (group B, Table 3) from Bosboukloof were treated statistically in the same way as the spate samples. A 'calibration' period for the fire was also obtained by combining the data for the pre-fire period.

At Westfalia D grab and spate sampling of suspended sediment was initiated just after the riparian treatment (Table 3), giving no pre-treatment calibration period. Analysis of the full range of water quality variables commenced just a year before the felling treatment (Dec'82-Jan'83) and could be used as the calibration period. Since the pH and EC were analysed at the local laboratory only from August 1985, the values from the HRI analyses were used for statistical analyses. Values for these two variables determined in unpreserved samples were generally preferred.

Water quality sampling at Witklip 2 only commenced partway through the series of riparian treatments. The riparian vegetation had been slashed and the first application of Roundup (which prevented re-growth of woody vegetation) was completed before sampling began. All data including that for a period of five years after the final treatment, the riparian zone burning in July 1985, was analysed to determine if there were any trends.

1.6 Statistical analytical techniques

The SAS statistical package (SAS Users Guide for PC, 1989; SAS/Graphs, 1992; SAS Language, 1992; SAS Procedures Guide, 1992) was used for all statistical analyses. A package for trend analyses, using SAS and Fortran programmes compiled by Reckhow *et al.* (1992), was also used.

The raw data were manipulated as follows to obtain similar standards for each variable:

i) In order to compensate for concentrations that lay below the detection limits of the instrumentation used for analysis, non-detectable values in all the data sets were replaced by one-half the detection limit for each variable (Harris *et al.* 1992).

ii) As sampling intervals varied between the different catchments the raw data was standardised by transforming it to mean monthly values (Reckhow *et al.* 1992). Concentrations for the different stages of each spate analysis were also averaged to a single (unweighted) concentration for each variable. These values were used for further analysis.

Tests of normality were done on the manipulated grab-sample data from the two control catchments, Lambrechtsbos-B in the Cape and Westfalia B in Transvaal, as well as from catchment 2 at Witklip (Appendix A). These test were done using the Univariate procedure in SAS and included normal probability plots, plots of histograms and the Shapiro-Wilk statistic, W, for normality (SAS Procedures Guide 1992; W statistic: Gilbert, 1987). Most variables were not normally distributed (Appendix A), and it was consequently decided to use non-parametric statistical tests for further analyses.

In order to get an indication of seasonal variation in water quality, box and whisker plots (Reckhow *et al.* 1992) were drawn of all variables from the two control catchments, one representing the winter- and one the summer rainfall area. Only the control catchments were used for this test, as variation in concentrations in other catchments might be related to management practices, and not natural fluxes. This technique also provided information on the mean, median, deviation round the median, dispersion and range of concentrations for each month (Figure 2).

To test for significant change in the water quality in catchments at Jonkershoek and Westfalia to which management practices were applied (treated catchments), the ratio of the concentrations for each variable from the treated (T) and control (C) catchments

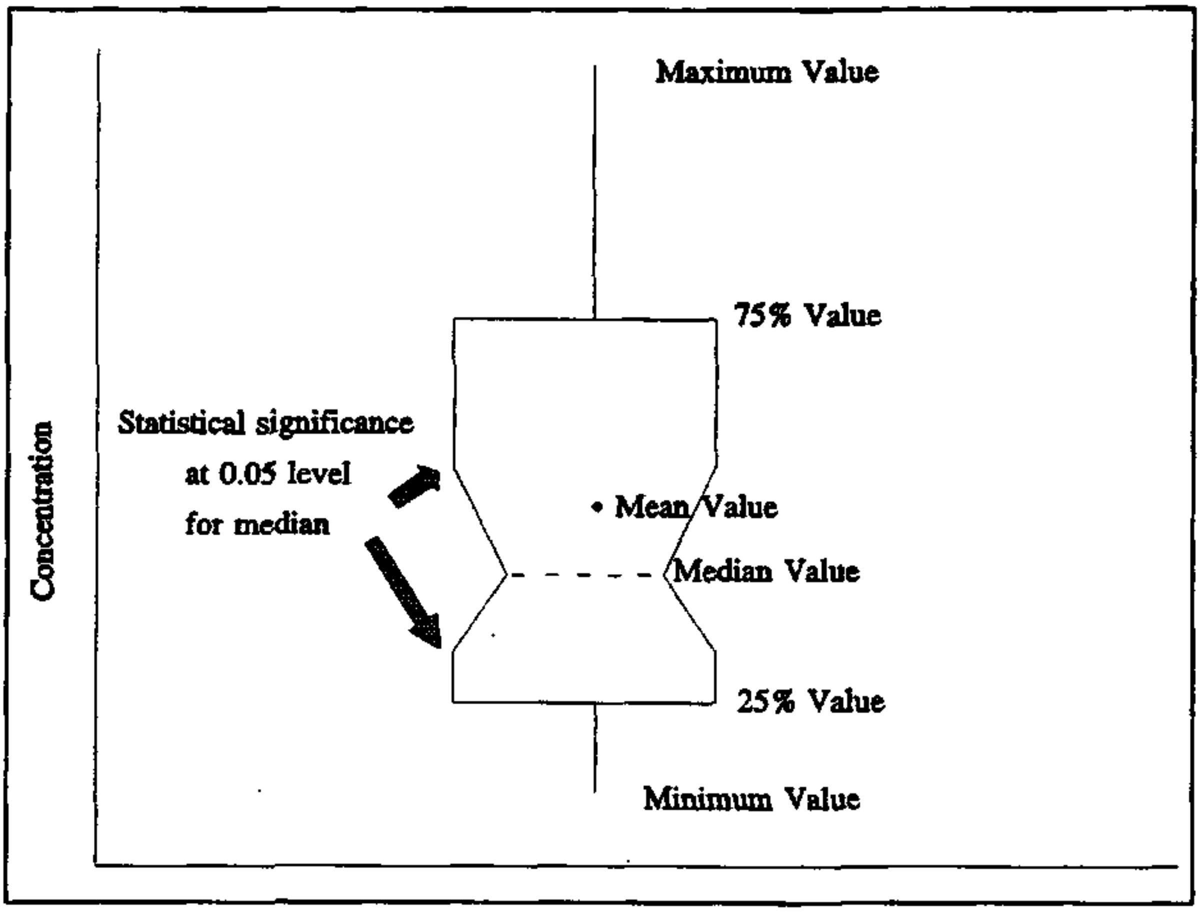


Figure 2 Important facets of the box and whisker plot. The statistical significance of the median (the height of the notch above and below the median) is based on work by McGill *et al.* (1978), where:
Notch limits = median ± (1.57 l / $\sqrt{n}$), with l = upper - lower quartile, and n = sample size.

was calculated (T/C). The relationships between the treated and control concentrations during the calibration period were not always constant, as could be seen from regression analyses of some variables in Jonkershoek and Witklip (van Wyk and Scott, 1993a & b). This is, however, still considered the best way to detect significant changes in concentration due to treatments. The monthly pre-treatment (calibration period) ratios were then tested against those for the post-treatment period using the non-parametric Mann-Whitney or Wilcoxon Rank Sums test (Zar, 1984, p138). This statistical method is recommended for comparative water quality analyses where data are not normally distributed, the number of observations unequal, and cognisance is taken of seasonality

(Sanders *et al.*, 1987; Harris *et al.*, 1992). The effects of seasonality are substantially reduced by the use of a control catchment. In all statistical analyses, data were analysed (where possible) for each of the three respective years following each treatment. Those variables that showed significant change in the third year were analysed for an additional year or more.

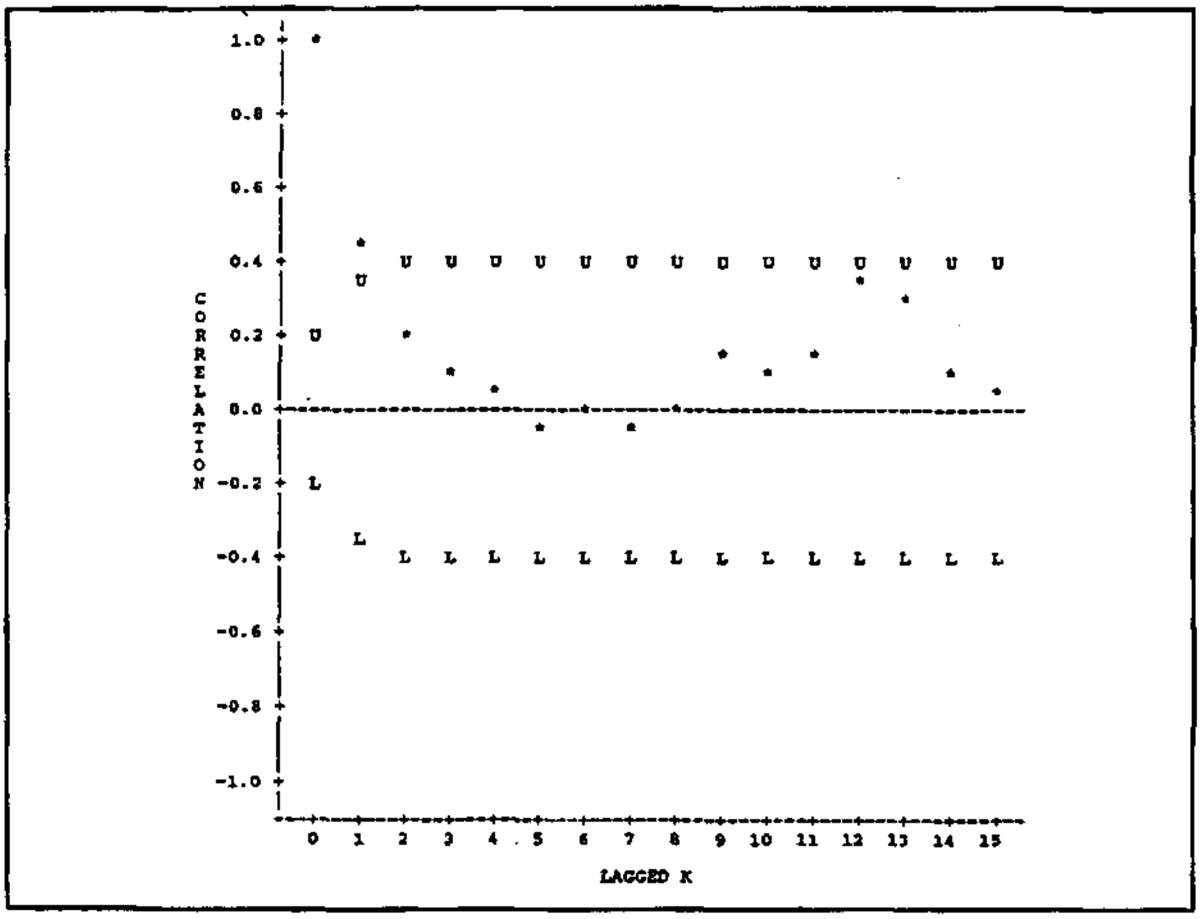


Figure 3 Correlogram of K^+ at Witklip2. The stars show the autocorrelation versus the monthly lag. The upper (U) and lower (L) levels of the 95% confidence limit are indicated.

Trend-analysis was used on the Witklip data to detect changes in water quality with time after the riparian and clearfelling treatments. The SAS programmes compiled by Reckhow *et al.* (1992) were used firstly to construct correlograms of all the variables analysed, the equations for which are found in Pankrantz (1983). This is a graphical illustration of autocorrelation values versus the lag, and can also be used to diagnose seasonality in the display of cyclical patterns (Figure 3). Where seasonality was detected a seasonal Kendall's Tau trend test was applied to each variable. Output from the latter included a correction for the covariance caused by autocorrelation (correlation over time), giving both serial- and non-serial-correlated statistics, and a seasonal Kendall-Sen slope estimate for the trend. The statistics used in these programs are described in Hirsch *et al.* (1982), Hirsch and Slack (1984) and Gilbert (1987). Those variables that showed a possible significant trend with time were then tested for autocorrelation. The lag1 and lag2 statistics, after de-seasonalising and de-trending, were used as diagnostics of autocorrelation. Where these fell within the upper limit of significance (0.05 level) the probability value for Z with no serial correlation was used. Otherwise that for serial correlation was used.

Correlation coefficients between the variables were calculated using Pearsons product moment statistics.

2 INDICATOR VARIABLES IN SPATE SAMPLES

2.1 Background

Sampling of spates often entails expensive equipment, regular routines of sample collection and usually a fixed structure, such as a weir where controlled sampling can take place. For this reason analyses of concentration levels in spates were treated separately from that of grab-samples to determine whether routine spate sampling is required for monitoring changes.

2.2 Results of analyses

The results of the analyses of the spate data are given in Appendix B, Tables I to III, and summarised in Table 3. Spates from Witklip 2 were not analysed as there were no control-analyses and the irregularity of spate analyses did not lend itself to trend analysis. Bosboukloof unfortunately had no pre-clearfelling period to use as a calibration for the applied management practice and the post-clearfelling years were therefore compared with each other. Opportunities for sampling at Westfalia D during the post-felling period were unfortunately irregular because of a drought that lasted from the end of 1982 into 1984. Rainfall was about 60% of mean annual precipitation (Bosch and Smith, 1989). This led to a low number of observations for the overall period, and the first two years after felling were combined for statistical analysis (Table III, Appendix B). Sample sizes for most of the variables were low because often only one spate per month was sent for analysis. Suspended sediment and electrical conductivity levels were determined for every spate sample.

2.2.1 Bosboukloof: Clearfelling and fire

The management practices applied at Bosboukloof resulted in a number of significant changes in the water quality during spates (Table I, Appendix B). The clearfelling resulted in significant changes between the post-clearfelling years in suspended sediment, Ca^{2+}, Mg^{2+}, SO_4^{2-}-S, NO_3^--N and F^- (Table 4). There were significant reductions relative to the control catchment from the first to the third year after clearfelling for all of these variables except SO_4^{2-}-S and F^-, which increased in the second and third post-treatment years respectively. The changes in Ca^{2+}, Mg^{2+} and F^- were, however, heavily influenced by non-detectable values for the spates from both the treated and control catchments. When non-detectable values were replaced by one half the detection limit, a major portion of the third post-treatment year (1985) showed constant ratios which did not represent a true change. Thus the only truly significant concentration changes were the increase in SO_4^{2-}-S and decreases in suspended sediment and NO_3^--N from the first to the third pre-clearfelling years (thus an increase directly following clearfelling).

Although there were increased T/C ratios for SO_4^{2-}-S in the second year following clearfelling, indicating increased concentrations in Bosboukloof relative to the control, actual concentration levels dropped from 7.81 to 6.45 mg l^{-1}. NO_3^--N showed an opposite trend. Mean concentrations were lower in the first year after treatment, increasing from 0.038 mg l^{-1} to 0.070 mg l^{-1} in the third year. Here though the T/C ratio dropped substantially from 3.4 to 1.2, implying that the clearfelling caused an increase in the first year following the felling. The sediment concentration was 172 mg l^{-1} after the clearfelling, and dropped to 149 mg l^{-1} by the third year, the mean T/C ratio also dropping from 5.5 to 1.3. These results illustrate the importance of a control catchment since a decrease in concentration can represent a relative increase when measured against values for a control catchment.

The effect of the fire on water quality variables in Bosboukloof was tested by combining the three post-clearfelling years as a calibration period. The relative changes in concentration between these years were very small and generally insignificant. Only the year before the fire was used as calibration period for suspended sediment , the values having returned to seemingly pre-treatment levels following clearfelling. In the year following the fire (1986) there were significant increases in spateflow concentrations of suspended sediment, K^+, Ca^{2+}, KN and TP and in the second year HCO_3^- (Table 4; Table I, Appendix B). The greatest effect of the fire could be seen in the suspended sediment concentration, where the T/C ratio changed from 1.3 in the pre-fire year, to 40.1 for the first year following the fire. Mean concentration levels for these periods increased 10-

fold from 149 to 1538 mg l^{-1}. In the first spate following the fire, suspended sediment levels rose to a maximum of 4014 mg l^{-1}.

All the other significantly affected water quality variables doubled or more than doubled in concentration the year following the fire. KN showed the greatest increase from a mean value of 1.432 to 8.830 mg l^{-1}, the T/C ratio increasing from 3.18 to 8.77. Concentrations of KN in the first two spates following the fire increased to 30.6 and 44.2 mg l^{-1} respectively. The first two spates (both in February) following the fire showed at least a five fold increase in concentration for all variables. The concentrations of HCO_3^- increased from a pre-fire mean of 4.2 mg l^{-1} to respectively 37.3 and 31.0 mg l^{-1} for the two spates following the fire, but the increase over the whole year was non-significant. All these water quality variable concentrations in the spates from March onwards were higher than those before the fire, but only about two-fold.

Table 4 Summary of water quality variables in spates significantly affected by the treatments. Arrows indicate direction of change (↑ increase, ↓ decrease).

Catchment	Treatment	Year	Significant changes
Bosboukloof	Clearfelling	1984	SO_4^{2-}-S(↑)
		1985	TSS(↑) Ca^{2+}(↓) Mg^{2+}(↓) NO_3^--N(↓) F^-(↑)
	Fire	1986	TSS(↑) K^+(↑) Ca^{2+}(↑) KN(↑) TP(↑)
		1987	HCO_3^-(↑)
Biesievlei	Clearfelling	1985	TSS(↑) SO_4^{2-}-S(↑)
		1987	EC (↑) NH_4^+-N(↑) KN(↓)
		1988	TSS(↓) EC (↑)

2.2.1 Biesievlei: Riparian clearing and clearfelling

The management practices at Biesievlei only had a significant effect on the concentrations of a few variable in spates (Table 4; Table II, Appendix B). None of the measured concentrations were significantly affected during the year of the riparian clearing, which included a rainy season. With the felling of the plantation, as with the Bosboukloof clearfelling, suspended sediment concentrations were significantly changed. At Biesievlei thought the change occurred only during the clearfelling (1985) and the third year (1988) following the felling and afforestation. Concentration levels during the calibration period were only 12.2 mg l^{-1} with the T/C ratio 0.867. Although concentration levels increased to 83 mg l^{-1} for 1988, with a mean T/C ratio of 3.0, the sum of scores for the clearing period was less than that expected for H_0. Thus the T/C ratio was generally lower than during the pre-clearing period, and the sediment concentration in the treated catchment significantly decreased. It is not clear what would have caused such a decrease in spate sediment concentrations.

Since the riparian clearing had no significant impact on the remaining variables, data from this year was combined with that of the remaining pre-clearfelling months to test the post-clearfelling period. As with Bosboukloof, SO_4^{2-}-S increased significantly in 1985, during clearfelling. Again there was a relative drop in concentration, very similar to that of Bosboukloof, but a increase in the mean T/C ratio. There were also significant changes in nitrogen concentrations, this time an increase in NH_4^+-N and a decrease in KN concentration. Although none of the major variables were affected by the treatment, significant increases in the electrical conductivity were detected for 1987 and 1988. These changes were however not large, being 10, 11 and 10 mS m^{-1} for the three periods. Some variables did thus change significantly in concentration but, as with the clearfelling of Bosboukloof, the absolute changes were not large.

2.2.3 Westfalia: Riparian clearing and felling of the forest

The suspended sediment concentrations at Westfalia D did not change significantly in the first and second years following the riparian treatment. In contrast to both the Jonkershoek catchments, the bulldozing and burning of the indigenous forest did not have a significant effect on any of the concentrations in spates (Table III, Appendix B). This could be attributed in part to the drought conditions that prevailed, though it was expected that any storm following this severe treatment would mobilise soil particles and ions.

2.3 Discussion

The quality of water during spates was clearly most significantly impacted by the fire that burnt Bosboukloof. Most of the effects were seen in the first two spates that followed the fire. Controlled burning of the indigenous fynbos catchments in Jonkershoek also led to significant increases in suspended sediment, nitrogen and phosphorus in spates, but the concentration changes were minor (van Wyk and Lesch, 1992; van Wyk *et al.*, 1992). The fire in the afforested catchment caused the catchment characteristics to change to such a degree that concentrations of the measured variables increased 300% and more in spates. The catchment did recover though and there were no long-term changes in concentration levels in spates.

It is likely that the lack of significant increases in concentrations immediately following the severe bulldozing and burning of Westfalia D, was due to the lack of sufficiently large storms after the clearing. By the time that major storms occurred two years later, the plantation and herbaceous cover was sufficiently established and prevented any major flushing of inorganic constituents, nutrients and sediment.

One of the most consistent indicators of the effects of forest management practices, except at Westfalia, was suspended sediment. According to Keller (1990), suspended sediment is mainly transported during spates, with the three to four largest spates contributing virtually the total export for that year (Campbell and Doeg, 1989). There is however some discrepancy here since Biesievlei, which did not have a riparian zone as a buffering strip, showed a decrease in suspended sediment outflow following total clearfelling, whereas Bosboukloof, of which only half the catchment was felled and the riparian zone retained, showed an increase. This could be related to the way in which the slash was piled (see section 1.2) and the lower mean slope of Biesievlei. For purposes of budget, i.e. determining the total export, it would be important to analyse suspended sediment in spates.

A study of some variables in spates in afforested catchments in Natal showed an increase in suspended sediment with an increase in streamflow (Simpson, 1991). The sediment concentration increased with rising flow, then decreased (quickly) as the spate abated. The mean value for a rising spate would thus underestimate the maximum concentration released by the spate, but it does account for the initial flushing-out of sediment and other variables. A comparison of concentrations in spates and baseflow in the Westfalia catchments, showed K^+, Ca^{2+} and Cl^- to be more concentrated in spates, with no differences in Na^+, Mg^{2+}, HCO_3^- and SO_4^{2-}-S, while Si was lower in spates (Lesch and van Wyk, in prep.).

The selective sampling and analysis of spates, and the failure to sample some major spates in some of the catchments, could have given a biased estimate of the actual impacts of storms on concentrations. It is however believed that the information provides an adequate basis for advice on indicator variables for monitoring.

2.4 Conclusions

There were no consistent changes in the concentrations of the measured variables in spates across all the different forest management practices. Only suspended sediment concentrations changed significantly, either increasing or decreasing, after three of the five management practices analysed here. This means that it is not possible to select specific variables to indicate the effect of management practices on spates. The only option remaining was to determine whether the analysis of grab samples could identify any consistent and significant changes in water quality. The high concentrations recorded in spates after the fire in Bosboukloof, however, indicate that it is necessary to sample at least the first few spates after an event of this kind.

3 INDICATOR VARIABLES IN GRAB SAMPLES

3.1 Background: Concentration levels and seasonality

The concentrations of variables in grab samples from two relatively undisturbed forested catchments were studied in order to compare concentration levels from different areas in South Africa, and in particular from winter and summer rainfall regions. Box and whisker plots of all the variables in the two control catchments, Lambrechtsbos-B and Westfalia B, were used to present monthly concentration levels and seasonal variation for each variable (Figures 4 and 5). It is clear from most of the plots that outlier values influence monthly means, whether greater or less than the median.

Concentration levels at Lambrechtsbos-B were mostly a little higher than those of Westfalia B. The concentrations from the indigenous forested catchment at Westfalia were generally similar to those from protected grassland areas in Natal (van Wyk, 1986) and an indigenous fynbos catchment near Lambrechtsbos-B (van Wyk *et al.*, 1992). Concentration levels of Na^+ and Cl^- were however elevated in the fynbos catchment, due mainly to the oceanic influence to precipitation (van Wyk 1990; van Wyk, 1991b; van Wyk and Lesch, 1992; Van Wyk *et al.*, 1992). The values of these two variables in the pine afforested Lambrechtsbos-B catchments were almost double those of the fynbos catchment. The Cl^- levels were not derived from the bedrock and Cl^- is not usually accumulated to a great extent in forest ecosystems (Likens *et al.*, 1977). Water loss through evaporation does increase concentrations of ions. This, together with the significant enrichment of some variables as precipitation passes through the canopy (Likens *et al.*, 1977), could account for the higher concentration levels of Cl^- and other variables in Lambrechtsbos-B. Compared to the fynbos catchment, the afforested catchment also showed elevated concentrations of Si, on average 5 mg l^{-1} higher, and HCO_3^-, 2 mg l^{-1} higher. Lambrechtsbos-B was planted 15 years prior to the first felling treatment in Bosboukloof, and the quality of the water was considered stable enough to use this catchment as a control.

