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Impact of the 1983 Wildfires on River Water Quality in East Gippsland, Victoria

Bruce C. Chessman

Latrobe Valley Water and Sewerage Board, P.O. Box 348, Traralgon, Vic. 3844.

Abstract

Eleven stream stations within the basins of the Bemm, Cann, Thurra, Wingan and Genoa Rivers were sampled during a 3-month interval following a prolonged drought and intense and extensive forest fires. Emphasis was placed on flows resulting from three major storms that occurred during this period. Water-quality impacts of the fires were intermingled with those of the preceding drought, and flow-related comparisons with pre-drought data showed appreciable increases in colour, turbidity, suspended solids, potassium and nitrogen levels in the Bemm River, which was only marginally affected by the fires. In the Cann and Genoa Rivers, with much larger proportions of catchment burnt, electrical conductivity and phosphorus concentrations also rose substantially. Marked depletion of dissolved oxygen (to <6 mg l^{-1}) was unique to streams with burnt catchments, but resulted from stagnant conditions at the end of the drought as well as from changes occurring at the time of the first post-fire storm. The fires had little obvious effect on temperature and pH regimes.

Peak turbidities and concentrations of suspended solids and phosphorus were much greater in the Cann and Genoa river systems than elsewhere. Maximum values for these indicators were 130 NTU, 2300 mg l^{-1} and over 0·8 mg l^{-1}, respectively. In the Thurra and Wingan basins, which were also burnt, stream suspended-solids levels were lower (<200 mg l^{-1}), but solutes sometimes reached very high maxima (indicated by peak electrical conductivities of up to 110 mS m^{-1}). Variations in catchment topography and soils and the relative importance of surface and subsurface flow probably account for these differences. The first post-fire storm produced the highest measured levels of many indicators in most streams, although the greatest flows were associated with the third storm. Nitrite and ammonia were notable exceptions to this generalization.

Estimates of catchment exports indicated high sediment yields and moderate to high phosphorus yields from the Cann and Genoa catchments, by comparison with other Australian data.

Introduction

In common with many other parts of south-eastern Australia, the far East Gippsland region of Victoria was devastated by intense and extensive forest fires during the early months of 1983 (Rawson *et al.* 1983). These fires followed a period of severe and prolonged drought, rainfall in the region for the 6 months to 31 January 1983 being only about half of the long-term average. Over 253 000 ha were burnt, including large portions of the catchments of the Cann and Genoa Rivers and other smaller streams. In the 3 months following the fires, the drought broke and heavy and sometimes intense rainstorms were experienced throughout the area. This study was undertaken to evaluate the impact of runoff from the burnt forests on river water quality during this period.

Effects of fire on stream systems have been reviewed by Tiedemann *et al.* (1979) using mainly North American examples. Principal impacts are increased baseflow, stormflow and total discharge, greater suspended sediment and turbidity levels, and rises in stream temperatures