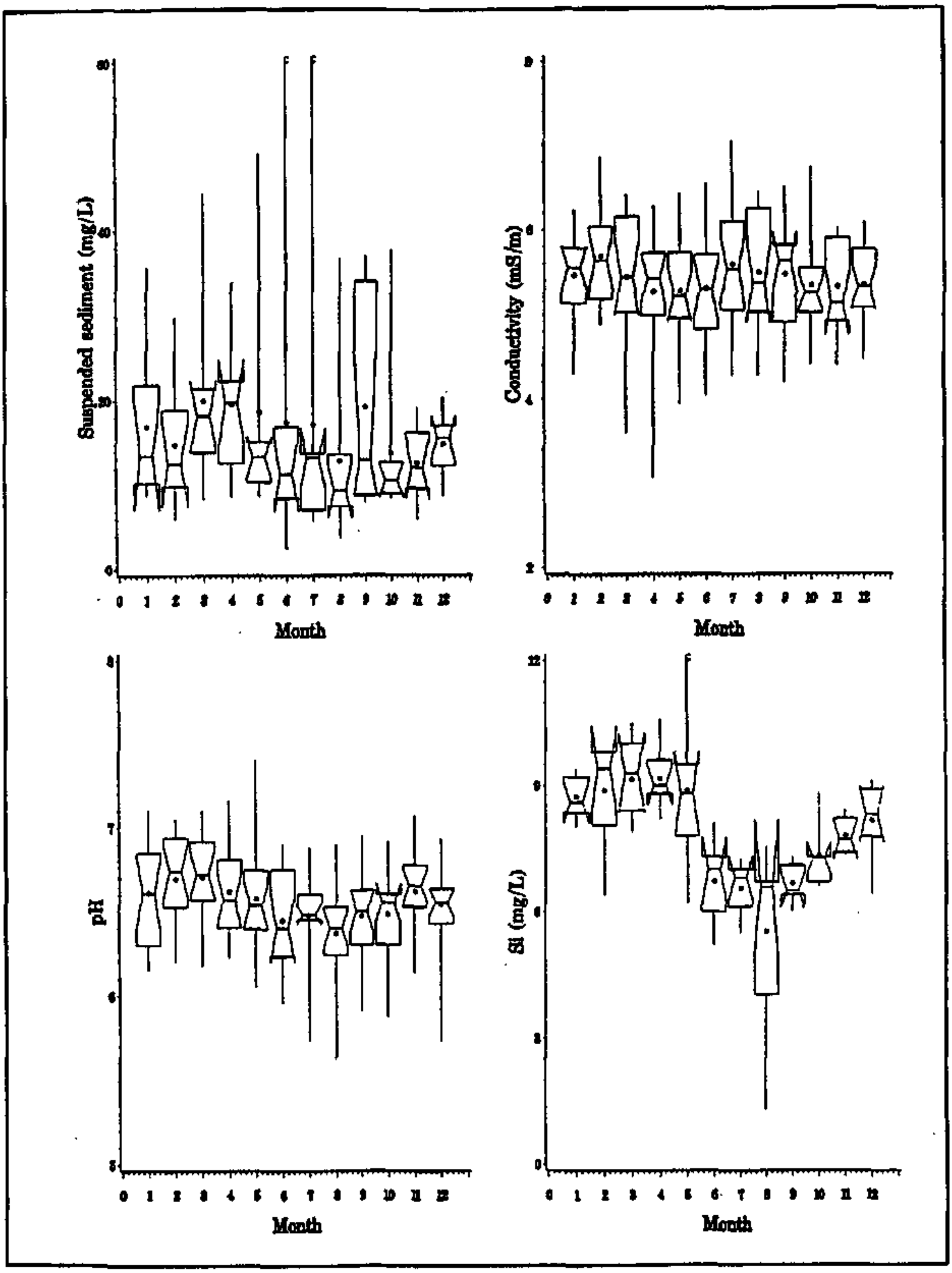
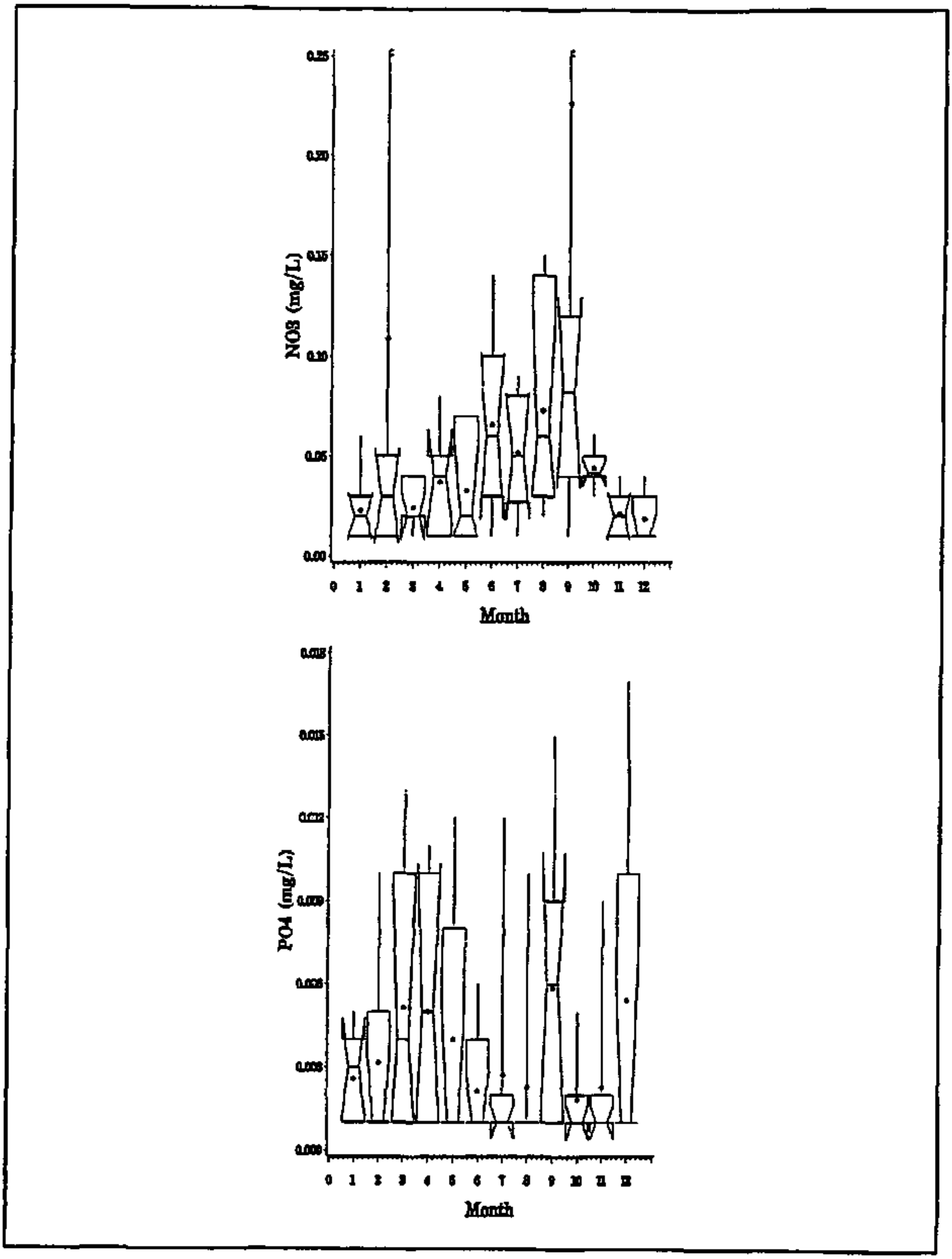


Figure 4 Seasonal trends in the concentrations of all variables from the control catchment Lambrechtsbos-B. Electrical conductivity, pH, Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^- were measured from 1974 to 1990, the rest of the variables from 1983 to 1990. See Figure 2 for an explanation of box and whisker plots.



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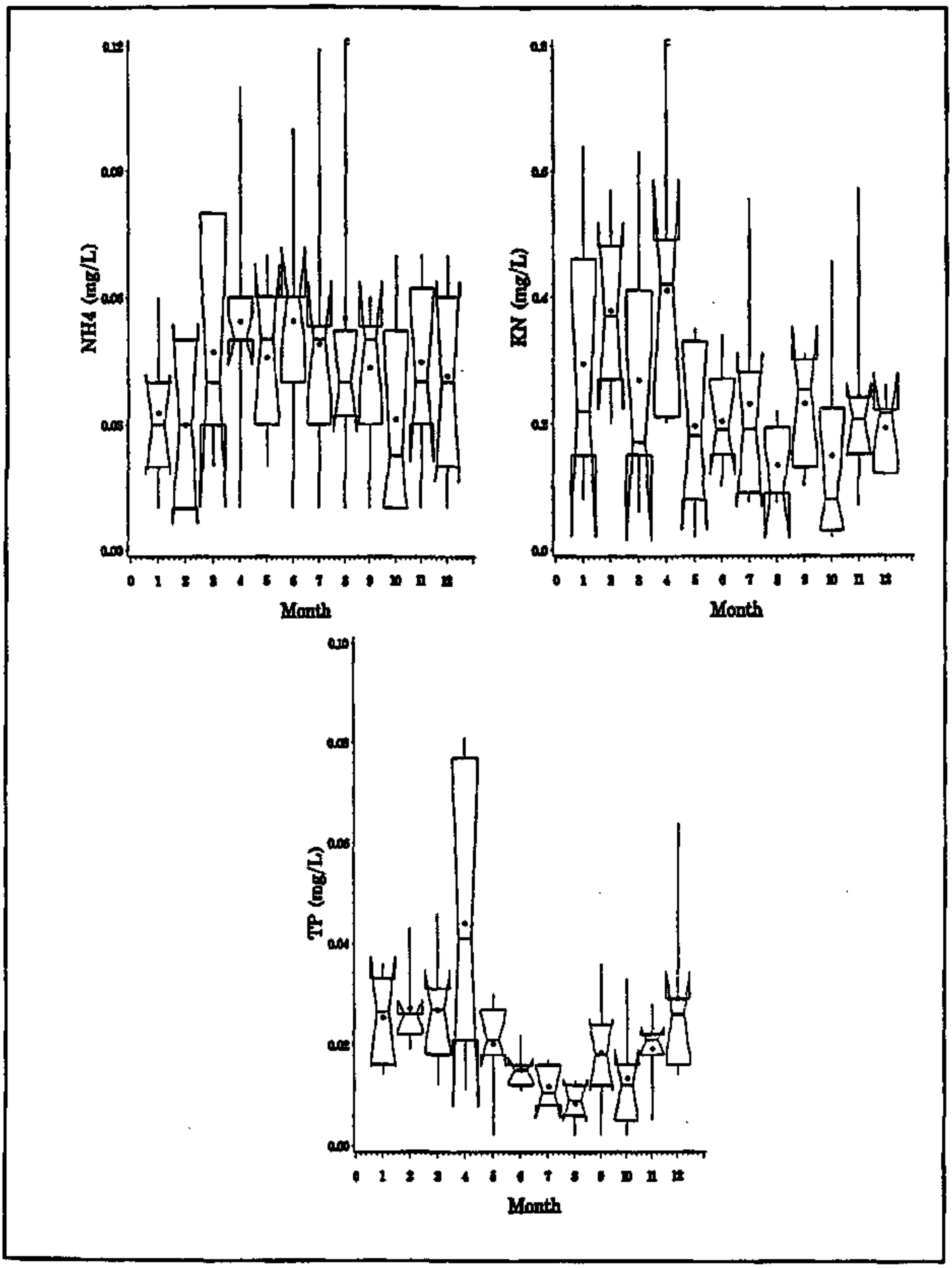

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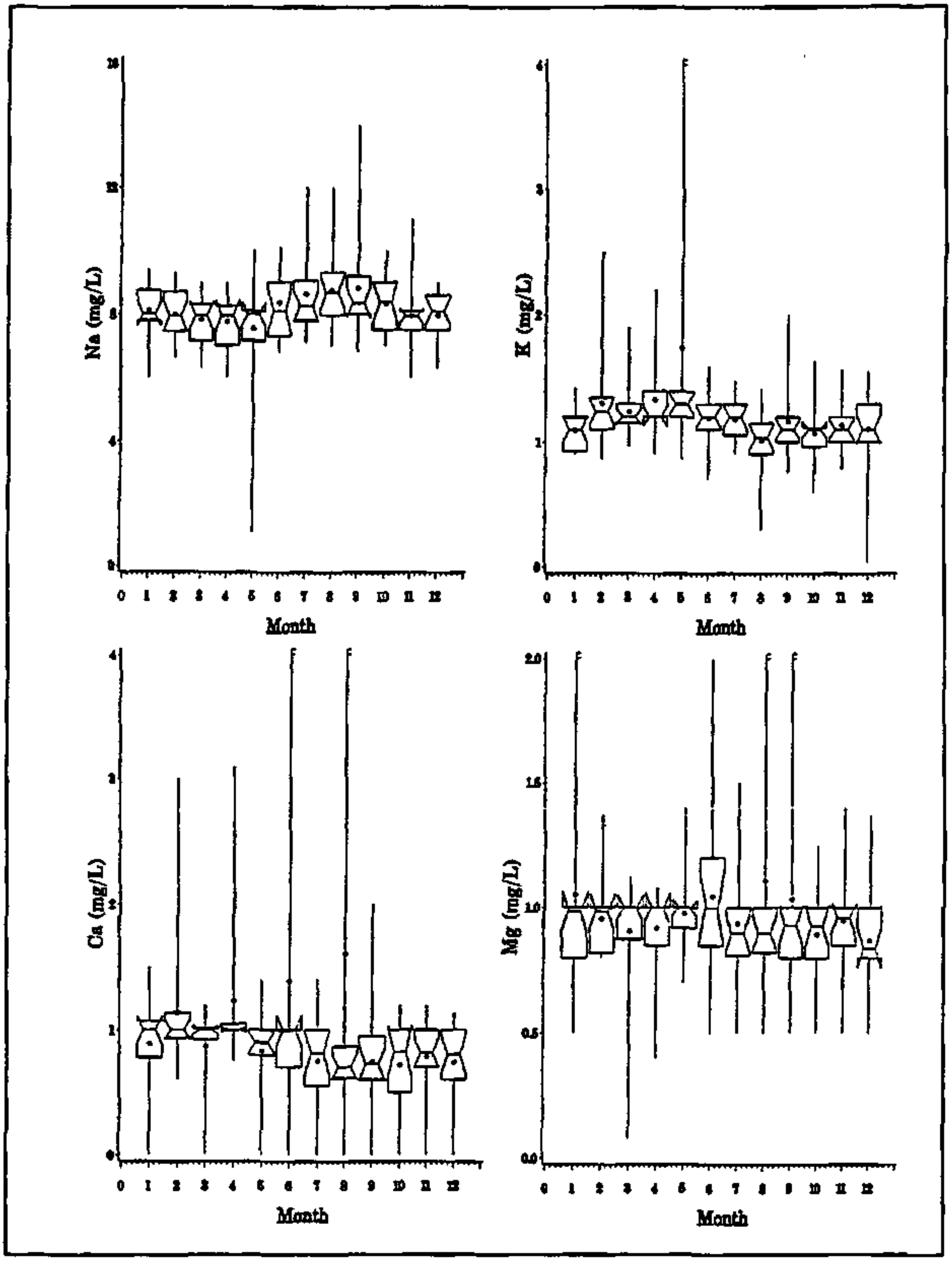

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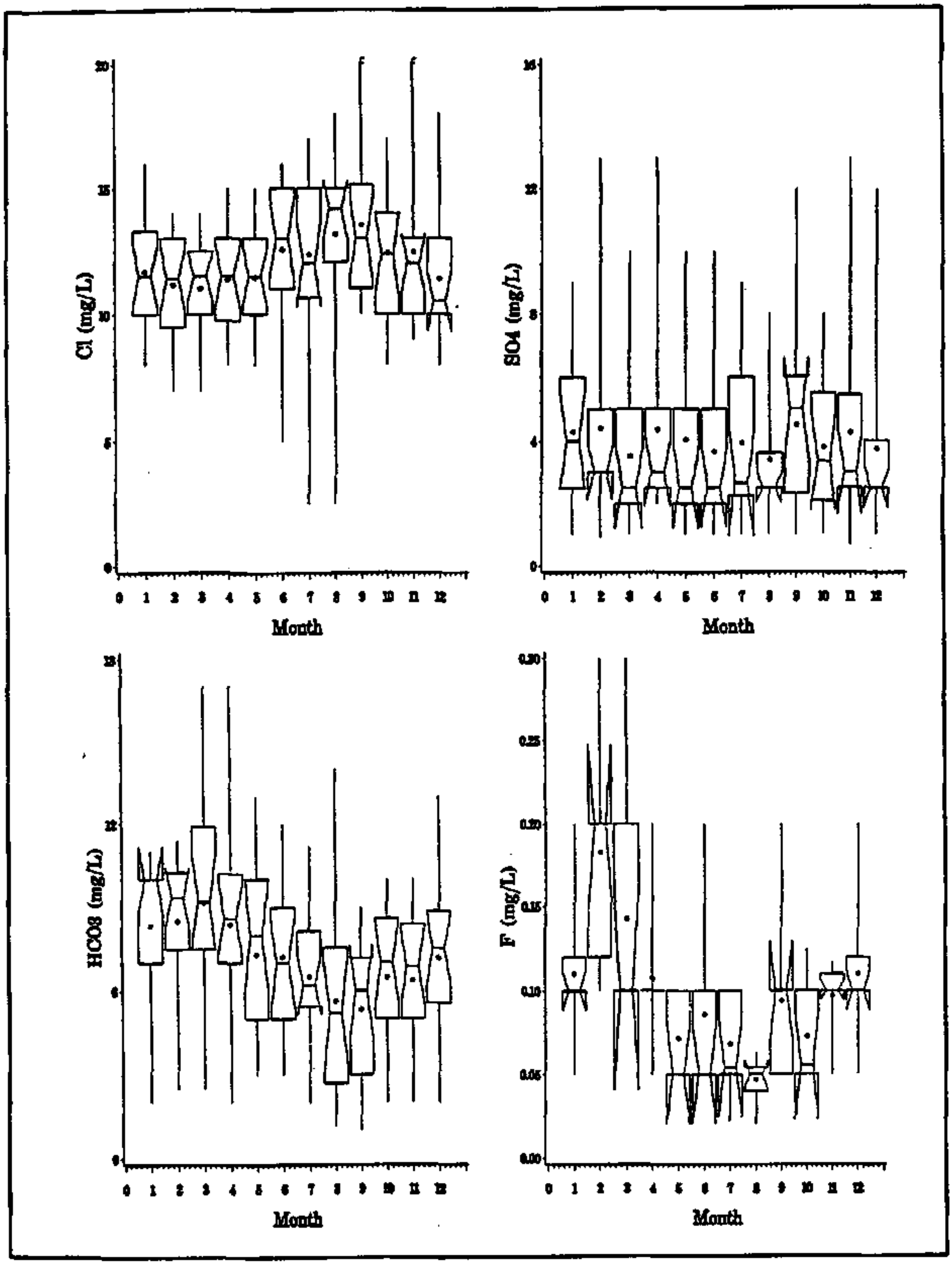

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Weathering of the soils and the underlying bedrock in a catchment and atmospheric inputs to a catchment are seen as the main contributors towards the type and amount of dissolved solids in streams from undisturbed mountain catchments (Likens *et al.*, 1977; Peters, 1984; Bailey *et al.*, 1987; Bricker and Rice, 1989; van Wyk and Lesch, 1992). In addition, significant amounts of nitrogen could be added to the system by the fixation of gaseous N_2 by microorganisms (Likens *et al.*, 1977). Despite these different conditions, the concentrations of most streamwater quality variables, especially from Westfalia, were in the same range as those found in a variety of undisturbed forested catchments worldwide (Likens *et al.*, 1977; Binkley *et al.*,1982; Swank and Waide, 1988). All measured values in the two control catchments lie well within the prescribed water quality criteria for rivers in South Africa, which is based on the protection of aquatic life (Kempster *et al.*, 1982). Most concentrations were lower than the mean or maximum criteria prescribed by at least an order of magnitude.

Few variables showed clear seasonal trends, with the 95% confidence levels of the medians overlapping for most months. At Lambrechtsbos-B some variables, notably Si, display strong seasonal patterns of decreased concentration in the wet winter months, and increases in the dry summer months (Figure 4). Other variables that show a similar tendency include suspended sediment, pH, K^+, HCO_3^-, F^-, KN and TP. A second pattern is that of increased concentration in the wettest months, followed by a decrease in the dry summer months. Variables with this tendency include NO_3^--N, NH_4^+-N, Na^+ and Cl^- (Figure 4).

At Westfalia, significance bands for the medians of all variables, except EC, overlapped substantially so no trends can be established (Figure 5). The variables do however show the two seasonal patterns observed at Lambrechtsbos-B. The first is a decrease in concentration in the wet summer months, e.g. pH, Si and NH_4^+-N. The second tendency is increased concentrations in the wet months, and include the EC and to some extent NO_3^--N, KN, TP, Na^+ and Cl^-.

The decrease in concentration during the wet season is usually ascribed to the diluting effect of the increased streamflow volume (Swank and Waide, 1988; Keller, 1990).

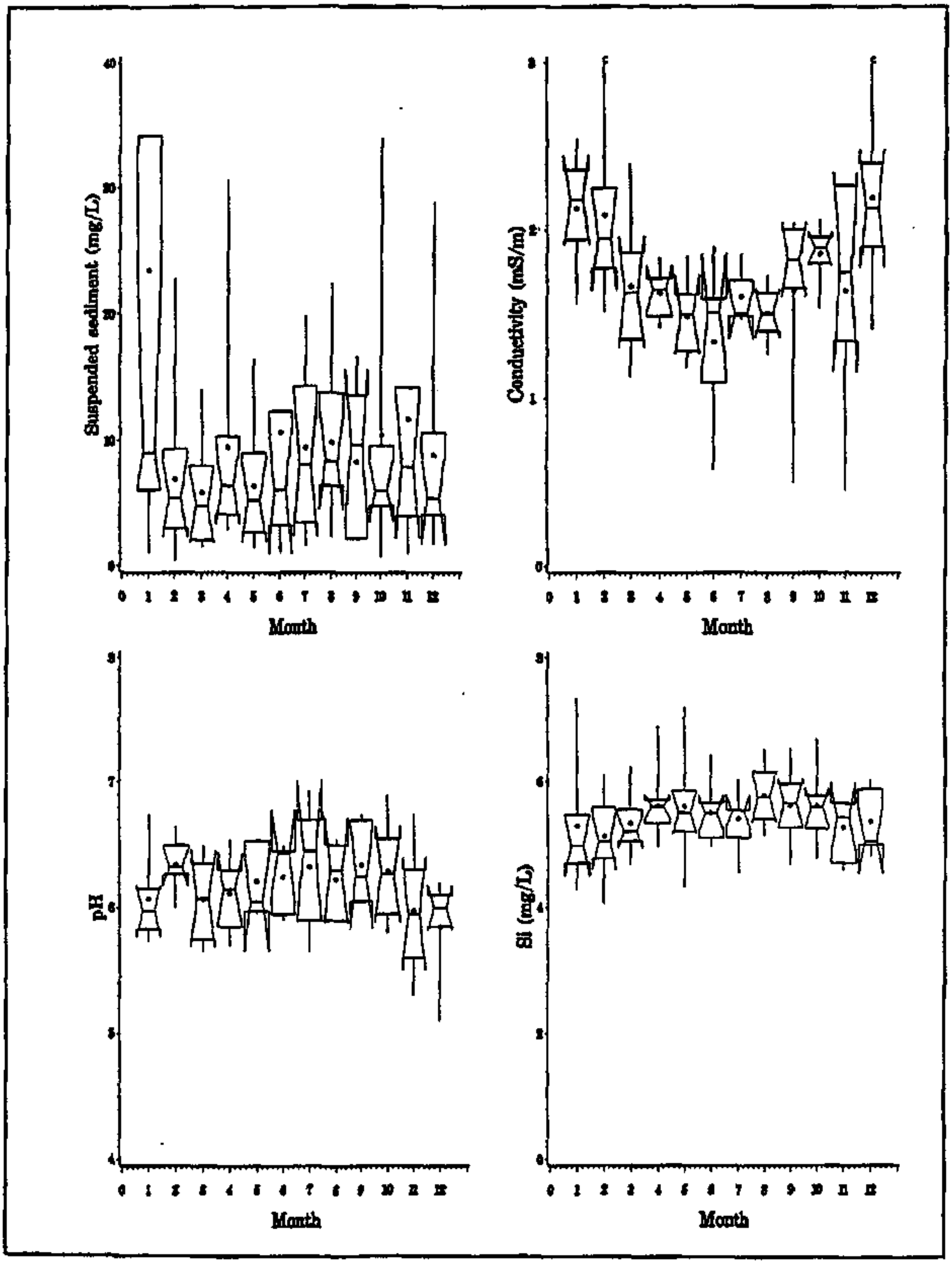
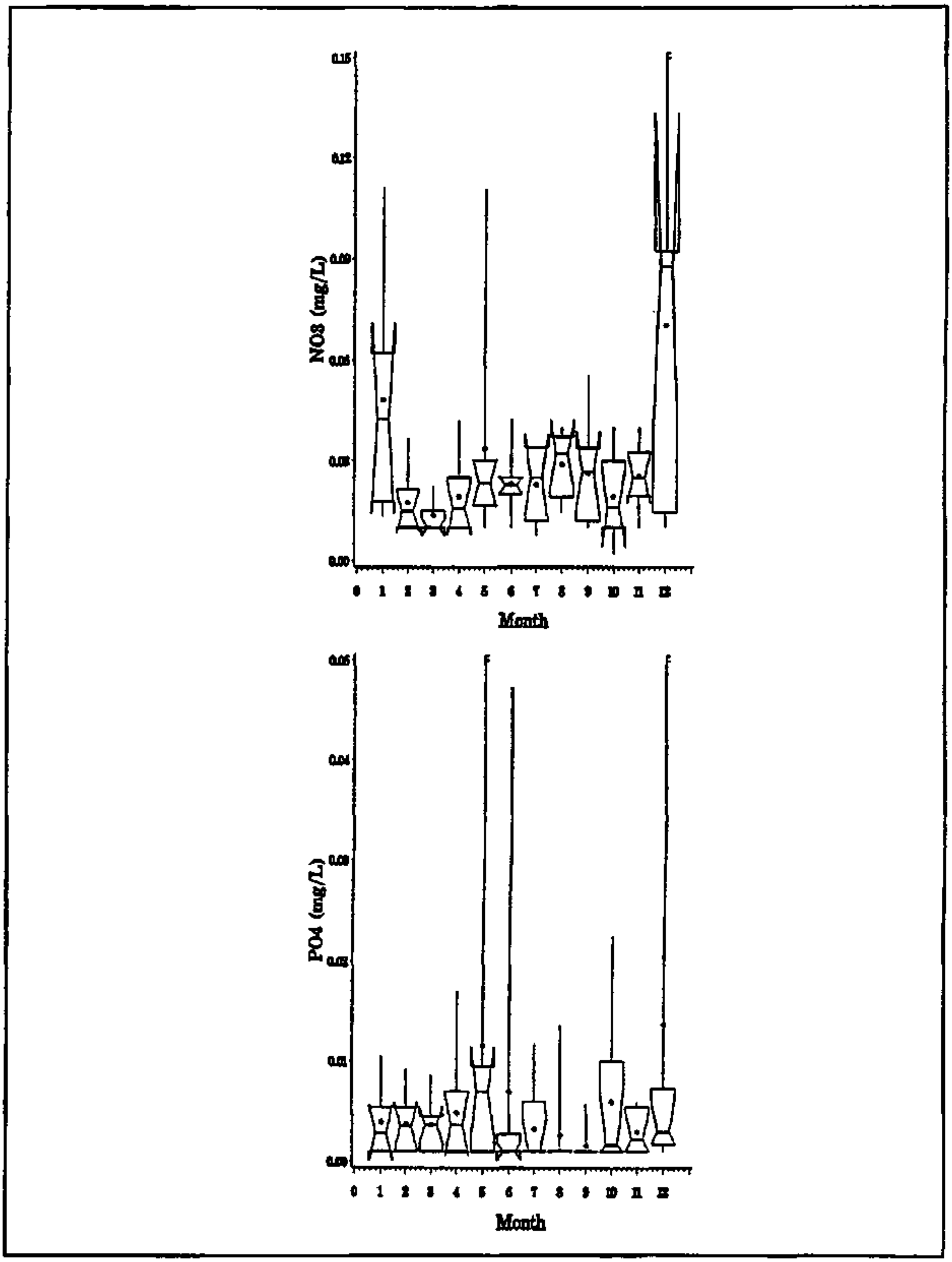


Figure 5 Seasonal trends in the concentrations of all variables from the control catchment Westfalia B, for the period 1981 to 1990. See Figure 2 for an explanation of box and whisker plots.



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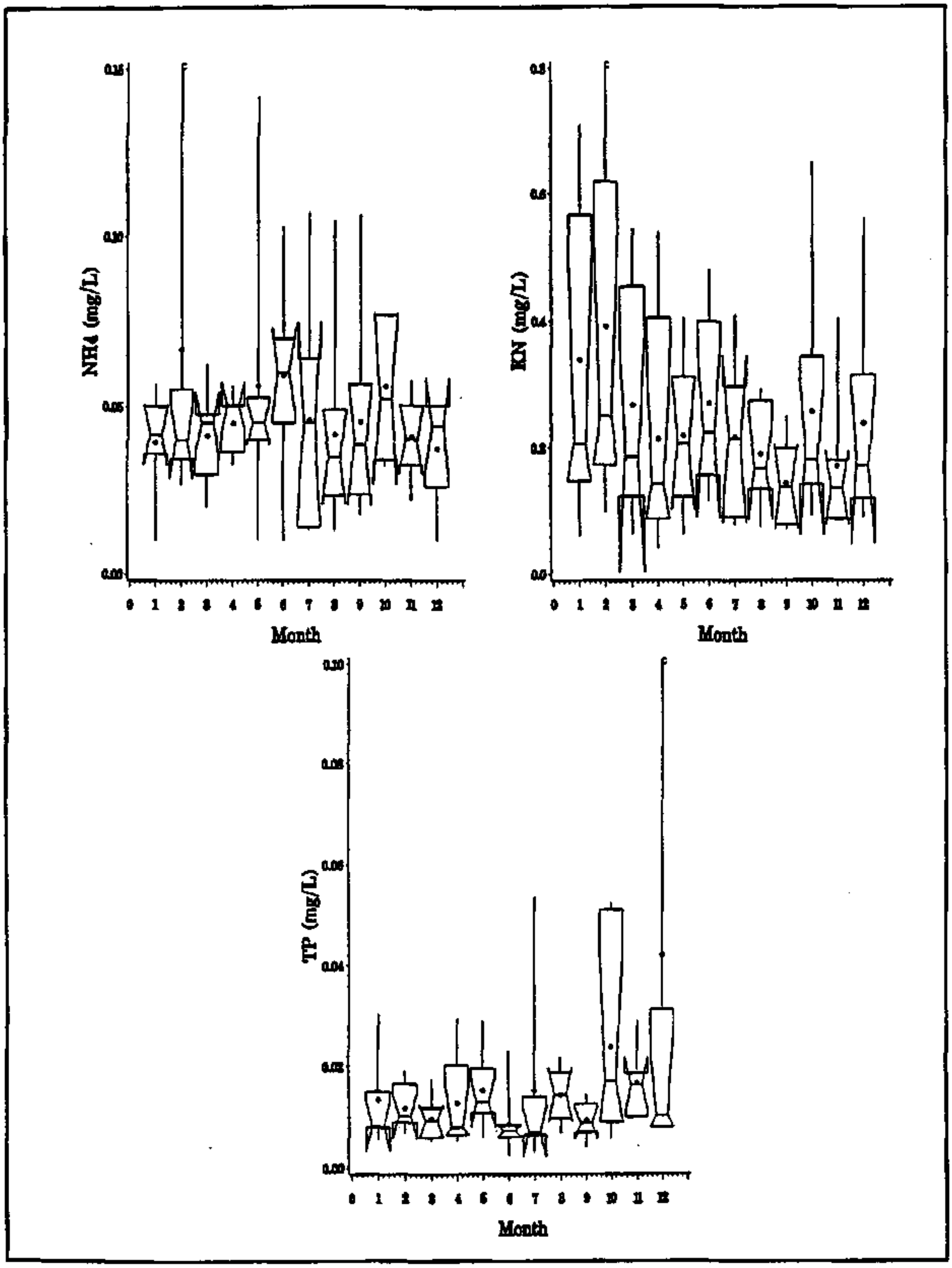

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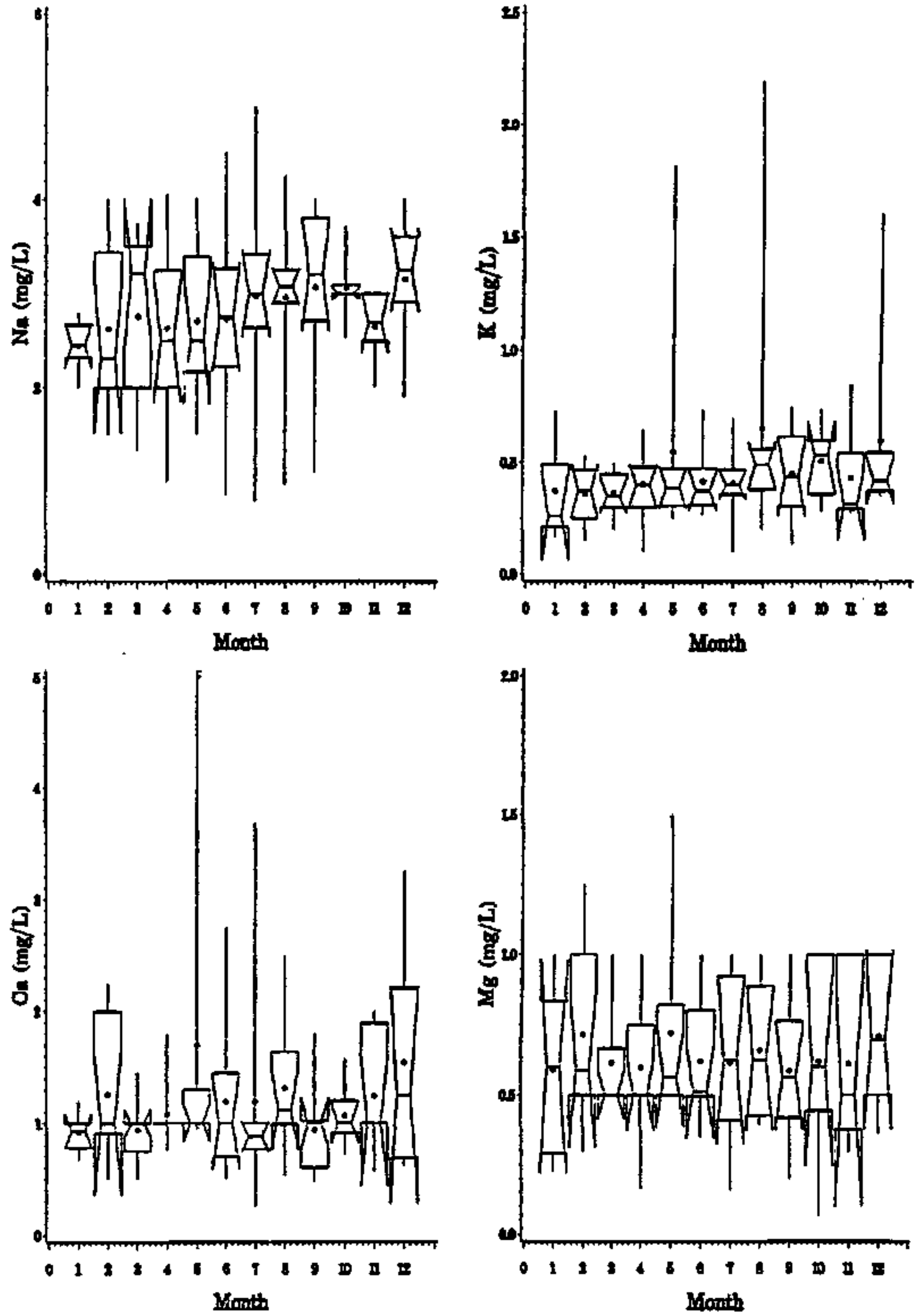

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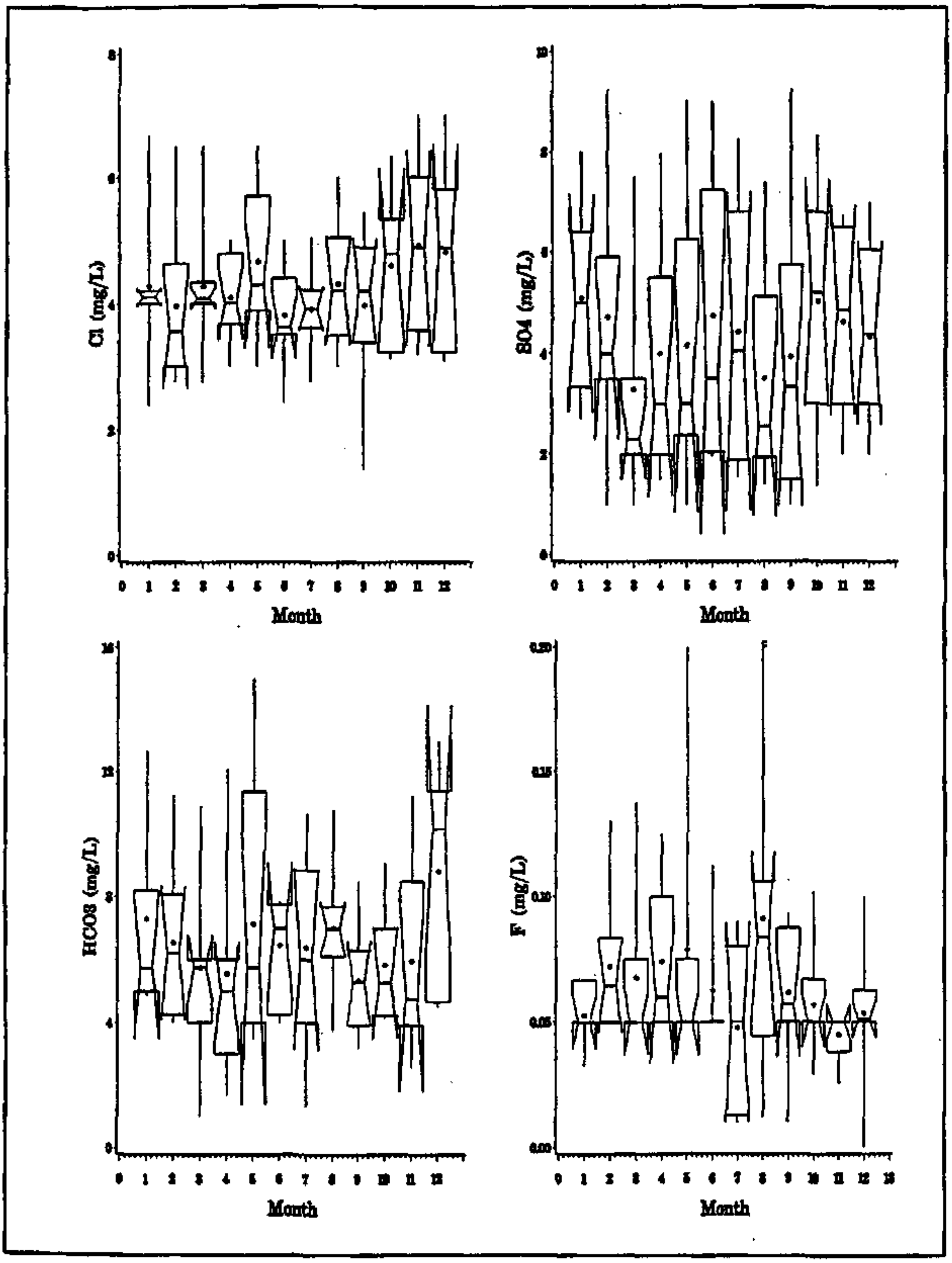

Figure 5 Continued

The increase in the NH_4^+-N concentration at the onset of the wet season in Lambrechtsbos-B can be attributed to the release of nitrogen liberated through the decomposition of vegetation during the preceding summer. Similar patterns were detected at Hubbard Brook (Likens *et al.*, 1977) and were attributed to the decomposition of organic matter after the leaf fall. Peaks in pineneedle fall have been detected in May in the Jonkershoek pine plantations (Versfeld and Donald, 1991). Oxidation of ammonia releases nitrate and this may explain the increased concentration of nitrate a few months later, at the height of the rainy season in Lambrechtsbos-B. Although the trends are not strong, KN and TP concentrations increased in both catchments during the summer. This could be linked to increased decomposition rates and biotic activity during the warmer periods in the forest floor. The floor of a forest is a very effective storage site for nutrients (Likens *et al.*, 1977). Na^+ and Cl^- concentration inputs to near-coastal streamwater are often linked, because of the marine influence on precipitation (van Wyk, 1991b). Na^+ is a nutrient and would be taken up by the plantation, but also released from decaying vegetation. The increase in both variables during the wet season could be attributed to release from the soil profile and their concentration levels in precipitation.

3.2 Results: Treatment effects

The results of the study of the effects of all the management practices on the quality of streamwater during low flow conditions (Tables IV to VI, Appendix B; Appendix C), are summarised in Table 5. It is important to note that some of the management practices applied, followed relatively close onto each other. The clearfelling of the riparian vegetation at Biesievlei for example was followed so closely by total clearfelling, that it is possible that the effects of the latter might have overshadowed the first. The clearing of the riparian vegetation probably also enhanced the effects of the total clearfelling. In the same way, it was not possible to distinguish between the effects of the different management practices at Witklip 2, as they all contributed to the changes in water quality.

Table 5 Summary of all treatment effects on variables concentrations in grab samples taken in the experimental catchments. The first two sites are in the south-western Cape, the third north-eastern Transvaal and the fourth eastern Transvaal. All treatments were followed directly by afforestation with commercial species. The highest level of significance for each management practice is indicated. TSS = total suspended sediment, EC = electrical conductivity, * $P < 0.05$, ** $P < 0.01$ and NS = not significant.

	Bosboukloof		Biesievlei		Westfalia	Witklip
Variable	Clearfelling not riparian zone	Fire	Riparian zone cleared	Clearfelling	Riparian treatment Felling of indigenous forest	Riparian treatment and clearfelling
TSS	**	*	**	**	**	NS
EC	**	**	NS	**	NS	NS
pH	**	**	NS	NS	NS	NS
Na^+	NS	**	*	*	NS	NS
K^+	*	**	*	NS	**	**
Ca^{2+}	**	**	NS	**	NS	**
Mg^{2+}	*	NS	NS	NS	NS	NS
NH_4^+-N	NS	NS	NS	NS	NS	NS
Cl^-	NS	NS	NS	*	*	NS
SO_4^{2-}-S	NS	*	NS	*	NS	*
HCO_3^-	**	*	NS	*	NS	NS
NO_3^--N	**	**	NS	NS	**	**
PO_4^{3-}-P	NS	**	*	*	**	NS
F^-	NS	NS	*	NS	NS	NS
KN	NS	*	*	NS	NS	*
TP	NS	**	NS	NS	NS	*
Si	NS	NS	NS	**	*	**

Another factor that probably influenced the results of the study severely, was the drought that occurred at the time of the clearing and afforestation of Westfalia D. Despite the two year drought, the study was continued to determine the longer-term effects of such a severe vegetation conversion on streamwater quality.

3.2.1 Suspended sediment

As in the spate analyses, suspended sediment was again an important factor, though mean concentrations were generally 10-fold less than the spate samples. At Bosboukloof, where half the catchment was clearfelled and the riparian zone left intact, the sediment concentration increased at least in the last year of felling and the year following felling (1983), then returned to lower, possibly more stable levels for the next two years. The changes were more apparent in the ratios between the treated and control (T/C) concentrations than in the concentrations *per se* (Figure 6; Table IV, Appendix B). The increased concentrations in Bosboukloof in 1983 raised the T/C ratio to 1.85 compared to the 1.25 for 1984-5. This ratio increased further to 2.57 the year after the fire. A more detailed analysis of soil movement after the fire is given by Scott and van Wyk (1990).

Increased sediment concentrations following the riparian clearing in Biesievlei were most pronounced in the year after clearing (Figure 6). The major increase following total clearfelling occurred in the second and third year after felling (Figure 6; Table V, Appendix B). Despite the major disturbances in the riparian zone, sediment concentrations increased in similar proportions to Bosboukloof. At Westfalia D a longer and very pronounced increase was detected in the monthly grab samples (Figure 6), although there was no change in suspended sediment in the spates following the bulldozing and burning of the indigenous forest. The increase was statistically significant only for the second year following felling (Table VI, Appendix B). In the plot of the summer and winter medians, it does however seem that the effect continued during the wet summer months (Figure 6). The increase in the T/C ratio was almost double that of the previous two catchments.

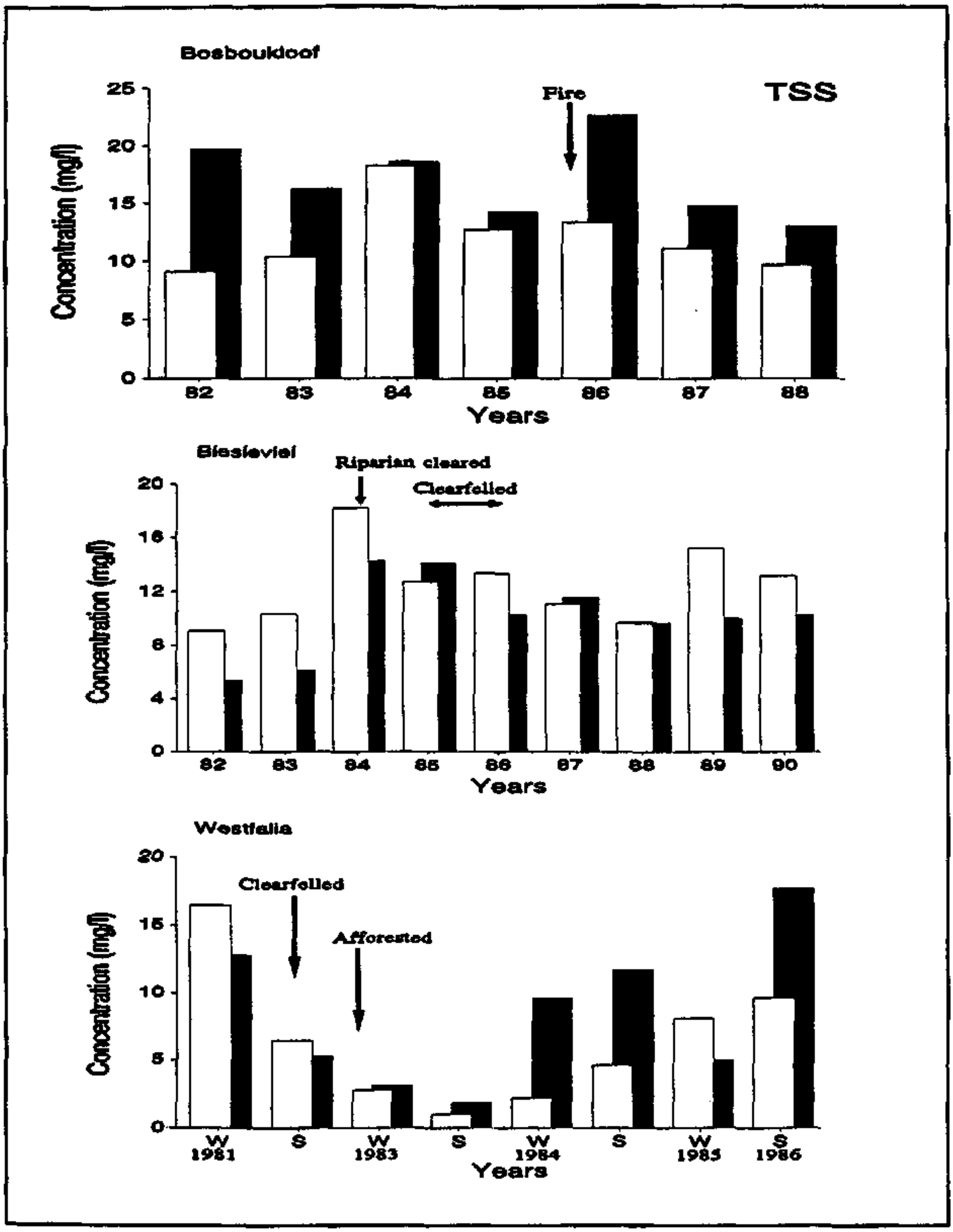

Figure 6 Histograms of treated (shaded) versus control (open) median concentrations of total suspended sediment (TSS) for the respective catchments where levels were significantly changed by treatment. The plot for Westfalia is divided into the six summer (S) and six winter (W) month periods.

There was no significant trend in the longer term for the suspended sediment from Witklip 2, though van Wyk and Scott (1993b) did find a doubling of weekly concentrations in the summer following the burning of the riparian zone. Despite the severe treatments applied to the riparian zone, and the clearfelling of the pine forest around the rivers, there were no significant sustained increases in sediment outflow. Short-term (e.g. yearly) significant changes could have been overlooked as statistical analyses were applied only over the full period.

It would thus seem that the vegetation conversion, from indigenous to commercial forests, using extreme site preparation techniques (bulldozing and burning), had the greatest effect on suspended sediment concentrations. The effects were greater and persisted for longer than those the other management practices, such as clearfelling and the removal of riparian vegetation.

3.2.2 Electrical conductivity and pH

Electrical conductivity (EC) and pH levels were only significantly affected by the management practices in the western Cape catchments. Although EC levels increased during the felling of Bosboukloof, the effects of the fire were far more important, especially the first year (Figure 7; Table IV, Appendix B). This increase in EC is a consequence of the significant increases in concentration in all the other major variables after the fire. Clearfelling had a limited effect on the EC in Biesievlei, with a significant increase during the felling and the first year following (Figure 7; Table V, Appendix B). Only the management practices applied in the Bosboukloof catchment affected the pH, the stream becoming significantly more acid from the final year of the clearfelling virtually until the third year after the fire (Figure 7; Table IV, Appendix B).