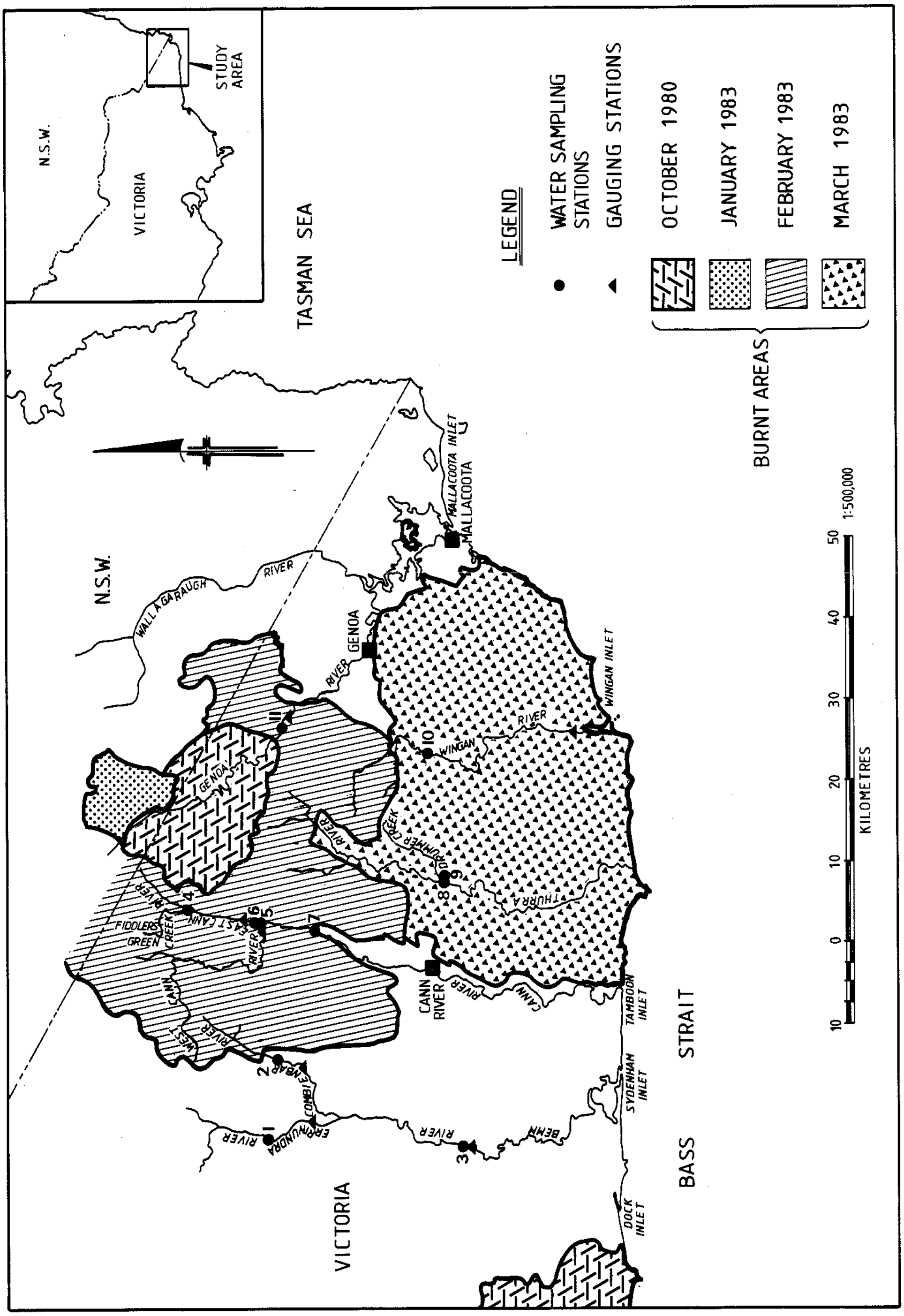


Fig. 1. Map of the study area, showing burnt areas, water-sampling stations and stream-gauging stations.

and concentrations of chemical nutrients. In Australia, many authors have reported augmented streamflow following intense fire (McArthur 1964; McArthur and Cheney 1965; Craig 1969; Brown 1972; Langford 1976; Mackay *et al.* 1980; Burgess *et al.* 1981; Mackay and Cornish 1982; O'Loughlin *et al.* 1982) and others have described runoff and erosion on burnt areas (Good 1973; Blong *et al.* 1982; Leitch *et al.* 1983; Atkinson 1984). In addition, several studies have evaluated fire-induced changes in stream water quality. Low-intensity prescribed burns have little or no impact (Midgley 1973; Mackay and Perrens 1979; Talsma and Hallam 1982), whereas wildfires produce considerable increases in suspended sediments (Brown 1972; Burgess *et al.* 1980, 1981), total solutes (Burgess *et al.* 1980, 1981) and major ions and nutrients (Midgley 1973; Anon. 1975; Smalls 1978; Condina *et al.* 1984). In other instances, however, little or no rise in turbidity or suspended sediment has been recorded following wildfire (Boughton 1970; Midgley 1973; Anon. 1975; Condina *et al.* 1984). These differences seem attributable to variations in factors such as soil type, weather following the fire, and rate of recovery of vegetation.

Study Area

Samples were taken within the basins of Bemm, Cann, Thurra, Wingan and Genoa Rivers (Fig. 1). These streams rise on the southern slopes of the Great Dividing Range between the Errinundra Plateau in Victoria and the southern tablelands of New South Wales. The Bemm, Cann and Genoa Rivers have extensive catchments extending to elevations over 1000 m, and the Thurra and Wingan are smaller rivers having their sources at lower altitudes. Rainfall in the catchments is plentiful, ranging from over 1400 mm annually in the headwaters of the Bemm River to a little below 1000 mm in parts of the Cann and Genoa river basins (Anon. 1974). It is also evenly distributed through the year, few locations having an average below 50 mm in any month. Heavy falls (>76 mm) within 24 h are more common than elsewhere in Victoria and may produce rapid increases in river flow (Linforth 1969).