3.2.3 Nitrate and Phosphate

Two important nutrients for plant growth, NO_3^--N and PO_4^{3-}-P, were both significantly affected by most management practices, the fire at Bosboukloof causing the highest increases in both elements (Figures 8 and 9). In terms of mean concentrations, NO_3^--N

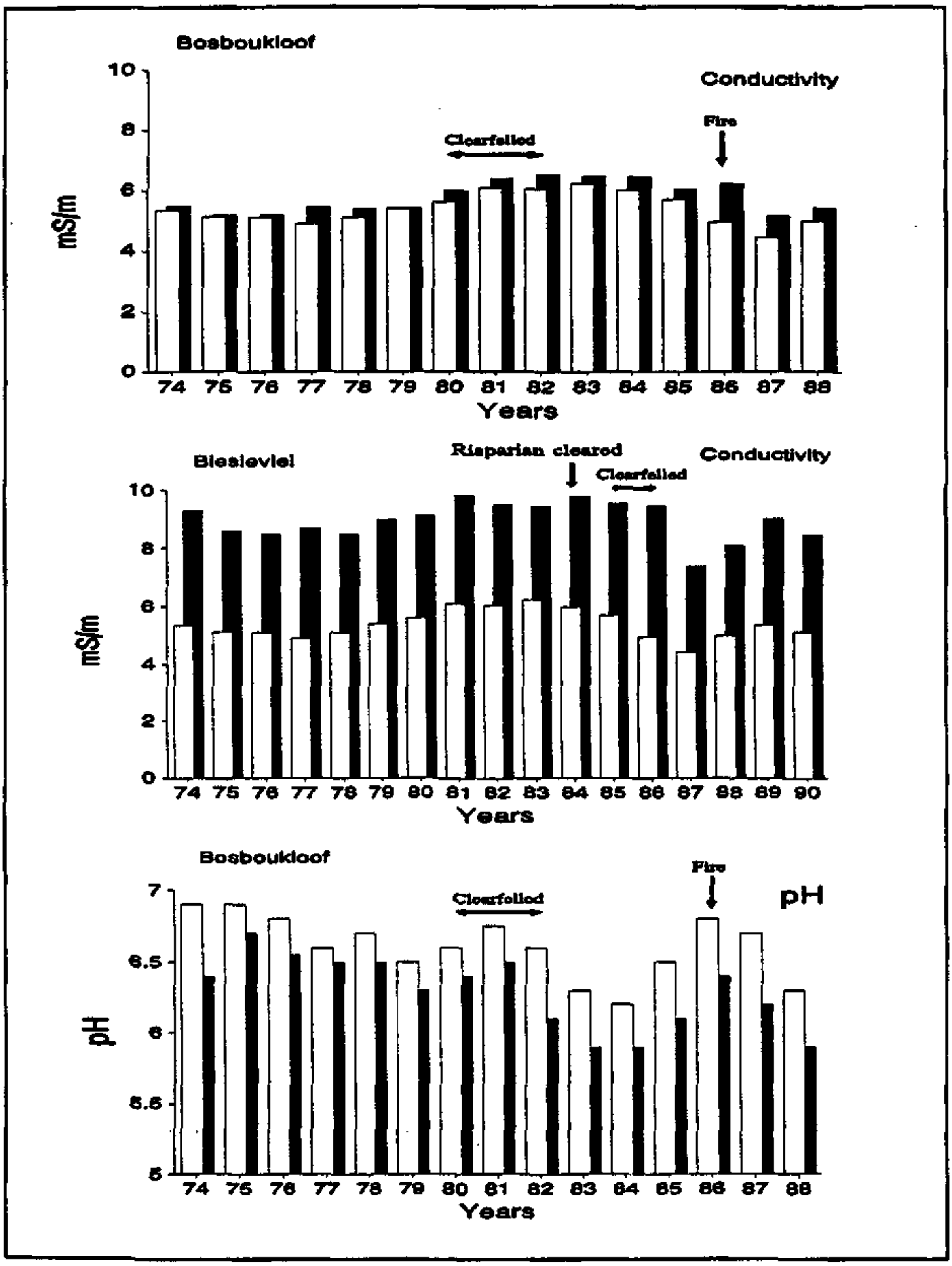

Figure 7 Histograms of treated (shaded) versus control (open) median concentrations of electrical conductivity and pH levels for the respective catchments where these were significantly changed by treatment.

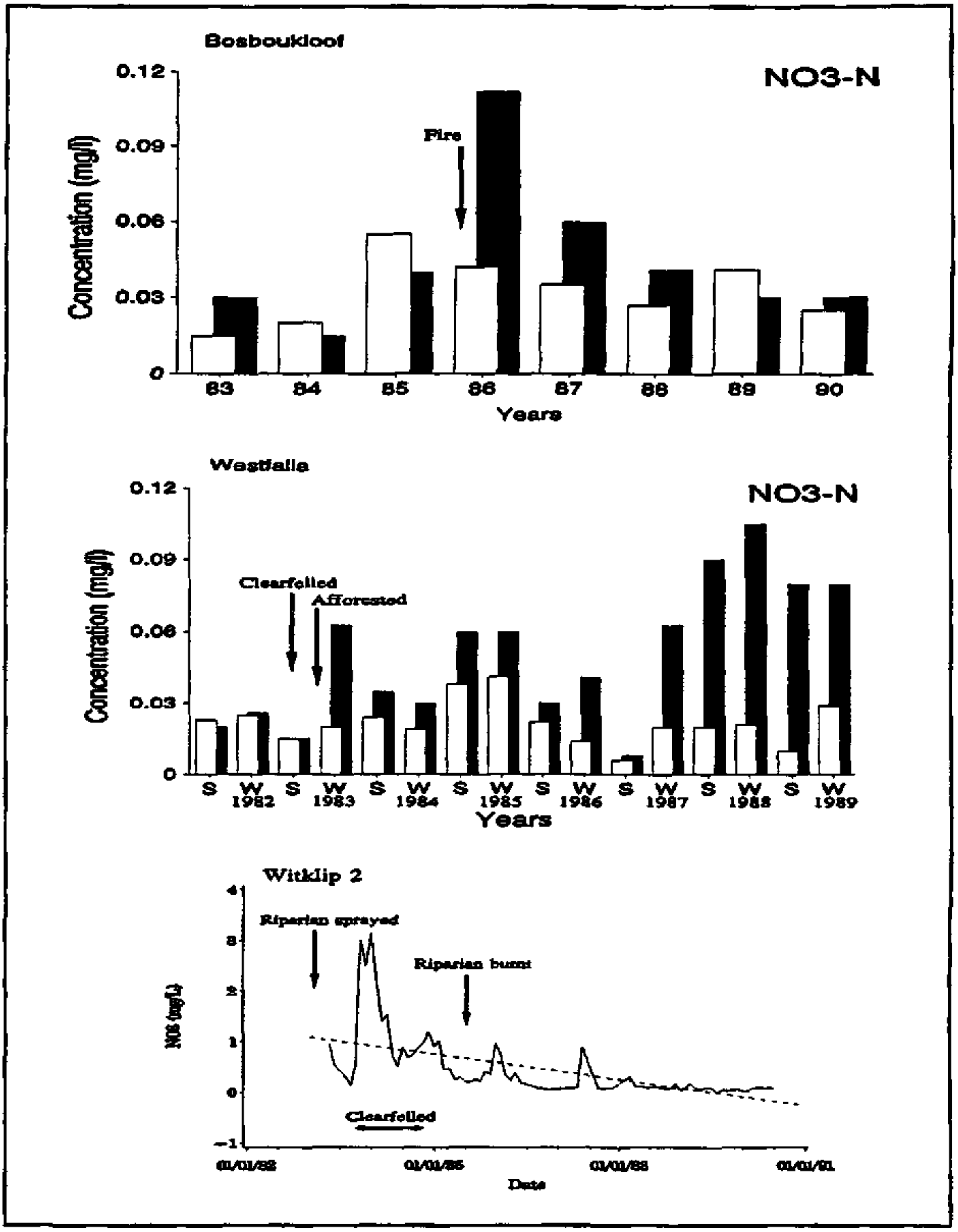

Figure 8 Histograms of treated (shaded) versus control (open) median concentrations and a trend plot of NO_3^--N for the respective catchments where levels were significantly changed by treatment. The histogram for Westfalia is divided into the six summer (S) and six winter (W) month periods. The trend plot shows real values (solid line) and a linear regression of concentration against time (dashed line).

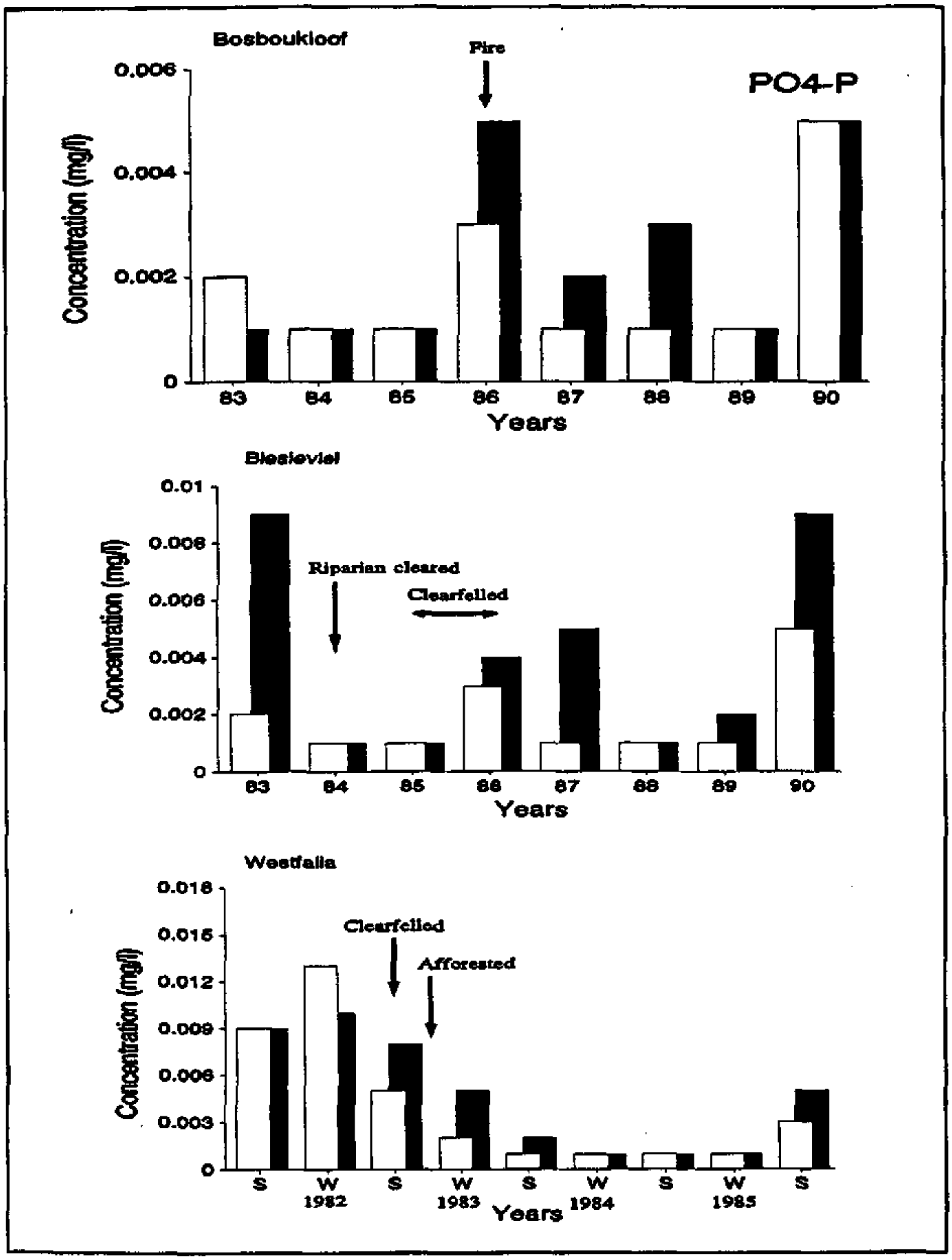

Figure 9 Histograms of treated (shaded) versus control (open) median concentrations of PO_4^{3-}-P for the respective catchments where levels were significantly changed by treatment. The data for Westfalia is divided into the six summer (S) and six winter (W) month periods.

rose from 0.041 mg l^{-1} the year before the fire, to 0.207 mg l^{-1} the year after, and the T/C ratio from 0.79 to 4.63. This effect was also seen, though not as extreme, in the median values for these years (Figure 8). A substantial amount of nitrogen was probably volatilised during the fire, but this was not quantified. The felling of the indigenous forest at Westfalia D resulted in a long-term increase in NO_3^--N concentrations (Table VI, Appendix B). Six years after the vegetation conversion concentrations had increased three-fold (Figure 8). At Witklip the concentration seemed highest directly after the spraying of the riparian zone with Roundup, with only a small increase after the burning (Figure 8). The extremely high concentrations, compared to the other catchments, could be due to a quick release of nitrogen following the decomposition of vegetation killed by the herbicide. Only the management practices at Biesievlei did not lead to an increase in NO_3^--N concentrations, despite the clearing of the riparian zone.

The PO_4^{3-}-P concentrations were very low, often being below the detection limits of analyses, and usually highly variable (Figure 9). Low concentration levels such as these lead to higher uncertainty, and greater difficulty in interpreting results. Increases in PO_4^{3-}-P concentrations in Bosboukloof and Westfalia D were experienced following management practices, in the former only after the fire and in the latter for the first year following clearfelling of the indigenous forest (Tables IV & VI; Appendix B). The changes in the PO_4^{3-}-P concentration in Biesievlei were more complex. It was generally higher than the other Jonkershoek catchments, but decreased drastically after the riparian clearing, and remained low in all but the second year following clearing (Figure 9; Table V, Appendix B).

3.2.4 Potassium and Calcium

The two cations most affected by forest management practices, were K^+ and Ca^{2+}. The increases in K^+ were short-term for both treatments at Bosboukloof and Biesievlei (Figure 10; Tables IV & V, Appendix B). The mean K^+ concentration increased from 0.940 mg l^{-1} before treatment to 1.494 mg l^{-1} the year after the Bosboukloof fire. The clearing of the riparian vegetation at Witklip 2 also did not have a long-term effect on the K^+ concentration (Figure 10). Mean concentrations here dropped from 1.094 mg l^{-1}

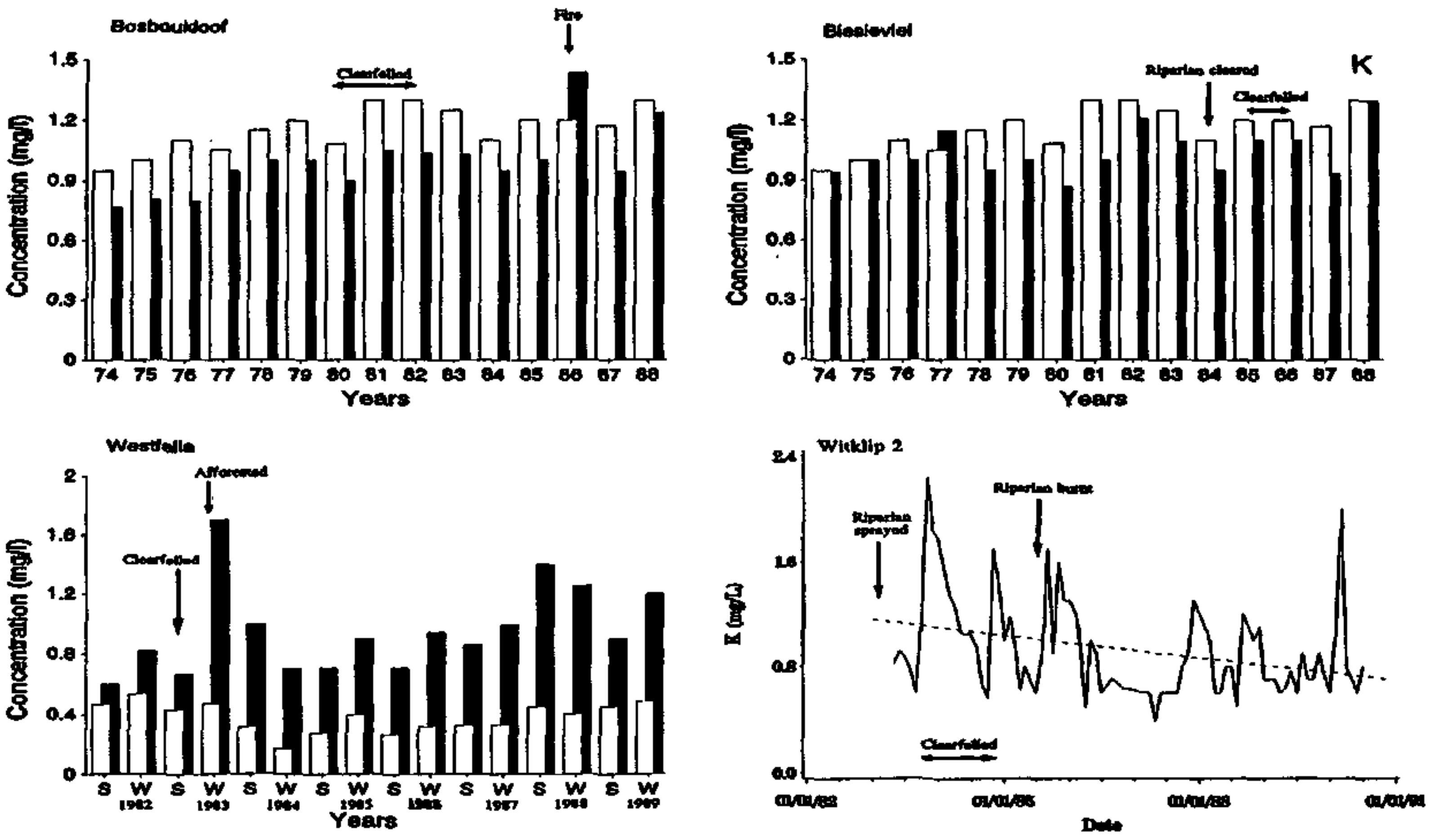

Figure 10 Histograms of treated (shaded) versus control (open) median concentrations and a trend plot of K^+ for the respective catchments where levels were significantly changed by treatment. Westfalia data is divided into the six summer (S) and six winter (W) month periods. The trend plot shows real values (solid line) and a linear regression of concentration against time (dashed line).

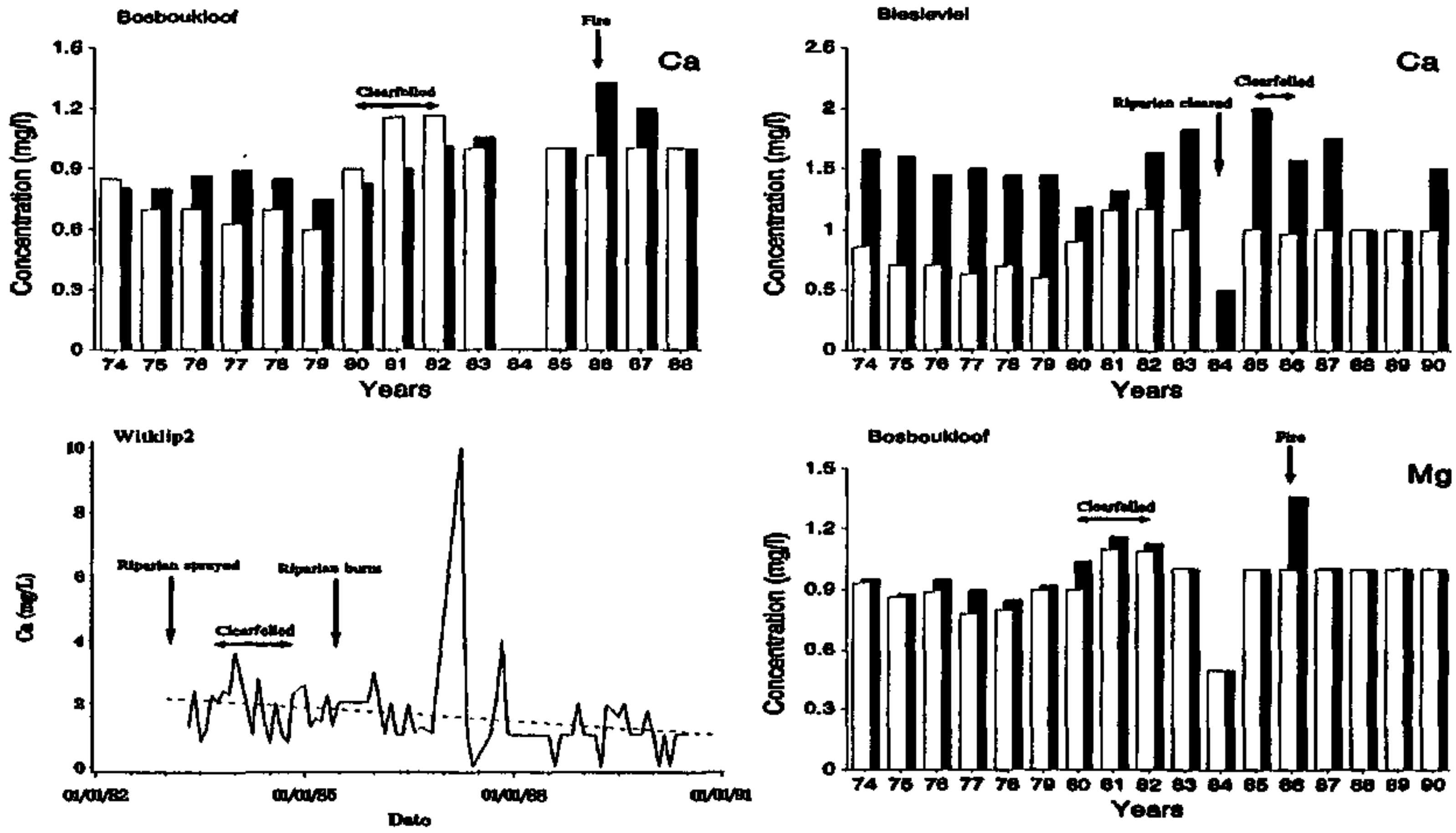

Figure 11 Histograms of treated (shaded) versus control (open) median concentrations and a trend plot of Ca^{2+} and Mg^{2+} for the respective catchments where levels were significantly changed by treatment. The trend plot shows real values (solid line) and a linear regression of concentration against time (dashed line).

during the treatment period, to 0.802 mg l^{-1} three years later. At Westfalia D the increase was long-term, lasting for at least seven years after felling of the indigenous forest (Figure 10; Table VI, Appendix B). Again, as with some of the other variables, the major effect, and the most long-term, followed the drastic clearing of the indigenous forest and conversion to commercial species.

In 1984 almost all Ca^{2+} concentrations decreased to below the detection limit at Jonkershoek (Figure 11). This is probably due to analytical error, as overall mean concentration levels of the other ions did not change. The management practices all had a very short-term effect on Ca^{2+} concentrations, and only the fire in Bosboukloof substantially increased the concentrations, from a pre-fire mean of 1.027 mg l^{-1} to 1.582 mg l^{-1} after the fire (Figure 11). Clearfellings in both Bosboukloof and Biesievlei led to decreases in the Ca^{2+} concentrations in streamwater (Tables IV & V, Appendix B).

3.2.5 Magnesium, Sodium and Chloride

Mg^{2+} was only significantly changed by the clearfelling in Bosboukloof, and then only in the third year after treatment, the actual decrease being negligible (Figure 11; Table IV, Appendix B). Significant treatment-induced changes in Na^{+} and Cl^{-} concentrations in Jonkershoek were reported by van Wyk and Scott (1993a). Cl^{-} changed significantly in the first year after the clearfelling of Biesievlei and Westfalia D. The decreases and increases were, however, small in real terms (Figure 12). Although Na^{+} concentrations showed a significant decrease during both the riparian and total clearing of Biesievlei (Figure 12; Table V, Appendix B), the only noteworthy increase was in the first year following the Bosboukloof fire. The available data on Mg^{2+}, Na^{+} and Cl^{-} is too variable to predict whether these variables would be increase or decrease in concentration by forest management practices.

3.2.6 Sulphate and Bicarbonate

Concentrations of SO_4^{2-}-S were highly variable for all three catchments where significant increases were noted following the application of management practices (Figure 13;

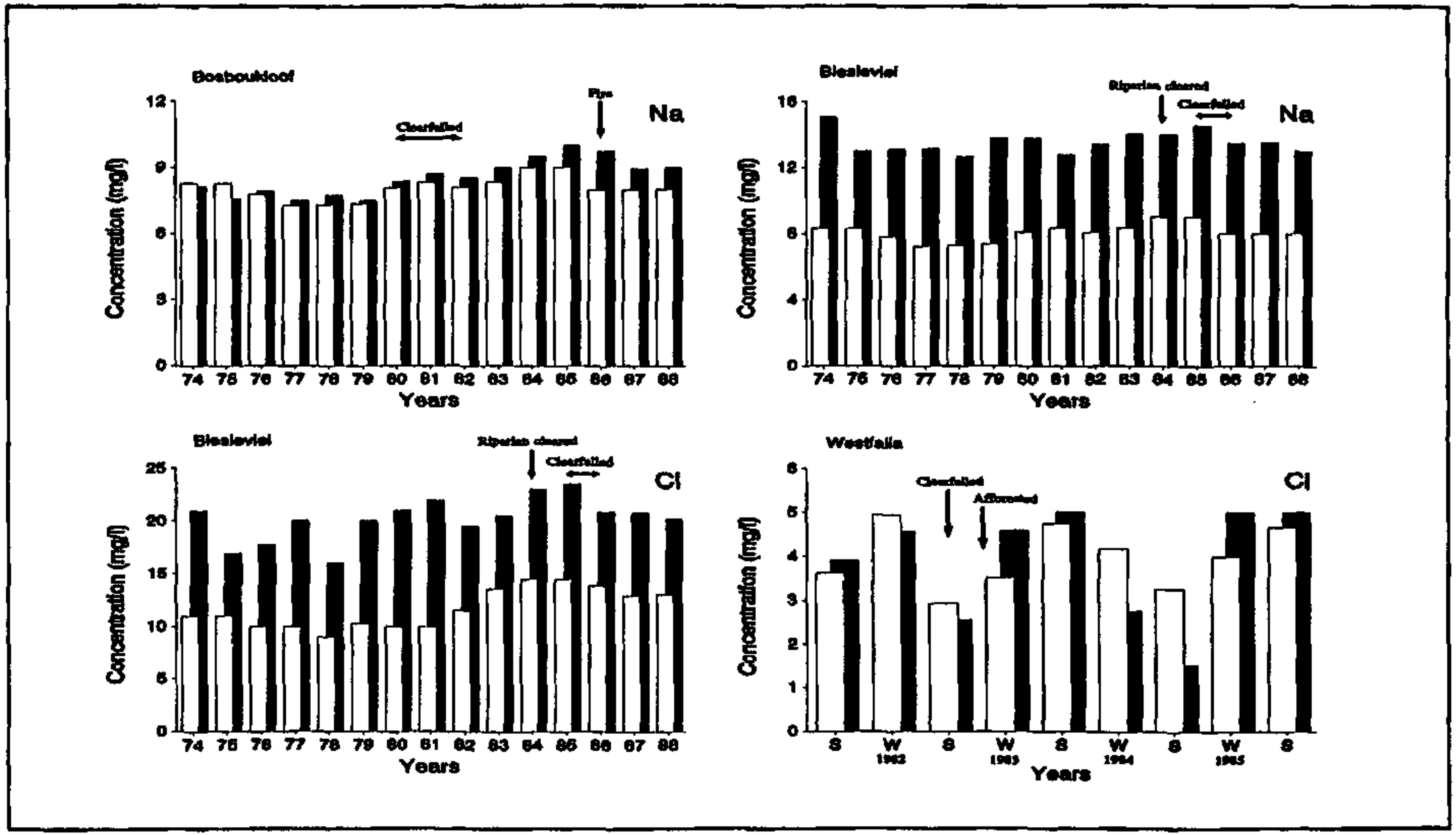

Figure 12 Histograms of treated (shaded) versus control (open) median concentrations of Na^+ and Cl^- for the respective catchments where levels were significantly changed by treatment. Westfalia data is divided into the six summer (S) and six winter (W) month periods.

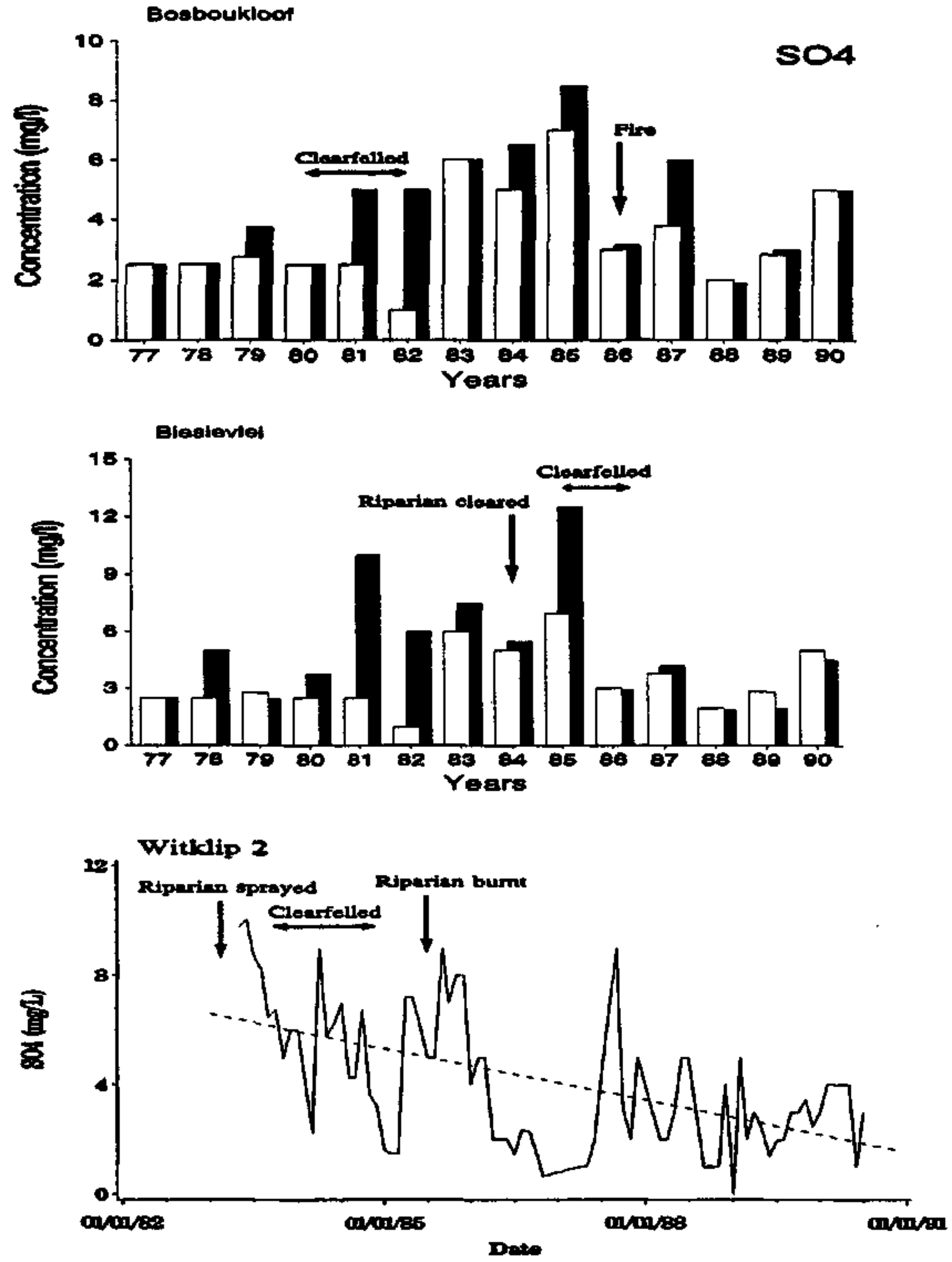

Figure 13 Histograms of treated (shaded) versus control (open) median concentrations and a trend plot of SO_4^{2-} for the respective catchments where levels were significantly changed by treatment. The trend plot shows real values (solid line) and a linear regression of concentration against time (dashed line).

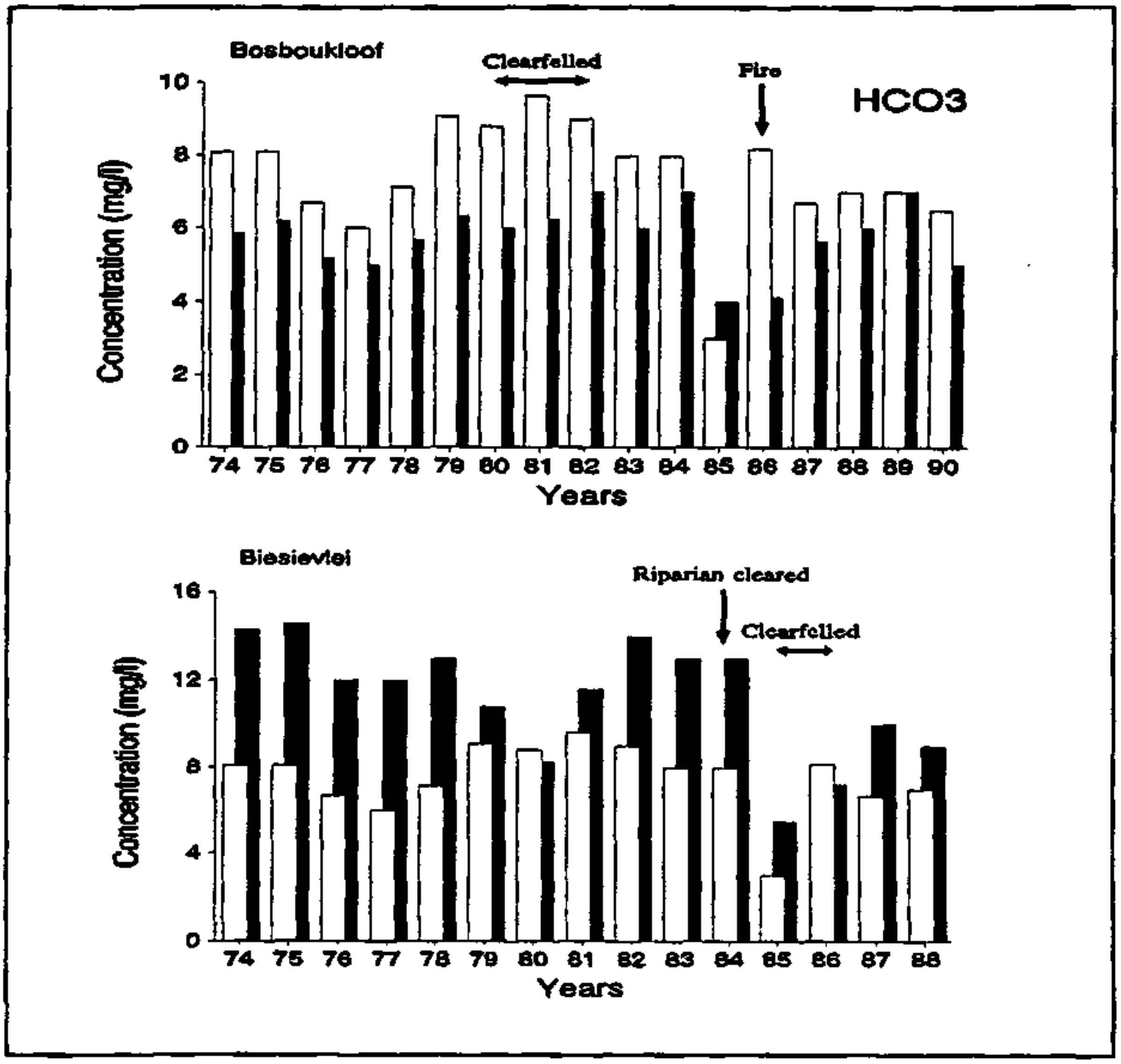

Figure 14 Histograms of treated (shaded) versus control (open) median concentrations of HCO$_3^-$ for the respective catchments where levels were significantly changed by treatment.

Appendix B; Appendix C), even during the calibration periods. This makes it difficult to detect actual changes. Although the changes in HCO$_3^-$ were not as variable as SO$_4^{2-}$-S, they were very small, for example the third year post-felling increase in Bosboukloof (Figure 14; Table IV, Appendix B). In Biesievlei, there was a decrease in HCO$_3^-$ during the year after clearfelling (Table V, Appendix B). There was also an unexplained decrease four years before felling commenced. The same trends can be seen in the K$^+$

(Figure 10) and Ca^{2+} (Figure 11) concentrations. HCO_3^- concentrations were only affected significantly in the Cape catchments.

3.2.7 Total Nitrogen and Phosphorus

Similar patterns in concentration were observed for KN and TP at Bosboukloof and Witklip 2 respectively (Figure 15). There were significant increases in both variables during the first year after the Bosboukloof fire and also in the third year for TP (Table IV, Appendix B). Both variables increased in concentration after the clearings at Witklip 2, KN by as much as 30% in the fourth year (Figure 15). These increases could indicate a slow increase in release rates with time of the two variables or that the variables were suppressed, or decreased, in concentration during the treatments, and returned to pre-treatment levels a few years after treatment. The evidence supports the former explanation, especially as NO_3^--N showed an increase following treatment (Figure 8). In both these studies the KN and TP were released after fire.

3.2.8 Silicon

Si concentrations in streamwater are very directly linked to the rate of solution from the soil and bedrock of the catchment. The significant decrease in concentration after the clearfelling of Biesievlei is thus surprising considering the amount of exposure of soil to rainfall and the significant increase in streamflow (van Wyk and Scott, 1993a) (Figure 16; Table V, Appendix B). Concentrations were however significantly increased at Westfalia D, but only for the first two years following clearfelling (Table VI, Appendix B). At Witklip 2 there was also a significant increase, especially after the initial clearing of the riparian zone (Figure 16). The very low value at Wiklip 2 in 1988 is ascribed to an unexplained non-detectable value for one month.

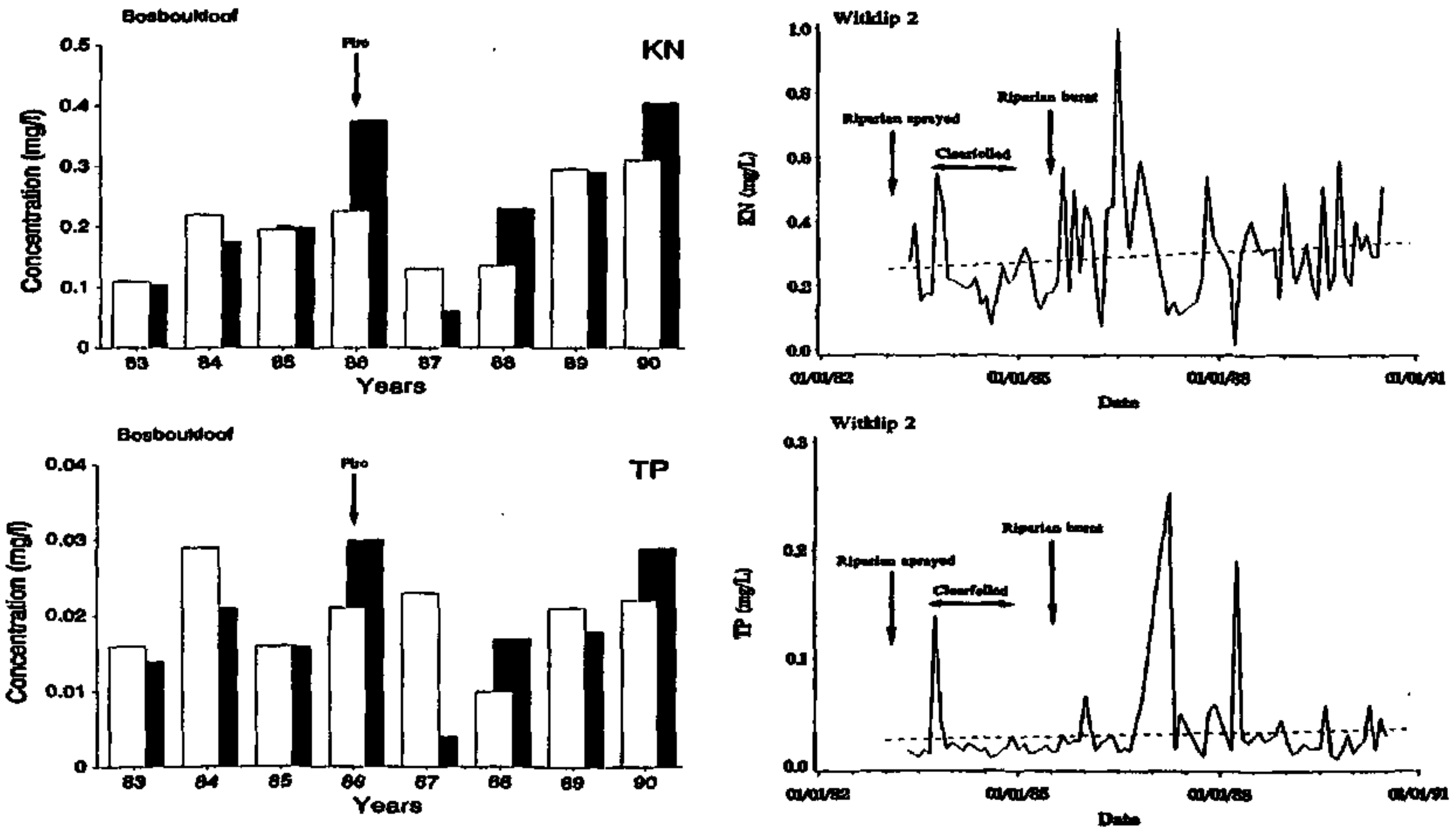

Figure 15 Histograms of treated (shaded) versus control (open) median concentrations and trend plots of KN and TP for the respective catchments where levels were significantly changed by treatment. The trend plots show real values (solid line) and a linear regression of concentration against time (dashed line).

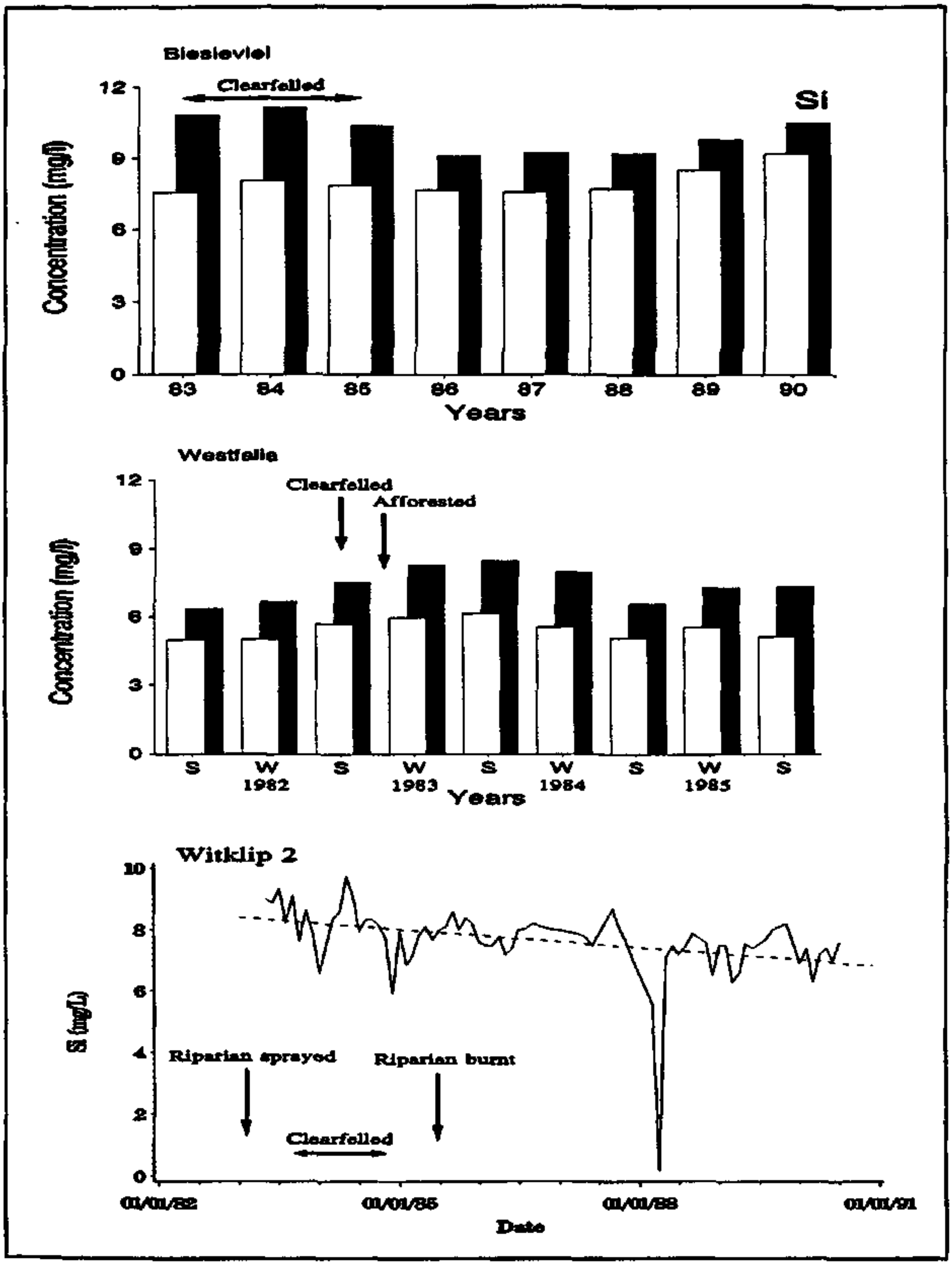

Figure 16 Histograms of treated (shaded) versus control (open) median concentrations and a trend plot of Si for the respective catchments where levels were significantly changed by treatment. Westfalia is divided into the six summer (S) and six winter (W) month periods. The trend plot shows real values (solid line) and a linear regression of concentration against time (dashed line).

3.3 Discussion

Although this study did not include all the different site-preparation, planting and clearfelling techniques applied in the general management of forests, it does cover the extremes of such management practices. The least disturbed catchment was Bosboukloof with its untouched riparian zone, that was clearfelled using standard logging techniques and then re-afforested simply by pitting and planting. The most disturbed was Westfalia D, with clearing of the riparian zone, followed by the bulldozing and burning of the indigenous forest before the entire catchment was pit-planted with *Eucalyptus grandis*.

At Witklip 2, the trends in all the variables, except KN and TP, indicate that the initial clearing of the riparian vegetation and the subsequent spraying with Roundup had the greatest effect on concentrations, resulting in significantly higher levels at the onset of sampling. The concentrations declined with time, possibly to pre-clearing levels three to four years later.

Suspended sediment has proved an important indicator of change due to forest management practices in both grab and spate samples. There is ample evidence that suspended sediment concentrations increase in streams after logging operations (eg. Campbell and Doeg, 1989). A previous study of the effect of the Bosboukloof fire on soils showed that this also caused suspended sediment loads and sediment in overland flow to increase significantly (Scott and van Wyk, 1990). Van Wyk (1986) also found highly significant increased mass export of sediment after a wildfire burnt a catchment in the Natal Drakensberg. Concentrations depend mainly on site factors such as soil type and slope, and also the degree of disturbance. Increases in concentration are however determined by the timing and intensity of rainfall following the treatment (Cornish, 1980; Campbell and Doeg, 1989). Severe treatments of catchments, such as severe preparation techniques for afforestation, are known to cause major sediment losses (Beasley, 1976; Campbell and Doeg, 1989). It is thus very likely that, had normal rainfall occurred at Westfalia during and after the clearfelling of catchment D, there would have been a much more severe and immediate increase in suspended sediment concentrations. The clearing was thus studied especially to determine long-term changes to water quality variable concentrations.

The NO_3^--N concentration in streamwater is a sensitive indicator of forest management practices (Swank, 1988) and generally of biological activity (Likens *et al.*, 1977). As with Bosboukloof, Westfalia D and Witklip 2 in this study, significantly increased concentrations of NO_3^--N have been reported elsewhere following clearfelling of afforested catchments (Dyck *et al.*, 1983; Lynch and Corbett, 1990) and after fire destroyed an afforested catchment in the Natal Drakensberg (van Wyk, 1986). Similarities could be drawn between Westfalia D and a catchment at Coweeta, USA, where conversion of indigenous hardwood forest to other species lead to an increase in NO_3^--N lasting for more than 25 years after the conversion (Swank, 1988). It seems that nitrate is released slowly from decaying litter, slash and roots remaining after the removal of the tree-trunks. The burning of vegetation also provides ash as a further source of nutrients.

Significant increases in K^+ concentrations occur after forested catchments are clearfelled (Arimitsu and Kato, 1981; Riekerk, 1983; Swank, 1988; Lynch and Corbett, 1990). The availability depends on its retention by biologically active plant tissues (Riekerk, 1983). The way K^+ behaves in nature seems to be closely linked to that of NO_3^--N, both being sensitive indicators of biologic activity (Likens *et al.*, 1977). As was found in the present study, the effects of clearfelling on K^+ concentrations were not necessarily seen directly following the felling, but sometimes only a year later, and then lasting for a few years (Swank, 1988). The prolific regrowth of natural vegetation following management practices and their uptake of available nutrients could play a major role in preventing an immediate enhanced outflow of especially plant nutrients, as was found in a study in New Zealand (Dyck *et al.*, 1983).

One would expect significant increases in electrical conductivity only when there are significant increases in the concentrations of major ions. This could be the reason why only three management practices registered slight increased levels in EC.