The upper catchments of all of the rivers consist primarily of dissected ridges punctuated by small intermontane basins. Upper Devonian granites and granodiorites and Ordovician sandstones and mudstones dominate the surface geology (Anon. 1974; Mallacoota 1 : 250 000 geological map, first Edn, 1976); both igneous and sedimentary rocks are widespread in the catchments of each of the rivers. Soils are mainly permeable, red friable earths (gradational) in the upper Bemm and Thurra basins, and less permeable, hard-setting loamy soils with clayey subsoils (duplex) in the upper Cann, Wingan and Genoa basins (Northcote 1962). Vegetation is varied, ranging from rainforest to heath, but is mainly wet sclerophyll forest in the upper Bemm catchment, dry sclerophyll forest in the upper Cann and Genoa catchments, and lowland sclerophyll forest in the Thurra and Wingan basins (Forbes *et al.* 1982; Anon. 1985).

Fire and Storm Sequence

Three fires occurred in the region during 1983 (Fig. 1). The first, in January, burnt a relatively small area of the Genoa River headwaters north of the New South Wales border. The second, discovered on 31 January, burnt 127 000 ha extending from the Cann River district to near Genoa and northward into New South Wales. In the upper Cann and Genoa river catchments, it encountered an area previously burnt in October 1980 and, in this region, burnt only sporadically. This fire was not controlled until mid February. The third fire ignited on 4 March. It burnt an area of 126 000 ha extending from Cann River to Genoa and southward to the coast, and was not controlled until 17 March.

Rainfall patterns during the first half of 1983 are exemplified in Fig. 2 by daily totals recorded at Combienbar (upper Bemm River catchment) in the west and Wroxham (middle Genoa River catchment) in the east. The first major storm after the fire, 20–22 March, produced intense falls throughout the area; the second, in April, yielded less intense but more prolonged rainfall, which was heavier in the west than in the east. The third large storm, in early May,