Riparian zones are generally regarded as buffers for the control of sediment release to streams (Clinnick, 1985). However, despite the felling of the riparian zones in Biesievlei and Witklip 2, suspended sediment did not increase significantly. Research in agricultural catchments has indicated that healthy riparian zones serve to stabilize the streambanks and store nutrients (Karr and Schlosser, 1987; Lowrance *et al.*, 1985), especially NO_3^--N and TP (Peterjohn and Correl, 1984), and KN, Ca^{2+} and Mg^{2+} (Lowrance *et al.*, 1984). The release of stored nutrients was, for example, seen in the highly significant increase in NO_3^--N in the Witklip 2 stream after the killing of the riparian vegetation with herbicide.

It must be stressed that grab- and spate-sample concentrations were, even for the fire-effects, below the maximum levels suggested for healthy aquatic life in rivers (Kempster *et al*, 1982). The only exception was suspended sediment in spates, especially after the Bosboukloof fire.

The inclusion of control catchments has proved invaluable, especially for detecting short-term changes. They eliminate the need to account for the effects of external factors on concentrations, which can often obscure the actual treatment effects. If it is not possible to include a control catchment in the monitoring system, and trend-detection is being used, then at least one external factor should be tested for trends. For example, rainfall was included in the analyses for Witklip 2 (Appendix C).

The overall picture that emerges from this study is that the extreme site preparation techniques applied at Westfalia D had the most severe and lasting effect on grab-sample concentration levels. To a certain extent the fire at Bosboukloof is also a reflection of a high-disturbance "management practice" to the catchment. The fire caused extreme increases in variable concentrations, particularly during spates. Thus, any extreme management practice resulting in severe disturbance to the upper soil layers in a catchment can be expected to have a significant effect on streamwater quality, and will have to be monitored within a sampling network. Normal, relatively low-disturbance forest management practices, induce some changes in concentrations, but the effects do not seem to be persistent and are mostly negligible when compared with water quality standards for river water (Kempster *et al*, 1982).

3.4 Conclusions

A number of water quality variables have been found to be indicators of management practices applied in forested catchment. Of these suspended sediment proved to be the most sensitive indicator, showing the level of disturbance of the upper soil layers. While being important nutrients for plant growth, NO_3^--N and PO_4^{3-}-P are also good indicators of change and can in addition indicate the state of a river for planktonic algae growth (i.e. chlorophyll *a*) (Harris et al, 1992). The cations K^+ and Ca^{2+} are both very good indicators of change due to management practices, K^+ being the more sensitive indicator of biological activity. Electrical conductivity can be used as an overall index of changes in the concentrations of major ions in the water, though it was not a strong indicator in this study.

4 CORRELATION ANALYSES

The concentrations of all water quality variables from each catchment included in this study were analysed to identify meaningful correlations. Strong relationships between variables would make it possible to predict one from the other, and thus reduce the number of variables in the analyses. This would reduce costs and be particularly useful when considering long-term monitoring objectives.

Most variables were weakly correlated with each other, the correlation coefficients being mostly below 0.40 (Appendix D). The only high correlation, of above 0.80, was between PO_4^{3-}-P and TP for Bosboukloof, Westfalia B and Witklip 2. This correlation was very low for the remaining catchments, showing that phosphate is not a consistently fixed proportion of the total amount of phosphorus. Another moderately high correlation was between KN and TP, which was 0.67 for Biesievlei and 0.70 for Westfalia D, but below 0.5 for the other catchments. The Ca^{2+} - Mg^{2+} correlation was as high as 0.72 for Witklip 2, but remained around 0.5 for the other catchments. The ratio between these two variables is often used to determine the origin (land or sea) of precipitation (Eaton *et al.*, 1973). There was a consistently low correlation between Na^+ and Cl^-, although both originate mainly from the same marine source in the Jonkershoek catchments. The low correlation can be explained by the fact that while Cl^{-1} would not be retained by the system and does not originate from the soil, Na^+ is actively exchanged with other cations (Likens *et al.*, 1977). Na^+ is also released from minerals during soil forming processes such as weathering, and from decaying vegetation.

It was surprising that there were low correlations between the EC and major variables like Na^+, Cl^-, HCO_3^- and SO_4^{2-}-S, as it is usually assumed that these variables have a major influence on EC levels. In a study of afforested catchments in Natal, Simpson (1991) similarly found low correlations between EC and other variables.

It can thus be concluded from these analyses that none of these variables can be used to predict any other with a reasonable degree of certainty.

5 CONSIDERATIONS FOR SELECTION OF SAMPLING SITES AND FREQUENCY

5.1 Selection of sampling sites

It is important to choose streamwater monitoring sites carefully so as to ensure that representative concentrations of elements in the streamwater from a particular catchment will be obtained. Sampling sites for the catchments used in this study were usually located at the lower-end, where the stream was calculated to leave the watershed. The argument is that all of the water (stream-, soil and groundwater) from a catchment with a given area should flow through that departure-point. This way streamflow can be calculated as rainfall equivalents and nutrient budgets (in- and outputs) determined. For general monitoring purposes, it is not necessary to concentrate on watersheds, but rather on the river system. Sanders *et al.* (1987) recognise three levels of decision: macrolocations, microlocations and representative locations. The macrolocation refers to streams to sample within a bigger catchment area, the microlocation to the position of sampling sites, and the representative location to sampling of a cross-section of a bigger river to give a lateral profile of the stream. The final location level is rarely important in upper mountain catchments, since the streams from these areas are normally fast-flowing, well-mixed and relatively small.

For less intensive monitoring sampling sites can be linked to the stream order as defined by Horton (1945). Sharp (1971) employed this method to sample a river network, dividing the network into portions with a roughly equal number of contributing tributaries (or headwater streams). The methodology and some examples are set out as guidelines in Part B.

5.2 Selection of sampling frequency

Some of the factors that are important in selecting sampling frequency include that of autocorrelation, where the value of one sample concentration is correlated with that of the next sample taken, and cost, i.e. the budget available for sampling. Sanders *et al.* (1987) suggests that confidence interval widths (R) calculated from the variance of the sample mean should be used to determine the correct frequency of sampling. This method requires historical data and is calculated as:

$$R = 2 \times 1.96\ \sigma/\sqrt{n}$$

which presents a 95 % probability for the sample mean to lie within this interval (width of the confidence interval about the mean); $\sigma = \sqrt{\text{estimated population variance}}$ (based on sample variance) and n = required sampling frequency. R is usually determined by the requirements of the monitoring agent. This equation assumes that serial correlation is not important. In calculating the frequency for a number of variables at a sampling point, it is simplest to calculate the weighted average of the confidence interval widths. Using K^+, Ca^{2+}, NO_3^--N, and PO_4^{3-}-P concentrations (up to 189 samples) at Lambrechtsbos B and the confidence interval as 1/2 the mean of the four concentrations, a sampling frequency of 39 samples per year was calculated, thus about three samples per month, not compensating for autocorrelation. Further calculations became too complex for the present study.

On the other hand, the analysis of the monthly averaged Witklip data, proved that four of the nine variables tested whose concentrations changed significantly as a result of clearings, were also autocorrelated at lag1, that is from one month to the next (Appendix C). There was no lag2 or any other autocorrelation, which would mean that in order to avoid autocorrelation affecting some variable concentrations, two-monthly sampling should be done. This type of analysis does however give the opportunity to compensate for autocorrelation in the final decision-making, so that sampling frequency adjustment might not be necessary.

Statistical analyses similar to that performed in this study, were applied to weekly, as opposed to monthly, variable concentrations at Westfalia to analyse changes due to the vegetation clearings (Scott and Lesch, 1993). The same variables were found to be significantly changed in both studies, indicating monthly sampling to be sufficient for detecting significant changes due to management practices. Harris *et al.* (1992) also found a monthly sampling frequency sufficient for purposes of detection of change in pH and total dissolved solids.

Budgetary-constraints will play an important role in the decision making. General short-term (1-2 year) and long-term (> 2 years) monitoring requires at least monthly sampling, while spate-specific sampling can also be used for short-term studies of the impacts of extreme events or management practices.

5.3 Sampling methods

The sampling methods employed in the experimental catchments described in this study (van Wyk, 1991a), and in other similar studies (Likens *et al.*, 1977; Swank and Waide, 1988) are recommended for general use. A full description of the methods are supplied as guidelines in Part B.

6 DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

Using data existing on the Forestek database, a study was made of the effects of different forestry management practices on streamwater quality. Sixteen water quality variables were studied in samples from six catchments in South Africa from both high- and low flow conditions, to determine which would be appropriate indicators of change due to forest management practices. An attempt was made to establish correlations between the variable concentrations studied. By incorporating available literature, frequency and methods of sampling were also determined.

This study concluded that spate sampling (sampling during high flow conditions) is only needed for the first two to four spates following a severe event or management practice. Generally, on a routine basis, monthly grab sampling would suffice for monitoring purposes. These samples should then be taken at a point just above where streams join, where the stream is well mixed and free-flowing. If appropriate, a control catchment could be sampled and compared with the treated catchment, in order to exclude external influences such as geology and weather from the study. For a more complex monitoring system, stream ordering techniques can be applied, using tributaries.

Water quality variables that proved to be good indicators of forest management practices include: suspended sediment, NO_3^--N, PO_4^{3-}-P, K^+ and Ca^{2+}. A reduced or simpler study could include analysis of only suspended sediment. The other variables can then be included when more information is required and a broader monitoring network is designed. None of the sixteen variables were consistently significantly correlated and could thus not be used as predictors of each other.

A study of monitoring in South African rivers identified the following six variables as indicative of different situations in a river, and important in a general monitoring strategy (Harris *et al.* 1992): Total dissolved salts (TDS), which can be derived from the EC and which indicates salinity levels; turbidity, of which suspended sediment can be a measure, to indicate erosion; *E.coli* to indicate contamination by human sewage; Chlorophyll *a* to indicate possible eutrophication (of which NO_3^--N and PO_4^{3-}-P could be a measure too);

pH to measure acidity from mines and acid rain, and potential toxicity; and dissolved oxygen to determine conditions for aquatic life. Mountain streams are generally not contaminated by human sewage. Oxygen demand for aquatic life is also not a problem because of the generally clean and aerated nature of the streams and the low salinity levels. pH is not an important indicator of change at present, but it might have to be included if acid rain becomes an important factor for the South African forestry industry. The variables that are recommended in this study for monitoring of afforested areas thus fall within that of the national monitoring system.

This study included only inorganic water quality variables. A study of the biological characteristics of a stream could provide a more sensitive indicator of change in a river system due to management practices. Recent studies have indicated that physical, chemical and biological monitoring combined could give a better indication of the health of an aquatic ecosystem (Dallas and Day, 1993; Roux *et al.*, 1993).

The following areas are seen as lacking in the present study and are recommended for further research:

(1) A detailed study of existing data, from this study and elsewhere, to determine statistically verified sampling frequencies to adequately monitor streamwater quality from plantations.

(2) The effect of the various established site preparation techniques on streamwater quality.

(3) Combining the results of this study of inorganic indicators with similar studies of biological indicators to identify potentially more sensitive means of determining change in montane headwater streams as influenced by afforestation.

PART B: GUIDELINES FOR THE MONITORING OF WATER QUALITY IN AFFORESTED AREAS

1 INTRODUCTION

This section contains guidelines for cost-effective monitoring of water quality in afforested areas. It covers criteria only for inorganic elements (variables) in streamwater. The guidelines deal with general procedures for monitoring of the impacts of all forest management practices. Figure 1 gives an indication of where the guidelines fall within the design of a total water quality monitoring system. The guidelines can apply to both short- and long-term monitoring strategies. This section is based on information analysed in Part A. It is important to note that the guidelines are for the determining of concentrations of variables in streamwater. In order to calculate loads, streamflow would have to be measured additionally.

- **NB**: Records of all sampling information should be kept for continuity. This includes information on where and why sampling positions were chosen.

2 WHERE TO SAMPLE

- The sampling point should be located at or beyond a zone of complete mixing down the river from the treated area to ensure that all concentrations are adequately dispersed. This allows for adequate mixing of the water, avoiding over-estimation of treatment-effects. An example would be to sample below a rocky, shallow area through which the stream flows at a substantial rate. Care must be taken not to sample directly below where a dust road crosses the stream.

- Sampling should be done just above the point where streams join, or a place closest to this point and where there is a zone of complete mixing.

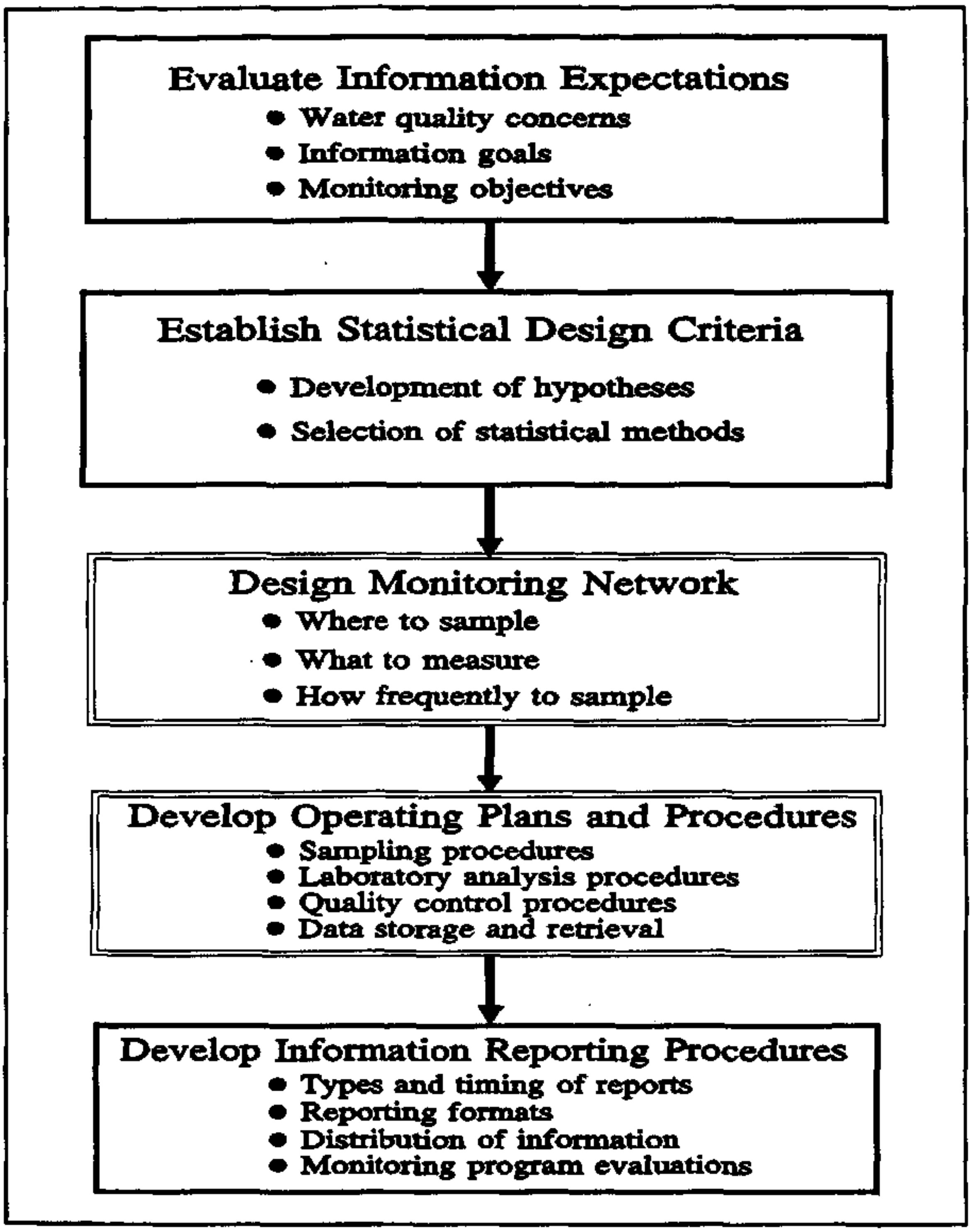

Figure 1 Five steps to use as general guidelines for the establishment of a total monitoring system (from Sanders *et al.*, 1987). The current study supplies information mainly for the third step (Design monitoring network) and to some extent the fourth step (steps indicated in double outlines). The first two steps deal with identifying information needs and statistical methods to be used to give the desired information. The final step devises how information is to be reported and evaluated.

- The best way to avoid confounding actual changes in water quality in the treated area with changes caused by variations in climate, is to simultaneously sample a stream from an untreated (control) area. The two areas should be close geographically and have similar slope, area, topography, aspect, soils, and if possible plantation species. The ratio between the concentration levels at these two catchments can then be used to detect change.

- If a specific management-effect in a sub-catchment is to be sampled, additional samples should be taken at a point where the stream leaves the whole catchment. A significant effect in a particular area might only have a minor impact on the quality of the water from the whole catchment.

  For example: The densely shaded area in Figure 2 is to undergo some form of treatment, but the stability of the soil is questionable. An untreated control catchment (lightly shaded) is to be monitored to determine the effects of treatment. Sampling could then be done at points A, B and C:

  A to determine the treatment effects,
  B to measure normal conditions for that period, and
  C to determine the magnitude and longevity of the treatment effect within the greater catchment area.

- For long-term (> 2 years) trend monitoring:
  - First construct a map of the greater afforested catchment area to be monitored, with all the important streams indicated.
  - Apply ordering of the streams, starting from the top of the catchment: Tributaries (headwater streams) and streams flowing into the catchment are given a magnitude of one. Where two tributaries flow together the resulting stream order is two; where a tributary and a second order stream flow together it is three (1 + 2 = 3); 2 + 2 = 4; 4 + 2 = 6, etc. (see Figure 2).
  - To determine a sampling hierarchy, first divide the catchment into a lower and an upper part of about the same size, using the number of tributaries:

    $$(\text{number of tributaries} + 1) / 2 = x$$

    The stream is sampled at the point closest to that ordered x for the upper half of the catchment (i.e. if $x = 8.5$, you should sample a stream with an order 8 or 9). The lower half is sampled where the stream leaves the catchment area (Figure 2). For more intense sampling, use the number of tributaries above and below the upper sampling point, treating each of the two area as a separate system (re-ordering the streams if need be). Determine the next sampling hierarchy by applying the formula above to each of the two sub-systems (Figure 2).

- This type of continued sub-division could be used to trace a specific site that is influencing water quality.
- The depth of hierarchical sampling will also depend on the funding available for sampling.

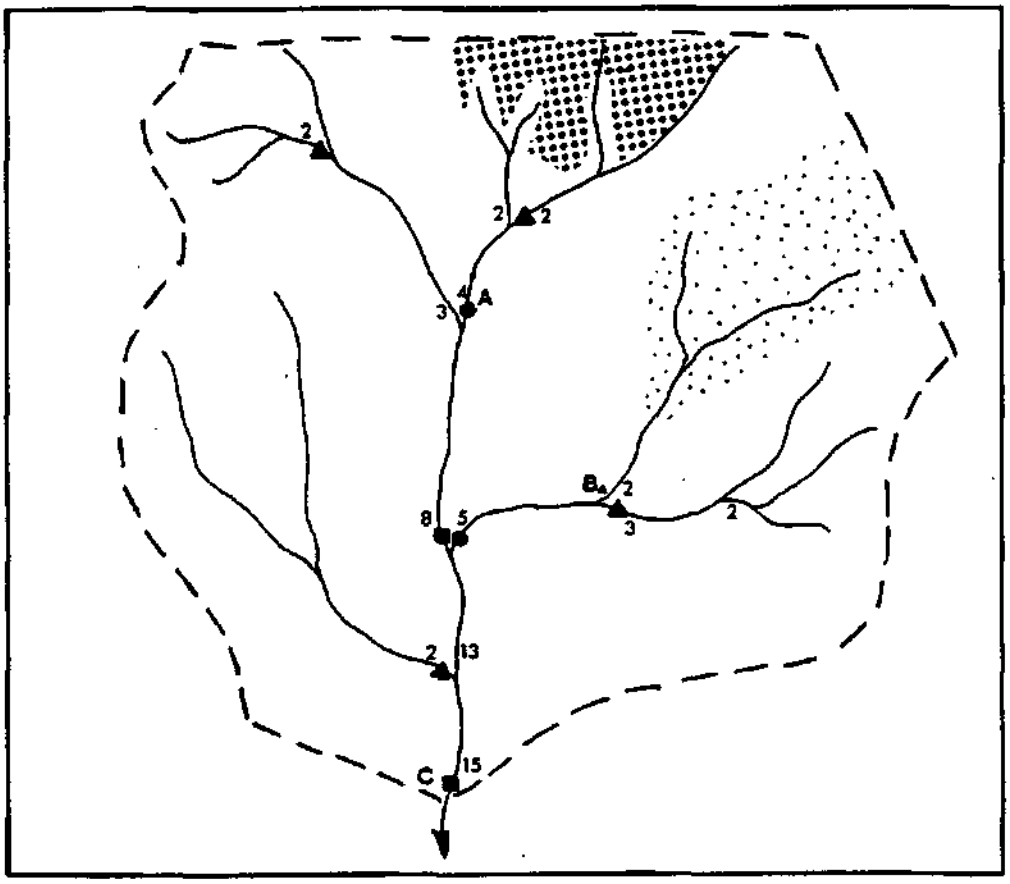

Figure 2 Schematic presentation of a catchment and river system. The stream ordering is numbered. Sampling sites are presented as: ■ 1st, ● 2nd and ▲ 3rd sampling hierarchy. Points A, B and C, as described in the text, are sampling points for a hypothetical forestry monitoring exercise. The deeply shaded area is the treated, and the lightly shaded area is the control catchment.

3 HOW TO SAMPLE

- Grab sampling (taking a sample directly from the stream by hand) at monthly intervals should suffice for long-term monitoring programs.

- Spate sampling (sampling during high flow conditions, after a sufficient rain event) will be necessary when sampling management-effects intensely, or when a major change has occurred (eg. fire, major soil slips, etc.).

- Sampling should commence at least a year before the management practice is applied to provide a baseline, or calibration period, against which the treatment period can be compared.

- For *grab sampling*:
    - ▸ A 500 ml polyethylene bottle with screw-top will contain enough sample for filtering and other analyses. Polyethylene bottles are preferred, as glass may contain certain micro-elements which could contaminate the sample.
    - ▸ Each bottle should be labelled and only used for a specific sampling site. In this way cross-contamination is avoided.
    - ▸ Bottles should also be rinsed in the stream before collecting the sample, to minimise contamination.
    - ▸ Bottles could be cleaned initially with commercially available ultra-pure washing detergents, and then rinsed well, under running de-ionised water (at least three times).
    - ▸ Any bottles that show signs of wear must be replaced, as this eliminates the growth of organic materials in cracks.
    - ▸ After sampling, the bottles must be placed immediately in an insulated container and stored at 4°C or less for as short a time as possible prior to analysis.

- For *spate sampling*:
    - A simple device such as that described by Van Wyk (1983) could be erected anywhere in the stream to sample at least the rising spate. Van Wyks sampler uses polyethylene 500-ml bottles attached at different heights, with airlocks to ensure no mixing once a bottle is filled. The samples should be collected as soon as possible after the spate.
    - The bottles should be treated in the same way as the grab-sample bottles.
    - If spate sampling is not done regularly, grab samples can be taken manually at regular intervals while the spate rises and falls. These samples can either be analysed separately, if detailed information on the spate is required, or combined into a single sample.

- Samples can be *preserved* in the following ways:
    - No preservatives are needed for suspended sediment sampling and/or determining pH and electrical conductivity (but samples must be kept at 4°C or colder).
    - By freezing with liquid nitrogen, or in a freezer, and keeping the samples frozen until they are analysed.
    - Contact the chosen laboratory and enquire their requirements for sample preservation. One example is to use mercuric-chloride (HgCl), of which ampules are available on request from the Hydrological Research Institute, Pretoria.

4 WATER QUALITY VARIABLES TO ANALYSE

From the investigation of existing water quality data, it became clear that there were five water quality variables that were important indicators of changes caused by the application of different forest management practices:

- ***The minimum monitoring requirement*** is to sample suspended sediment, or measure turbidity.

- ***A more intensive monitoring strategy*** should include the following additional variables:
  - nitrate (NO_3^--N) - especially for long-term change
  - phosphate (PO_4^{3-}-P)
  - potassium (K^+) - especially for long-term change
  - calcium (Ca^{2+})

- If there is reason to believe that stream acidification could be a problem, then pH should be included.

- Electrical conductivity is a good measure of the total ionic concentration and can be included if changes to major-ion concentrations are considered important (e.g. following a severe treatment).

5 SAMPLE ANALYSIS

- Suspended sediment concentrations can be analysed at the monitoring base. It is determined by vacuum filtration of the sample through fine-pored filter paper (eg. 0.45 μ Whatman GF/C filters). A 250 ml sample is usually sufficient. The filter paper is weighed before use, dried (at 105°C) after filtration, cooled in a desiccator containing silica gel, and weighed again to determine the sediment mass. Calculate the concentration by dividing the sediment mass with the original sample volume and converting to mg l^{-1}.

- Simple turbidity meters are available commercially, for direct measurements in streams.

- Electrical conductivity- and pH meters are commercially available, and no special laboratory is required within which to operate the instruments. Measurements are performed with the samples at 25°C.