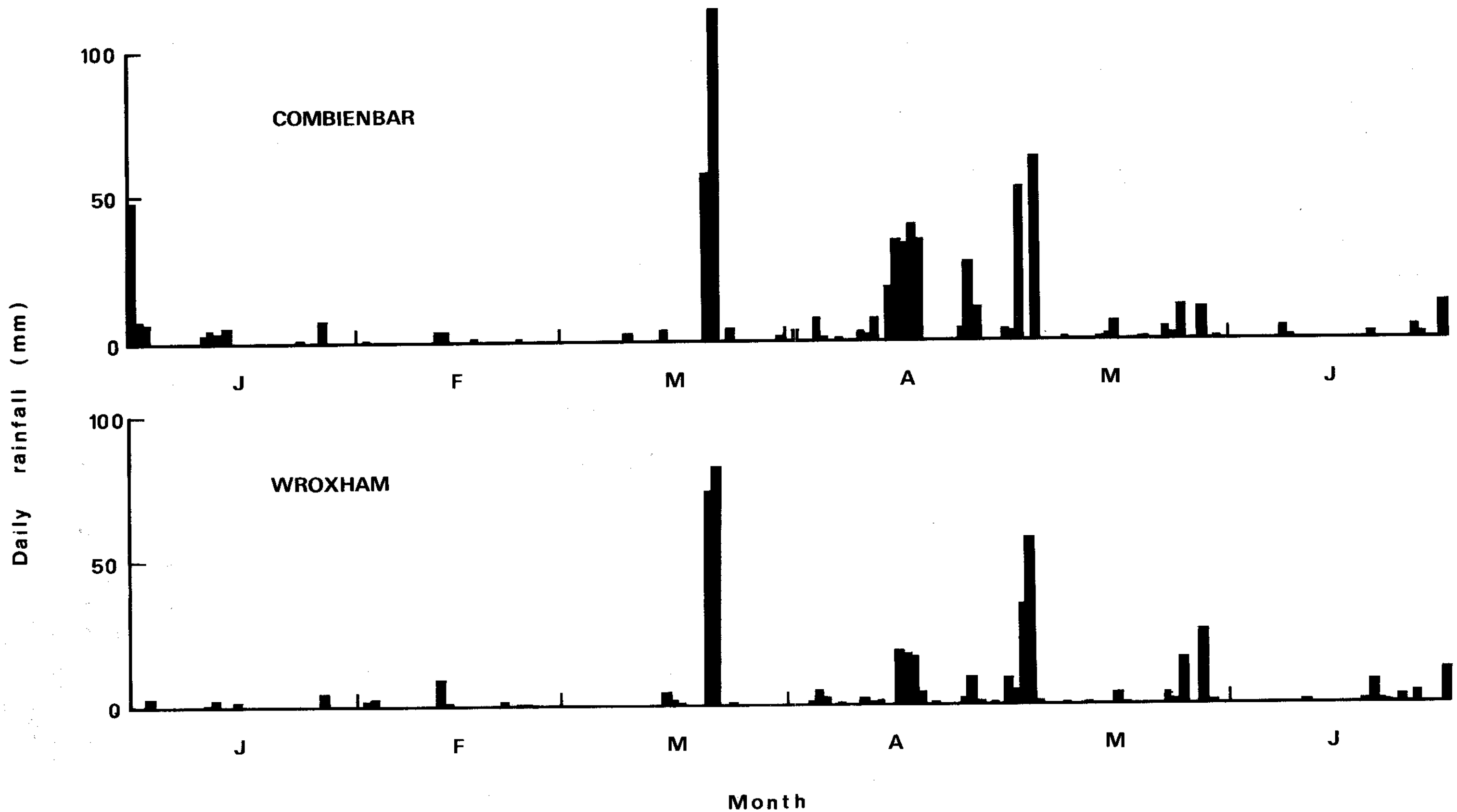


Fig. 2. Daily rainfall totals at Combienbar and Wroxham for the period January–June 1983. (Data from the Commonwealth Bureau of Meteorology.)

resulted in comparable falls in both areas. Streamflows (Fig. 3) generally declined from January to February and remained low until the March storm when they sharply rose in all river systems. The May storm produced the highest discharge peaks in all streams; the effect of the April storm was less pronounced in the east than in the west, reflecting the difference in rainfall.