- The concentrations of the remaining variables should be determined by reputable laboratories; about a 250-ml sample will be required. It is important to determine whether the laboratory can analyse at the low concentration levels required for water from afforested catchments. PO_4^{3-}-P needs to be detected at least at the 0.005 mg l^{-1} level.

6 STATISTICAL TREATMENT OF DATA

- A number of water quality data analysis packages are available for IBM compatible computers. One of these is the "WQSTAT II" software package (Phillips *et al.*, 1989) which is freely available from the Department of Water Affairs and Forestry.

- A good guideline for permissable baseline concentration values for different uses of water can be obtained from Kempster *et al.* (1982).

- Department of Water Affairs and Forestry (1991) have published new water quality guidelines that include all the areas of South Africa.

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APPENDIX A: Tests for normality

Results of tests of normality of all water quality variable concentrations in three of the catchment used in this study. The Shapiro-Wilk statistic (W) for normality is tested. If W is close to 1 the sample is normaly distributed.

Lambrechtsbos-B : South-western Cape

Variables	**Sample size**	**W**	**Significance (Prob < W)**
TSS	102	0.762	0.0001
Conductivity	198	0.989	0.9030
pH	198	0.986	0.7306
Na^+	188	0.916	0.0001
K^+	188	0.454	0.0001
Ca^{2+}	189	0.425	0.0001
Mg^{2+}	189	0.589	0.0001
NH_4^+-N	83	0.883	0.0001
Cl^-	189	0.965	0.0034
SO_4^{2-}-S	154	0.840	0.0001
HCO_3^-	187	0.960	0.0004
NO_3^--N	83	0.324	0.0001
PO_4^{3-}-P	83	0.702	0.0001
F^-	83	0.799	0.0001
KN	75	0.892	0.0001
TP	75	0.852	0.0001
Si	83	0.969	0.1635

Westfalia B : North-eastern Transvaal

Variables	Sample size	W	Significance (Prob < W)
TSS	107	0.779	0.0001
Conductivity	68	0.954	0.0324
pH	68	0.976	0.4775
Na^+	88	0.973	0.2746
K^+	89	0.665	0.0001
Ca^{2+}	85	0.675	0.0001
Mg^{2+}	88	0.942	0.0010
NH_4^+-N	94	0.755	0.0001
Cl^-	88	0.961	0.0387
SO_4^{2-}-S	86	0.906	0.0001
HCO_3-	87	0.949	0.0049
NO_3^--N	94	0.677	0.0001
PO_4^{3-}-P	94	0.418	0.0001
F^-	94	0.794	0.0001
KN	83	0.841	0.0001
TP	83	0.438	0.0001
Si	94	0.972	0.1966

Witklip 2: Eastern Transvaal

Variables	Sample size	W	Significance (Prob < W)
TSS	100	0.551	0.0001
Conductivity	72	0.970	0.2439
pH	72	0.926	0.0003
Na^+	74	0.949	0.0106
K^+	74	0.865	0.0001
Ca^{2+}	74	0.661	0.0001
Mg^{2+}	74	0.561	0.0001
NH_4^+-N	74	0.856	0.0001
Cl^-	74	0.967	0.0001
SO_4^{2-}-S	74	0.928	0.0003
HCO_3^-	74	0.989	0.9554
NO_3^--N	74	0.650	0.0001
PO_4^{3-}-P	74	0.316	0.0001
F^-	74	0.745	0.0001
KN	74	0.904	0.0001
TP	74	0.492	0.0001
Si	74	0.744	0.0001

APPENDIX B: Results of Wilcoxon Rank Sums tests

In the following tables (I to VI) results are given of the Wilcoxon Rank Sums test for treatment effects on the water quality variable concentrations from all the catchments analysed. For all the tests the ratio treated/control was used. Where possible a calibration (or pre-treatment) period was used, and these ratios tested against those for post-treatment years. Where this was not possible, alternatives are indicated in the table heading. In most cases, except where otherwise indicated, the sample size N1 represents the number of observations used for the calibration period, and N2 that for the different post-treatment periods tested. "TSS" refers to total suspended sediment, and EC to electrical conductivity. Levels of significance indicated are: NS = not significant, * = $P < 0.05$ and ** = $P < 0.01$.

Table I Results for **spateflow** from Bosboukloof (Lambrechtsbos-B the control) in Jonkershoek. There was no calibration period. Post-clearfelling years (P-C yrs), 1983 to 1985 were compared with each other, then used as "calibration" period for three post-fire years (P-F yrs). Clearfelling occurred from 1980 to 1982 and the fire 18 February 1986.

Variable	Period analysed		Sample size		Z	Significance level for rejection of H_o no change	
			N1	N2			
TSS	P-C yrs :	1st vs 2nd	13	18	-0.661	0.5089	NS
		1st vs 3rd	13	21	2.055	0.0398	*
	P-F yrs :	1st	21	20	4.630	0.0001	**
		2nd	21	37	-0.583	0.5603	NS
		3rd	21	31	0.392	0.6953	NS
EC	P-C yrs :	1st vs 2nd	10	6	0.488	0.6255	NS
		1st vs 3rd	10	9	0.041	0.9674	NS
	P-F yrs :	1st	25	10	1.808	0.0707	NS
		2nd	25	8	0.987	0.3235	NS
		3rd	25	9	1.327	0.1844	NS
Na$^+$	P-C yrs :	1st vs 2nd	9	5	0.933	0.3506	NS
		1st vs 3rd	9	8	1.011	0.3120	NS
	P-F yrs :	1st	25	8	0.252	0.8010	NS
		2nd	25	8	0.525	0.5995	NS
		3rd	25	9	1.093	0.2742	NS
K$^+$	P-C yrs :	1st vs 2nd	9	5	1.867	0.0619	NS
		1st vs 3rd	9	8	0.625	0.5317	NS
	P-F yrs :	1st	25	8	2.878	0.0040	**
		2nd	25	8	1.533	0.1252	NS
		3rd	25	9	1.327	0.1844	NS
Ca^{2+}	P-C yrs :	1st vs 2nd	9	5	-0.804	0.4217	NS
		1st vs 3rd	9	8	-2.264	0.0236	*
	P-F yrs :	1st	25	8	2.976	0.0029	**
		2nd	25	8	0.947	0.3435	NS
		3rd	25	9	0	0.9999	NS
Mg^{2+}	P-C yrs :	1st vs 2nd	9	5	-1.473	0.1407	NS
		1st vs 3rd	9	8	-2.144	0.0321	*
	P-F yrs :	1st	25	8	1.702	0.0887	NS
		2nd	25	8	0.486	0.6273	NS
		3rd	25	9	-1.897	0.0578	NS
NH$_4^+$-N	P-C yrs :	1st vs 2nd	9	5	-0.400	0.6888	NS
		1st vs 3rd	9	8	-1.120	0.2625	NS
	P-F yrs :	1st	25	8	-1.034	0.3011	NS
		2nd	25	8	0.106	0.9160	NS
		3rd	25	9	0.491	0.6233	NS
Si	P-C yrs :	1st vs 2nd	9	5	0	0.9999	NS
		1st vs 3rd	9	8	1.684	0.0922	NS
	P-F yrs :	1st	25	8	0.189	0.8501	NS
		2nd	25	8	0.357	0.7210	NS
		3rd	25	9	1.561	0.1184	NS

Variable	Period analysed		Sample size		Z	Significance level for rejection of H_0 no change	
			N1	N2			
Cl^-	P-C yrs :	1st vs 2nd	9	5	0.267	0.7897	NS
		1st vs 3rd	9	8	-1.144	0.8852	NS
	P-F yrs :	1st	25	8	0.063	0.9498	NS
		2nd	25	8	-1.575	0.1152	NS
		3rd	25	9	-0.488	0.6255	NS
SO_4^{2-}-S	P-C yrs :	1st vs 2nd	9	5	2.002	0.0453	*
		1st vs 3rd	9	8	1.203	0.2290	NS
	P-F yrs :	1st	27	8	1.043	0.2971	NS
		2nd	25	8	0	0.9999	NS
		3rd	25	9	-1.622	0.1048	NS
HCO_3^-	P-C yrs :	1st vs 2nd	9	5	0	0.9999	NS
		1st vs 3rd	9	8	-0.626	0.5314	NS
	P-F yrs :	1st	25	8	1.324	0.1853	NS
		2nd	25	8	2.376	0.0175	*
		3rd	25	9	1.625	0.1041	NS
NO_3^--N	P-C yrs :	1st vs 2nd	9	5	-1.333	0.1824	NS
		1st vs 3rd	9	8	-2.935	0.0033	**
	P-F yrs :	1st	25	8	0.399	0.6898	NS
		2nd	25	8	1.071	0.2840	NS
		3rd	25	9	-0.703	0.4822	NS
PO_4^{3-}-P	P-C yrs :	1st vs 2nd	9	5	0.533	0.5938	NS
		1st vs 3rd	9	8	-0.920	0.3577	NS
	P-F yrs :	1st	27	8	0.610	0.5420	NS
		2nd	25	8	-1.620	0.1052	NS
		3rd	25	9	0.196	0.8450	NS
F^-	P-C yrs :	1st vs 2nd	9	5	1.011	0.3119	NS
		1st vs 3rd	9	8	2.540	0.0111	*
	P-F yrs :	1st	25	8	1.019	0.3083	NS
		2nd	25	8	-0.759	0.4481	NS
		3rd	25	9	-1.366	0.1718	NS
KN	P-C yrs :	1st vs 2nd	9	5	1.600	0.1096	NS
		1st vs 3rd	9	8	0.818	0.4134	NS
	P-F yrs :	1st	25	8	3.214	0.0013	**
		2nd	25	8	0.021	0.9832	NS
		3rd	25	9	0.664	0.5069	NS
TP	P-C yrs :	1st vs 2nd	9	5	0.400	0.6892	NS
		1st vs 3rd	9	8	0.048	0.9616	NS
	P-F yrs :	1st	25	8	2.962	0.0031	**
		2nd	25	8	-0.399	0.6898	NS
		3rd	25	9	-0.508	0.6118	NS

Table II Results for **spateflow** from Biesievlei (Lambrechtsbos-B the control) in Jonkershoek. Where there were no significant differences between the pre-treatment, riparian and clearfelling year, the data was lumped together and used as a calibration period for three post-clearfelling years (P-C yrs), 1986-88.

Variable	Period analysed	Sample size		Z	Significance level for rejection of H_0	
		N1	N2			
TSS	Riparian treatment	63	19	-0.506	0.6132	NS
	Clearfelling year	63	12	2.161	0.0307	*
	P-C yrs : 1st	63	14	0.192	0.8481	NS
	2nd	63	36	-1.713	0.0867	NS
	3rd	63	25	-2.267	0.0234	*
EC	Riparian treatment	8	8	-0.368	0.7132	NS
	Clearfelling year	8	7	0.289	0.7723	NS
	P-C yrs : 1st	23	9	-0.273	0.7853	NS
	2nd	23	8	2.325	0.0201	*
	3rd	23	8	2.144	0.0320	*
Na^+	Riparian treatment	8	8	0.158	0.8747	NS
	Clearfelling year	8	7	0.405	0.6854	NS
					0.8999	NS
	P-C yrs : 1st	23	9	0.126		
	2nd	23	8	1.197	0.2134	NS
	3rd	23	8	0	0.9999	NS
K^+	Riparian treatment	8	8	-1.208	0.2271	NS
	Clearfelling year	8	7	0.752	0.4519	NS
	P-C yrs : 1st	23	9	0.042	0.9665	NS
	2nd	23	8	0.723	0.4700	NS
	3rd	23	8	-1.106	0.2686	NS
Ca^{2+}	Riparian treatment	8	8	0.899	0.3685	NS
	Clearfelling year	8	7	-0.871	0.3837	NS
	P-C yrs : 1st	23	9	-0.256	0.7982	NS
	2nd	23	8	-0.597	0.5505	NS
	3rd	23	8	-0.729	0.4658	NS
Mg^{2+}	Riparian treatment	8	8	-1.161	0.2456	NS
	Clearfelling year	8	7	-1.582	0.1136	NS
	P-C yrs : 1st	23	9	-1.947	0.0515	NS
	2nd	23	8	-0.724	0.4692	NS
	3rd	23	8	-0.856	0.3918	NS
NH_4^+-N	Riparian treatment	8	8	-0.053	0.9575	NS
	Clearfelling year	8	7	-0.579	0.5625	NS
	P-C yrs : 1st	23	9	0.631	0.5282	NS
	2nd	23	8	2.447	0.0144	*
	3rd	23	8	0.842	0.3996	NS
Si	Riparian treatment	8	8	-0.368	0.7132	NS
	Clearfelling year	8	7	-1.678	0.0933	NS
	P-C yrs : 1st	23	9	-1.844	0.0652	NS
	2nd	23	8	-0.293	0.7692	NS
	3rd	23	8	-0.203	0.8390	NS

Variable	Period analysed	Sample size		Z	Significance level for rejection of H_o	
		N1	N2			
Cl^-	Riparian treatment	8	8	0.263	0.7929	NS
	Clearfelling year	8	7	-0.984	0.3253	NS
	P-C yrs : 1st	23	9	-0.943	0.3456	NS
	2nd	23	8	-1.197	0.2315	NS
	3rd	23	8	-1.422	0.1550	NS
SO_4^{2-}-S	Riparian treatment	8	8	-0.263	0.7927	NS
	Clearfelling year	8	7	2.143	0.0321	*
	P-C yrs : 1st	16[1]	9	0.284	0.7767	NS
	2nd	16	8	-1.011	0.3121	NS
	3rd	16	8	-1.630	0.1031	NS
HCO_3^-	Riparian treatment	8	8	-0.895	0.3706	NS
	Clearfelling year	8	7	0.058	0.9539	NS
	P-C yrs : 1st	23	9	-1.237	0.2160	NS
	2nd	23	8	0.474	0.6353	NS
	3rd	23	8	-0.429	0.6678	NS
NO_3^--N	Riparian treatment	8	8	-0.263	0.7929	NS
	Clearfelling year	8	7	0.405	0.6854	NS
	P-C yrs : 1st	23	9	0.629	0.5294	NS
	2nd	23	8	1.106	0.2687	NS
	3rd	23	8	0.926	0.3547	NS
PO_4^{3-}-P	Riparian treatment	8	8	0.158	0.8745	NS
	Clearfelling year	8	7	-0.058	0.9537	NS
	P-C yrs : 1st	23	9	0.168	0.8664	NS
	2nd	23	8	-1.269	0.2046	NS
	3rd	23	8	0.476	0.6343	NS
F^-	Riparian treatment	8	8	1.546	0.1222	NS
	Clearfelling year	8	7	-0.872	0.3833	NS
	P-C yrs : 1st	23	9	-0.896	0.3704	NS
	2nd	23	8	-0.116	0.9080	NS
	3rd	23	8	0.370	0.7116	NS
KN	Riparian treatment	8	8	-1.418	0.1563	NS
	Clearfelling year	8	7	1.215	0.2243	NS
	P-C yrs : 1st	23	9	-0.126	0.8999	NS
	2nd	23	8	-1.964	0.0496	*
	3rd	23	8	-0.248	0.8039	NS
TP	Riparian treatment	8	8	-1.313	0.1893	NS
	Clearfelling year	8	7	1.100	0.2716	NS
	P-C yrs : 1st	23	9	-0.084	0.9332	NS
	2nd	23	8	-1.332	0.1829	NS
	3rd	23	8	-1.377	0.1685	NS

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[1] Used only 1st and 2nd clearfelling years.

Table III Results for spateflow from Westfalia catchments D (catchment B the control). The clearfelling of Catchment D occurred from December 1982 to January 1983. Post-clearfelling years analysed, are indicated.

Variable	**Period analysed**	**Sample size**		**Z**	**Significance level for rejection of H_o = no change**	
		N1	**N2**			
TSS	1st	18	6	0.433	0.6648	NS
	2nd	18	2	-0.441	0.6592	NS
EC	1 st & 2nd	5	8	0.220	0.8262	NS
Na^+	1st & 2nd	5	8	-1.098	0.2723	NS
K^+	1st & 2nd	5	8	-0.220	0.8262	NS
Ca^{2+}	1st & 2nd	5	8	0.512	0.6084	NS
Mg^{2+}	1st & 2nd	5	8	0.368	0.7129	NS
NH_4^+-N	1st & 2nd	5	6	1.391	0.1643	NS
Si	1st & 2nd	5	8	-1.830	0.0673	NS
Cl^-	1st & 2nd	5	6	-0.366	0.7144	NS
SO_4^{2-}-S	1st & 2nd	4	8	-0.085	0.9323	NS
HCO_3^-	1st & 2nd	5	8	-1.244	0.2134	NS
NO_3^--N	1st & 2nd	5	8	0.659	0.5101	NS
PO_4^{3-}-P	1st & 2nd	5	7	0.974	0.3299	NS
F^-	sample size too small to test					
KN	sample size too small to test					
TP	sample size too small to test					

Table IV Results for **grab samples** from Bosboukloof (Lambrechtsbos B the control) catchments in Jonkershoek. There was no calibration period for NO_3^--N, PO_4^{3-}-P, NH_4^+-N, F, S_x, KN, TP. For these the post-clearfelling year (P-C yrs), 1983 - 1985, were compared with each other and if not significantly different, used as 'calibration' period for three post-fire years (P-F yrs). Clearfelling occurred from 1980 - 1982 and the fire 18 February 1986.

Variable	Period analysed		Sample size		Z	Significance level for rejection of H_0 = no change	
			N1	N2			
TSS	P-C yrs :	1st vs 2nd	21	12	-2.676	0.0075	**
		1st vs 3rd	21	14	-2.778	0.0055	**
	P-F yrs :	1st	26	10	2.490	0.0128	*
		2nd	26	12	-0.361	0.7180	NS
		3rd	26	12	0.989	0.3226	NS
EC	3 clearfelling years		66	36	2.987	0.0028	**
	P-C yrs :	1st	66	12	0.436	0.6627	NS
		2nd	66	12	1.655	0.0979	NS
		3rd	66	14	2.729	0.0064	**
	P-F yrs :	1st	66	10	3.158	0.0016	**
		2nd	66	12	4.120	0.0001	**
		3rd	66	12	2.306	0.0211	*
		4th	66	12	1.212	0.2256	NS
pH	3 clearfelling years		66	36	4.737	0.0001	**
	P-C yrs :	1st	66	12	3.677	0.0002	**
		2nd	66	12	4.522	0.0001	**
		3rd	66	14	4.818	0.0001	**
	P-F yrs :	1st	66	10	1.606	0.1083	NS
		2nd	66	12	3.691	0.0002	**
		3rd	66	12	4.854	0.0001	**
		4th	66	12	-0.727	0.4672	NS
Na^+	3 clearfelling years		64	35	0.982	0.3261	NS
	P-C yrs :	1st	64	12	1.428	0.1534	NS
		2nd	64	12	-0.387	0.6991	NS
		3rd	64	12	0.879	0.3793	NS
	P-F yrs :	1st	64	12	3.632	0.0003	**
		2nd	64	12	1.341	0.1798	NS
		3rd	64	11	0.683	0.4944	NS
K^+	3 clearfelling years		64	35	-1.403	0.1606	NS
	P-C yrs :	1st	64	12	-1.626	0.1039	NS
		2nd	64	12	-2.176	0.0295	*
		3rd	64	12	-1.570	0.1164	NS
	P-F yrs :	1st	64	12	3.773	0.0002	**
		2nd	64	12	-0.200	0.8416	NS
		3rd	64	11	0.307	0.7585	NS
		4th	66	12	-0.727	0.4672	NS

Variable	Period analysed		Sample size		Z	Significance level for rejection of H_0 = no change	
			N1	N2			
Ca^{2+}	3 clearfelling years		64	35	-4.033	0.0001	**
	P-C yrs :	1st	64	12	1.471	0.1414	NS
		2nd	64	12	-1.316	0.1882	NS
		3rd	64	12	0.136	0.8915	NS
	P-F yrs :	1st	64	12	3.050	0.0023	**
		2nd	64	12	1.078	0.2810	NS
		3rd	64	11	0.564	0.5727	NS
Mg^{2+}	3 clearfelling years		64	35	0.214	0.8307	NS
	P-C yrs :	1st	64	12	0	0.9999	NS
		2nd	64	12	-1.743	0.0813	NS
		3rd	64	11	-2.292	0.0219	*
	P-F yrs :	1st	64	12	1.407	0.1595	NS
		2nd	64	12	0.414	0.6792	NS
		3rd	64	11	-0.428	0.6690	NS
NH_4^+-N	P-C yrs :	½ 1st + 2nd vs 3rd	18	12	0.340	0.7342	NS
	P-F yrs :	1st	31	10	-0.883	0.3773	NS
		2nd	31	12	0.085	0.9327	NS
		3rd	31	11	0.015	0.9880	NS
Si	P-C yrs :	½ 1st + 2nd vs 3rd	18	12	0.995	0.3198	NS
	P-F yrs :	1st	31	10	0.015	0.9879	NS
		2nd	31	12	-0.203	0.8391	NS
		3rd	31	11	0.057	0.9544	NS
Cl^-	3 clearfelling years		64	35	0.887	0.3752	NS
	P-C yrs :	1st	64	12	-1.290	0.1969	NS
		2nd	64	12	-0.706	0.4804	NS
		3rd	64	12	0.221	0.8252	NS
	P-F yrs :	1st	64	12	1.824	0.0681	NS
		2nd	64	12	0.513	0.6079	NS
		3rd	64	11	1.521	0.1283	NS
SO_4^{2-}-S	3 clearfelling years		29	34	-1.738	0.0823	NS
	P-C yrs :	1st	29	12	-0.293	0.7697	NS
		2nd	29	12	-0.077	0.9386	NS
		3rd	29	12	0.046	0.9635	NS
	P-F yrs :	1st	29	12	0.878	0.3800	NS
		2nd	29	12	2.341	0.0192	*
		3rd	29	11	-2.208	0.0273	*
		4th	29	11	1.196	0.2316	NS

Variable	Period analysed		Sample size		Z	Significance level for rejection of H_o = no change	
			N1	N2			
HCO_3^-	3 clearfelling years		62	35	-3.071	0.0021	**
	P-C yrs :	1st	62	12	0.301	0.7635	NS
		2nd	62	12	1.285	0.1988	NS
		3rd	62	12	3.752	0.0002	**
	P-F yrs :	1st	62	12	-1.027	0.3042	NS
		2nd	62	12	1.468	0.1421	NS
		3rd	62	11	2.431	0.0151	*
		4th	62	11	1.459	0.1446	NS
NO_3^--N	P-C yrs :	½ 1st + 2nd vs 3rd	18	12	-2.758	0.0058	**
	P-F yrs :	1st	13[2]	10	3.695	0.0002	**
		2nd	13	12	2.916	0.0036	**
		3rd	13	11	2.774	0.0055	**
		4th	13	11	1.136	0.2560	NS
PO_4^{3-}-P	P-C yrs :	½ 1st + 2nd vs 3rd	18	12	1.692	0.0907	NS
	P-F yrs :	1st	32	10	3.175	0.0015	**
		2nd	32	12	0.949	0.3428	NS
		3rd	32	11	2.055	0.0399	*
		4th	31	11	0.952	0.3411	NS
F^-	P-C yrs :	½ 1st + 2nd vs 3rd	18	12	-1.181	0.2374	NS
	P-F yrs :	1st	31	10	0.866	0.3866	NS
		2nd	31	12	-1.816	0.0694	NS
		3rd	31	11	0.494	0.6216	NS
KN	P-C yrs :	½ 1st + 2nd vs 3rd	18	12	-0.127	0.8989	NS
	P-F yrs :	1st	31	8	2.557	0.0106	*
		2nd	31	7	0.113	0.9100	NS
		3rd	31	10	1.867	0.0619	NS
TP	P-C yrs :	½ 1st + 2nd vs 3rd	18	12	0.530	0.5963	NS
	P-F yrs :	1st	31	8	2.838	0.0043	**
		2nd	31	7	-0.942	0.3462	NS
		3rd	31	10	2.141	0.0322	*
		4th	31	11	0.057	0.9544	NS

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[2] Use only year before fire for 'calibration' period, significantly lowered concentration.

Table V Results for grab samples from Biesievlei (Lambrechtsbos B the control) in Jonkershoek. The riparian treatment year (1984) was tested seperately, as was the clearfelling year (1985/6). There was only a short calibration period for NO_3^--N, PO_4^{3-}-P, NH_4^+-N, F, S_i, KN, TP. Where the riparian treatment did not have a sigificant effect for these, it was added to the pre-treatment period giving a longer 'calibration' period to test the effect of the clearfelling period on three post-clearfelling years (P-C yrs).

Variable	Period analysed		Sample size N1	Sample size N2	Z	Significance level for rejection of H_o no change	
TSS	Riparian treatment		21	15	3.145	0.0017	**
	Clearfelling year		21	11	1.508	0.1316	NS
	P-C yrs :	1st	21	9	1.991	0.0465	*
		2nd	21	12	2.040	0.0414	*
		3rd	21	12	2.938	0.0033	**
EC	Riparian treatment		101	15	-0.074	0.9410	NS
	Clearfelling year		101	11	2.327	0.0200	*
	P-C yrs :	1st	101	9	3.501	0.0005	**
		2nd	101	12	0.927	0.3538	NS
		3rd	101	12	-0.387	0.6989	NS
pH	Riparian treatment		101	15	-0.082	0.9344	NS
	Clearfelling year		101	11	0.235	0.8145	NS
	P-C yrs :	1st	101	9	-1.341	0.1798	NS
		2nd	101	12	-1.086	0.2776	NS
		3rd	101	12	-1.580	0.1142	NS
NA^+	Riparian treatment		94	15	-2.177	0.0295	*
	Clearfelling year		94	11	-2.056	0.0398	*
	P-C yrs :	1st	94	9	0.047	0.9627	NS
		2nd	94	12	-0.439	0.6608	NS
		3rd	94	11	-1.476	0.1401	NS
K^+	Riparian treatment		94	15	-2.268	0.0234	*
	Clearfelling year		94	11	-0.158	0.8748	NS
	P-C yrs :	1st	94	9	0.663	0.5075	NS
		2nd	94	12	-1.442	0.1493	NS
		3rd	94	11	-0.037	0.9707	NS
Ca^{2+}	Riparian treatment		94	15	-1.942	0.0521	NS
	Clearfelling year		94	11	-0.204	0.8381	NS
	P-C yrs :	1st	94	9	-0.082	0.9348	NS
		2nd	94	12	-1.049	0.2943	NS
		3rd	94	11	-4.117	0.0001	**
Mg^{2+}	Riparian treatment		94	15	-0.976	0.3290	NS
	Clearfelling year		94	11	-0.953	0.3403	NS
	P-C yrs :	1st	94	9	0.316	0.7519	NS
		2nd	94	12	-0.757	0.4492	NS
		3rd	94	11	-1.706	0.0879	NS
NH_4^+-N	Riparian treatment		7	15	-0.395	0.6925	NS
	Clearfelling year		22	11	-0.658	0.5108	NS
	P-C yrs :	1st	22	9	-0.959	0.3376	NS
		2nd	22	12	0.641	0.5216	NS
		3rd	22	11	0.142	0.8871	NS

Variable	Period analysed		Sample size		Z	Significance level for rejection of H_0 no change	
			N1	N2			
Si	Riparian treatment		7	15	1.480	0.1388	NS
	Clearfelling year		19	11	-1.248	0.2120	NS
	P-C yrs :	1st	19	9	-2.066	0.0388	*
		2nd	19	12	-3.143	0.0017	**
		3rd	19	11	-2.883	0.0039	**
Cl^-	Riparian treatment		94	15	-1.817	0.0692	NS
	Clearfelling year		94	11	-0.774	0.0760	NS
	P-C yrs :	1st	94	9	-2.226	0.0260	*
		2nd	94	12	-1.371	0.1702	NS
		3rd	94	11	-1.068	0.2857	NS
SO_4^{2-}	Riparian treatment		59	15	-1.203	0.2291	NS
	Clearfelling year		59	11	-0.066	0.9477	NS
	P-C yrs :	1st	59	9	-2.162	0.0306	*
		2nd	59	12	-0.965	0.3344	NS
		3rd	59	11	-2.126	0.0335	*
HCO_3^-	Riparian treatment		91	15	-0.286	0.7752	NS
	Clearfelling year		91	11	-2.067	0.0387	*
	P-C yrs :	1st	91	9	-2.542	0.0110	*
		2nd	91	12	-0.005	0.9959	NS
		3rd	91	11	-1.743	0.0814	NS
NO_3^--N	Riparian treatment		7	15	0.458	0.6466	NS
	Clearfelling year		22	11	-0.535	0.5927	NS
	P-C yrs :	1st	22	9	0.893	0.3721	NS
		2nd	22	12	1.244	0.2135	NS
		3rd	22	11	-0.344	0.7309	NS
PO_4^{3-}-P	Riparian treatment		7	15	2.490	0.0128	*
	Clearfelling year		7	8	2.213	0.0269	*
	P-C yrs :	1st	7	12	2.084	0.0371	*
		2nd	7	12	0.722	0.4702	NS
		3rd	7	11	2.289	0.0221	*
F^-	Riparian treatment		7	15	2.054	0.0400	*
	Clearfelling year		7	8	-0.136	0.8918	NS
	P-C yrs :	1st	7	12	0.220	0.8257	NS
		2nd	7	12	-0.135	0.8923	NS
		3rd	7	11	0.048	0.9621	NS
KN	Riparian treatment		7	15	-0.176	0.8601	NS
	Clearfelling year		22	11	1.050	0.2936	NS
	P-C yrs :	1st	22	7	0.535	0.5925	NS
		2nd	22	7	0.026	0.9797	NS
		3rd	22	10	1.565	0.1175	NS
TP	Riparian treatment		7	15	-0.987	0.3237	NS
	Clearfelling year		22	11	-1.872	0.0613	NS
	P-C yrs :	1st	22	7	-1.452	0.1464	NS
		2nd	22	7	-1.198	0.2310	NS
		3rd	22	10	0.102	0.9190	NS

Table VI Results for water quality variable concentrations in grab samples from Westfalia catchments D (*catchment B the control*). The clearfelling of catchment D occurred from December 1982 to January 1983. Post-clearfelling years analysed, are indicated.

Variable	Period analysed	Sample size		Z	Significance level for rejection of H_o no change	
		N1	N2			
TSS	1st	12	12	1.010	0.3123	NS
	2nd	12	12	-3.320	0.0007	**
	3rd	12	10	1.220	0.2225	NS
EC	1st	14	12	1.157	0.2472	NS
	2nd	14	12	1.569	0.1167	NS
	3rd	14	12	1.595	0.1108	NS
Na^+	1st	14	12	1.620	0.1052	NS
	2nd	14	7	-1.119	0.9109	NS
	3rd	14	11	-0.137	0.8911	NS
K^+	1st	14	12	3.163	0.0016	**
	2nd	14	8	2.423	0.0154	*
	3rd	14	11	2.765	0.0057	**
	4th	14	10	3.894	0.0001	**
	5th	14	8	2.696	0.0070	**
	6th	14	9	3.685	0.0002	**
	7th	14	9	2.677	0.0074	**
Ca^{2+}	1st	14	12	0.797	0.4253	NS
	2nd	14	7	0.336	0.7371	NS
	3rd	14	11	-0.356	0.7219	NS
Mg^{2+}	1st	14	12	0.232	0.8168	NS
	2nd	14	7	0.037	0.9702	NS
	3rd	14	11	1.287	0.1980	NS
NH_4^+-N	1st	14	12	-1.003	0.3159	NS
	2nd	14	12	-0.849	0.3960	NS
	3rd	14	12	-1.829	0.0673	NS
Si	1st	14	12	2.083	0.0372	*
	2nd	14	12	2.135	0.0328	*
	3rd	14	12	0.797	0.4253	NS
Cl^-	1st	14	12	1.980	0.0477	*
	2nd	14	7	0.560	0.5758	NS
	3rd	14	11	1.122	0.2617	NS
SO_4^{2-}	1st	10	12	-1.352	0.1765	NS
	2nd	10	12	0.165	0.8689	NS
	3rd	10	11	-0.813	0.4164	NS
HCO_3^-	1st	12	12	1.415	0.1512	NS
	2nd	12	8	-1.660	0.0970	NS
	3rd	12	11	-0.646	0.5181	NS
NO_3^--N	1st	14	12	2.083	0.0372	*
	2nd	14	12	2.212	0.0269	*
	3rd	14	12	2.803	0.0051	**
	4th	14	10	3.720	0.0002	**
	5th	14	8	3.414	0.0006	**
	6th	14	9	3.938	0.0001	**
	7th	14	9	3.685	0.0002	**

Variable	Period analysed	Sample size		Z	Significance level for rejection of H_o no change	
		N1	N2			
PO_4^{3-}-P	1st	14	12	2.701	0.0069	**
	2nd	14	12	0.701	0.4832	NS
	3rd	14	12	-1.566	0.1174	NS
F^-	1st	13	12	0.571	0.5679	NS
	2nd	13	12	0.683	0.4949	NS
	3rd	13	12	0.935	0.3498	NS
KN	1st	4	12	-1.516	0.1296	NS
	2nd	4	12	-1.517	0.1293	NS
	3rd	4	12	0.061	0.9517	NS
TP	1st	4	12	-0.910	0.3631	NS
	2nd	4	12	-1.758	0.0787	NS
	3rd	4	12	-0.061	0.9517	NS

APPENDIX C: Results of trend tests on Witklip data

Results of the Kendall's Tau test for trend in the concentration of all variables analysed in grab samples from Witklip, catchment 2. The P-values represent the probability of Z-values for the test static. The slope statistic is Sen's nonparametric estimate of slope: (a) presents the standard Kendall test and (b) the seasonal Kendall's Tau test.

Variable		Tau Statistic	P-value without serial correction	P-value with serial correction	Slope statistic $(\text{mg l}^{-1}\text{a}^{-1})$
TSS[1]	(a)	0.020	0.777		6.56×10^{-3}
	(b)	0.020	0.850	0.892	0.0665
EC[2]	(a)	- 0.140	0.101		- 0.0549
	(b)	- 0.241	0.034	0.193	- 0.657
pH	(a)	- 0.038	0.563		$- 8.61 \times 10^{-4}$
	(b)	- 0.041	0.755	0.875	- 0.01
Na^+	(a)	- 0.164	0.032		$- 3.42 \times 10^{-3}$
	(b)	- 0.199	0.040	0.247	- 0.1
K^+	(a)	- 0.237	2.42×10^{-3}		3.91×10^{-3}
	(b)	- 0.341	5.76×10^{-4}	0.053	- 0.048
Ca^{2+}	(a)	- 0.326	2.26×10^{-5}		$- 8.33 \times 10^{-3}$
	(b)	- 0.370	1.20×10^{-4}	0.014	- 0.125
Mg^{2+}	(a)	0.093	0.188		0
	(b)	0.057	0.555	0.646	0
NH_4^+-N	(a)	- 0.060	0.447		$- 3.82 \times 10^{-5}$
	(b)	- 0.090	0.384	0.672	$- 8 \times 10^{-4}$

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[1] Total suspended sediment

[2] Electrical conductivity

Continued...

Variable		Tau Statistic	P-value without serial correction	P-value with serial correction	Slope statistic (mg $l^{-1} a^{-1}$)
Cl^-	(a)	0.046	0.555		0
	(b)	0.104	0.304	0.412	0.0625
SO_4^{2-}	(a)	- 0.346	9.54×10^{-6}		- 0.05
	(b)	- 0.403	4.82×10^{-6}	0.040	- 0.6996
HCO_3^-	(a)	- 0.020	0.805		0
	(b)	0.028	0.809	0.810	0
NO_3^--N	(a)	- 0.617	0		$- 7.28 \times 10^{-3}$
	(b)	- 0.768	0	4.33×10^{-3}	- 0.0918
PO_4^{3-}-P	(a)	- 0.136	0.071		0
	(b)	- 0.180	0.063	0.424	1.67×10^{-4}
F^-	(a)	- 0.051	0.504		0
	(b)	- 0.052	0.618	0.670	0
KN	(a)	0.162	0.039		1.11×10^{-3}
	(b)	0.237	0.018	0.101	0.0124
TP	(a)	0.166	0.034		7.69×10^{-5}
	(b)	0.228	0.023	0.173	8.33×10^{-4}
Si	(a)	- 0.387	7.90×10^{-7}		- 6.014
	(b)	- 0.441	9.48×10^{-6}	0.025	- 0.147
rainfall	(b)	- 0.068	0.510	0.449	- 1.5

Result of correlation analyses to determine the presence of serial-correlation in variable concentrations that showed a significant trend at Witklip catchment 2 (see previous Table). The upper and lower limits are determined at the 0.05 significance level. Significant correlation is present when the correlation statistic is greater than the upper limit.

Variable	Lagged adjusted	Correlation	Upper Limit	Lower Limit
Conductivity	1	0.517	0.408	- 0.408
	2	0.170	0.443	- 0.443
Na^+	1	0.471	0.354	- 0.354
	2	0.345	0.379	- 0.379
K^+	1	0.254	0.354	- 0.354
	2	0.087	0.361	- 0.361
Ca^{2+}	1	- 0.074	0.354	- 0.354
	2	- 0.119	0.354	- 0.354
SO_4^{2-}	1	0.367	0.354	- 0.354
	2	0.312	0.369	- 0.369
NO_3^--N	1	0.586	0.354	- 0.354
	2	0.351	0.392	- 0.392
KN	1	0.212	0.354	- 0.354
	2	0.032	0.359	- 0.359
TP	1	- 0.005	0.354	- 0.354
	2	0.027	0.354	- 0.354
Si	1	0.190	0.354	- 0.354
	2	0.030	0.358	- 0.358

APPENDIX D: *Results of correlation analyses*

Correlation analyses were performed on all variables from all of the catchments used in this study. Pearsons product-moment correlation coefficients are given for each variable. EC = electrical conductivity. TSS = total suspended sediment.

Table I Correlation coefficients between water quality variables from Bosboukloof

EC	pH	Na^+	K^+	Ca^{2+}	Mg^{2+}	NH_4^+-N	Cl^-	SO_4^{2-}-S	HCO_3^-	NO_3^--N	PO_4^{3-}-P	F^-	KN	TP	SI	
0.138	0.204	0.234	0.024	0.208	0.231	0.049	0.099	-0.022	0.114	0.087	-0.001	-0.037	0.397	0.147	0.032	TSS
	-0.206	0.219	0.082	0.073	0.119	-0.076	0.348	0.237	0.117	-0.127	-0.062	0.110	0.024	-0.006	0.019	EC
		-0.164	-0.134	0.000	-0.029	0.281	-0.353	-0.107	-0.055	0.105	-0.034	0.129	0.119	0.001	-0.011	*pH*
			0.143	0.164	0.051	0.122	0.303	0.131	-0.146	-0.001	-0.018	-0.049	0.225	0.057	0.027	Na^+
				0.212	0.171	0.265	0.301	-0.108	0.026	0.032	0.025	0.054	0.130	0.060	0.091	K^+
					0.525	0.275	0.202	-0.052	0.246	0.091	-0.013	0.053	0.215	0.057	0.021	Ca^{2+}
						0.298	0.143	0.200	0.099	0.153	-0.001	0.199	0.289	0.118	-0.132	Mg^{2+}
							0.161	-0.105	-0.115	0.344	0.430	0.023	0.258	0.418	-0.121	NH_4^+-N
								0.111	-0.122	-0.008	0.102	-0.077	0.291	0.240	0.101	Cl^-
									-0.257	-0.199	0.015	-0.010	-0.164	0.026	0.005	SO_4^{2-}-S
										-0.073	-0.040	0.031	-0.113	-0.056	-0.048	HCO_3^-
											0.058	0.108	0.191	0.032	-0.308	NO_3^--N
												-0.051	0.087	0.935	-0.019	PO_4^{3-}-P
													0.045	-0.081	-0.066	F^-
														0.314	0.030	KN
															0.043	TP

Table II Correlation coefficients between water quality variables from Bieslevlei

EC	pH	Na^+	K^+	Ca^{2+}	Mg^{2+}	NH_4^+-N	Cl^-	SO_4^{2-}-S	HCO_3^-	NO_3^--N	PO_4^{3-}-P	F^-	KN	TP	Si	
-0.114	0.080	0.048	-0.056	-0.020	-0.146	-0.053	0.079	-0.019	0.023	-0.182	0.072	-0.052	0.168	0.313	0.273	TSS
	-0.298	0.149	0.022	0.061	0.120	0.045	0.290	0.295	-0.093	0.126	-0.228	-0.423	0.094	0.039	0.123	EC
		-0.235	-0.075	0.002	-0.052	0.354	-0.439	-0.143	0.029	0.000	0.093	0.287	0.025	-0.016	-0.147	pH
			0.042	0.189	0.210	0.155	0.471	0.202	-0.062	0.341	-0.155	-0.226	0.027	-0.036	0.106	Na^+
				-0.012	0.016	0.191	0.246	-0.082	-0.136	0.034	-0.065	-0.038	0.066	0.014	-0.012	K^+
					0.656	0.162	0.069	0.033	0.149	-0.005	0.104	0.115	0.080	0.071	0.095	Ca^{2+}
						0.368	0.164	0.040	0.153	0.276	-0.120	-0.019	0.038	-0.051	-0.043	Mg^{2+}
							0.073	-0.121	-0.168	0.380	0.027	0.054	0.128	-0.004	-0.139	NH_4^+-N
								0.064	-0.323	0.141	-0.209	-0.510	0.050	0.053	0.214	Cl^-
									-0.148	-0.020	-0.136	-0.130	-0.113	0.100	0.209	SO_4^{2-}-S
										-0.157	0.144	0.086	-0.121	0.006	0.169	HCO_3^-
											-0.233	-0.337	0.021	-0.357	-0.539	NO_3^--N
												0.381	0.035	0.306	0.128	PO_4^{3-}-P
													0.040	0.131	-0.045	F^-
														0.672	0.033	KN
															0.402	TP

Table III Correlation coefficients between water quality variables from Lambrechtsbos B

EC	pH	Na^+	K^+	Ca^{2+}	Mg^{2+}	NH_4^+-N	Cl^-	SO_4^{2-}-S	HCO_3^-	NO_3^--N	PO_4^{3-}-P	F^-	KN	TP	Si	
-0.063	-0.053	0.055	-0.029	-0.012	-0.004	-0.015	0.024	-0.019	0.063	0.100	0.027	0.023	0.063	0.215	0.201	TSS
	-0.162	0.321	0.101	-0.027	0.010	-0.158	0.207	0.189	0.129	0.065	-0.171	-0.134	0.058	-0.167	-0.188	EC
		-0.227	-0.176	-0.032	0.015	0.298	-0.385	-0.019	0.218	0.046	0.007	0.113	0.019	0.200	0.179	pH
			-0.327	0.032	0.143	-0.088	0.455	0.141	-0.180	0.400	0.001	-0.248	-0.023	-0.189	-0.218	Na^+
				0.042	0.039	0.133	0.001	0.066	-0.006	-0.019	0.019	0.050	0.297	0.157	0.273	K^+
					0.523	0.029	0.074	-0.015	0.202	0.171	0.055	0.095	0.022	0.015	0.092	Ca^{2+}
						0.396	0.086	-0.065	0.119	0.414	0.338	0.195	0.197	0.069	0.046	Mg^{2+}
							0.002	-0.154	0.066	0.046	0.217	-0.021	0.104	0.019	-0.168	NH_4^+-N
								0.184	-0.239	0.268	-0.103	-0.244	-0.027	-0.203	-0.351	Cl^-
									-0.254	-0.144	-0.126	-0.030	-0.208	0.047	0.024	SO_4^{2-}-S
										0.003	0.189	0.333	0.151	0.240	0.391	HCO_3^-
											0.373	0.025	0.051	-0.036	-0.158	NO_3^--N
												0.217	0.007	0.253	0.146	PO_4^{3-}-P
													0.377	0.303	0.409	F^-
														0.458	0.215	KN
															0.427	TP

Table IV Correlation coefficients between water quality variables from Westfalia B

EC	pH	Na^+	K^+	Ca^{2+}	Mg^{2+}	NH_4^+-N	Cl^-	SO_4^{2-}-S	HCO_3^-	NO_3^--N	PO_4^{3-}-P	F^-	KN	TP	Si	
-0.017	0.024	-0.106	-0.018	0.114	0.022	0.037	0.036	0.007	-0.141	0.165	0.024	-0.010	0.154	-0.016	-.030	TSS
	-0.052	0.105	0.056	0.065	0.396	-0.007	0.417	0.107	0.124	-0.093	0.234	0.176	0.371	0.278	-0.193	EC
		-0.073	-0.001	0.279	0.031	0.202	-0.188	0.190	0.274	0.181	-0.017	0.208	-0.169	0.022	0.226	pH
			0.345	0.042	0.153	-0.143	0.052	0.309	0.137	0.084	0.190	0.225	-0.219	0.116	0.014	Na^+
				0.112	0.050	0.081	0.301	-0.049	0.139	0.283	0.308	-0.039	-0.021	0.081	-0.059	K^+
					0.438	-0.059	0.304	0.006	0.460	0.129	0.089	0.230	0.097	0.211	-0.041	Ca^{2+}
						-0.028	0.425	0.320	0.243	-0.072	0.063	0.406	0.127	0.138	0.127	Mg^{2+}
							-0.049	0.066	0.035	-0.026	0.235	0.010	0.141	0.068	-0.260	NH_4^+-N
								-0.090	-0.020	0.010	0.203	0.127	0.052	0.255	-0.281	Cl^-
									0.131	0.107	-0.002	0.039	-0.339	0.037	0.345	SO_4^{2-}-S
										0.290	0.186	0.144	0.152	0.267	0.083	HCO_3^-
											0.335	-0.172	-0.113	0.357	-0.041	NO_3^--N
												-0.003	0.235	0.927	-0.099	PO_4^{3-}-P
													-0.002	0.041	0.021	F^-
														0.275	-0.327	KN
															0.048	TP

Table V Correlation coefficients between water quality variables from Westfalia D

EC	pH	Na^+	K^+	Ca^{2+}	Mg^{2+}	NH_4^+-N	Cl^-	SO_4^{2-}-S	HCO_3^-	NO_3^--N	PO_4^{3-}-P	F^-	KN	TP	Si	
0.017	-0.216	-0.074	-0.088	0.082	0.122	-0.113	0.085	-0.001	-0.211	0.0191	-0.098	-0.127	0.149	0.173	0.045	TSS
	0.007	0.201	0.142	0.127	0.000	-0.014	0.169	0.208	0.008	-0.045	-0.011	0.106	0.042	0.088	0.124	EC
		0.002	0.109	0.049	-0.070	0.156	-0.344	0.182	0.306	-0.035	0.106	0.208	-0.181	-0.152	-0.102	pH
			0.584	0.277	0.390	0.316	0.423	0.262	0.264	-0.070	0.060	0.127	0.119	0.132	0.272	Na^+
				0.332	0.414	0.300	0.399	0.305	0.237	0.270	0.063	0.042	0.178	0.172	0.251	K^+
					0.391	0.212	0.439	0.223	0.358	0.148	0.064	-0.090	0.068	0.087	0.049	Ca^{2+}
						0.264	0.576	0.129	0.130	0.203	-0.229	0.153	0.327	0.322	0.353	Mg^{2+}
							0.220	0.056	0.279	-0.109	0.362	0.011	0.006	-0.035	-0.076	NH_4^+-N
								-0.172	0.016	0.134	-0.085	0.025	0.408	0.381	0.154	Cl^-
									0.281	-0.107	-0.074	0.186	-0.330	-0.328	0.228	SO_4^{2-}-S
										-0.194	0.144	0.059	-0.026	0.059	0.101	HCO_3^-
											-0.105	0.061	0.156	0.068	-0.163	NO_3^--N
												-0.023	0.124	0.147	-0.327	PO_4^{3-}-P
													0.023	-0.055	0.035	F^-
														0.699	0.007	KN
															0.266	TP

Table VI Correlation coefficients between water quality variables from Witklip 2

EC	pH	Na^+	K^+	Ca^{2+}	Mg^{2+}	NH_4^+-N	Cl^-	SO_4^{2-}-S	HCO_3^-	NO_3^--N	PO_4^{3-}-P	F	KN	TP	Si	
0.219	-0.093	-0.046	0.124	0.013	0.315	0.132	0.157	-0.148	0.280	-0.057	-0.039	0.003	0.068	0.079	-0.166	TSS
	-0.158	0.424	0.392	0.533	0.568	0.445	0.091	0.289	0.252	0.126	0.382	-0.124	-0.114	0.229	0.239	EC
		0.021	-0.228	0.026	0.019	0.169	-0.336	0.203	-0.003	-0.431	0.033	-0.328	0.098	0.100	-0.047	pH
			0.338	0.151	0.260	0.142	0.532	0.426	0.179	0.163	0.021	0.115	0.043	0.010	0.220	Na^+
				0.150	0.124	-0.070	0.253	0.204	0.0776	0.701	-0.107	0.111	0.180	-0.071	0.051	K^+
					0.722	0.254	-0.172	-0.091	-0.087	0.117	0.812	-0.100	-0.038	0.574	0.080	Ca^{2+}
						0.182	0.086	-0.080	0.054	0.073	0.726	0.004	-0.028	0.555	0.027	Mg^{2+}
							0.037	-0.275	0.036	-0.177	0.166	-0.168	0.241	0.092	0.024	NH_4^+-N
								0.098	0.158	0.008	-0.206	0.162	0.309	-0.059	0.014	Cl^-
									0.178	0.198	-0.197	0.029	-0.130	-0.234	0.394	SO_4^{2-}-S
										0.099	-0.267	0.032	-0.085	-0.218	-0.007	HCO_3^-
											-0.118	0.114	-0.080	-0.124	0.065	NO_3^--N
												0.067	-0.083	0.806	-0.032	PO_4^{3-}-P
													0.024	-0.075	0.065	F
														-0.044	0.142	KN
															-0.473	TP