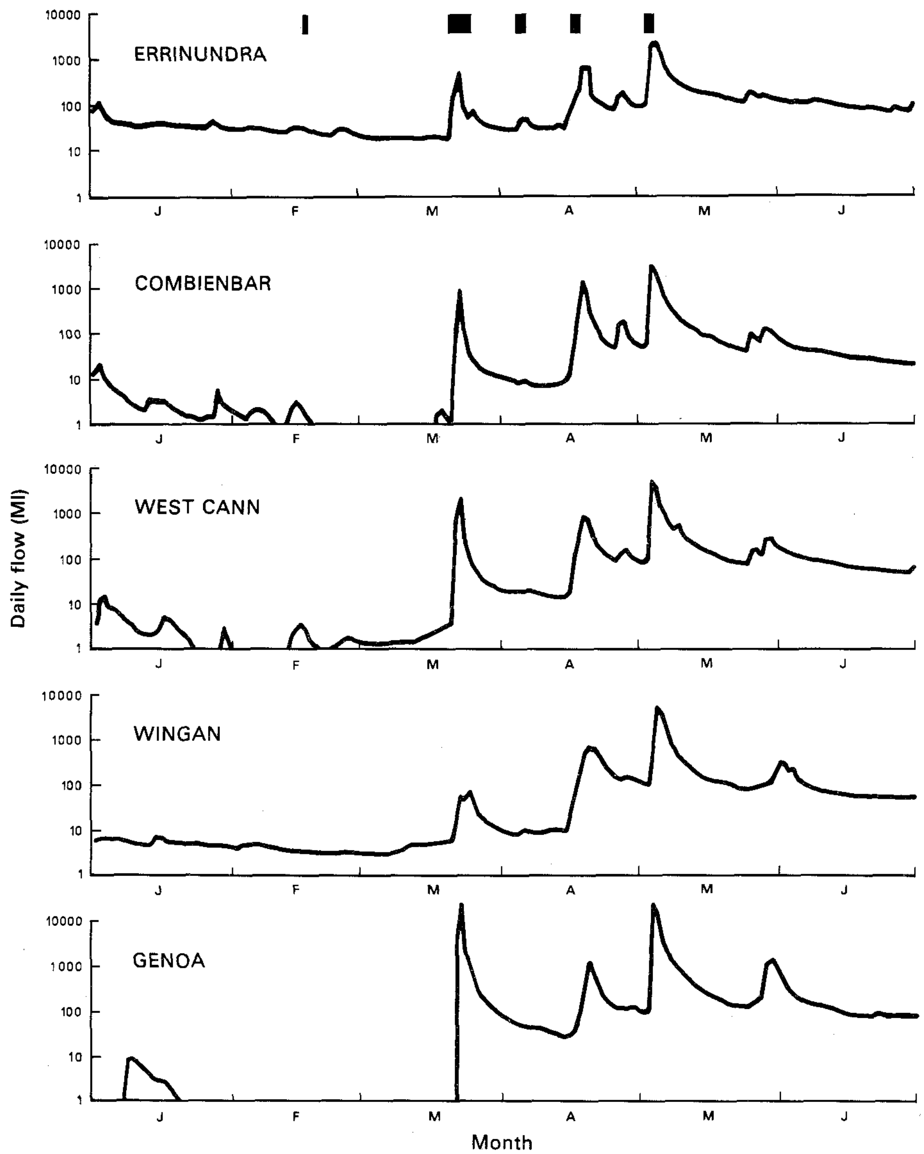


Fig. 3. Hydrographs for selected rivers in East Gippsland for the period January–June 1983 (data from the Rural Water Commission of Victoria). Flows below 1 Ml day^{-1} are not shown, and water-quality sampling dates are indicated by bars above the top graph. See Fig. 1 for locations of gauging stations.

Table 1. Details of the sampling stations on streams in East Gippsland

Station No.	Stream	Location	Latitude (S.)	Longitude (E.)	Elevation (m)	Catchment area (km^2)	% of catchment burnt in 1983
1	Errinundra River	Errinundra Road	37°23·9′	148°53·5′	200	110	0
2	Combienbar River	Combienbar	37°23·5′	149°0·7′	220	100	40
3	Bemm River	Princes Highway	37°36·5′	148°54·1′	80	730	7
4	Fiddlers Green Creek	Cann Valley Highway	37°17·7′	149°12·6′	260	40	100
5	West Cann River	Weeragua	37°22·3′	149°11·9′	160	320	98
6	East Cann River	Weeragua	37°22·4′	149°11·8′	180	150	98
7	Cann River	Noorinbee North	37°26·0′	149°11·7′	140	560	98
8	Thurra River	Princes Highway	37°34·2′	149°16·2′	140	190	100
9	Drummer Creek	Princes Highway	37°34·3′	149°16·3′	140	50	100
10	Wingan River	Princes Highway	37°32·8′	149°27·2′	100	120	95
11	Genoa River	Wangarabell	37°23·4′	149°29·6′	100	750	50

Materials and Methods

Sampling stations were established on 11 streams: the Errinundra, Combienbar, Bemm, West Cann, East Cann, Cann, Thurra, Wingan and Genoa Rivers, and Fiddlers Green and Drummer Creeks (Fig. 1 and Table 1). Catchments of all stations were at least 90% forested. The Errinundra station had a totally unburnt catchment, and the Bemm station had only 7% of its catchment burnt. The catchments of the Combienbar and Genoa stations were about half burnt, and for the remaining sites the proportion of catchment burnt was above 90%. Sampling was concentrated around the three major storms in late March, mid April and early May (see Fig. 3). Low-flow samples were also taken in mid February, before any surface runoff from burnt areas, and again in early April. The total number of samples per station varied, mainly for logistical reasons, between three and eight. The Wingan River was sampled on the fewest occasions because it did not begin to flow at the sampling station until mid April.

Water samples were obtained from the surface at mid-stream using a polyethylene bucket. Temperature and pH were determined on site using a standard mercury thermometer and Watson Victor model 5002 pH meter, respectively. Samples for determination of dissolved oxygen were obtained in 300-ml glass bottles and fixed in the field with manganous sulfate and alkaline azide reagents. Samples for colour, turbidity, suspended solids, electrical conductivity and potassium determinations were placed in 1-litre polyethylene bottles. Phosphorus and nitrogen samples were collected in Whirlpaks, placed on ice and frozen within 12 h. Analytical methods are summarized in Table 2.

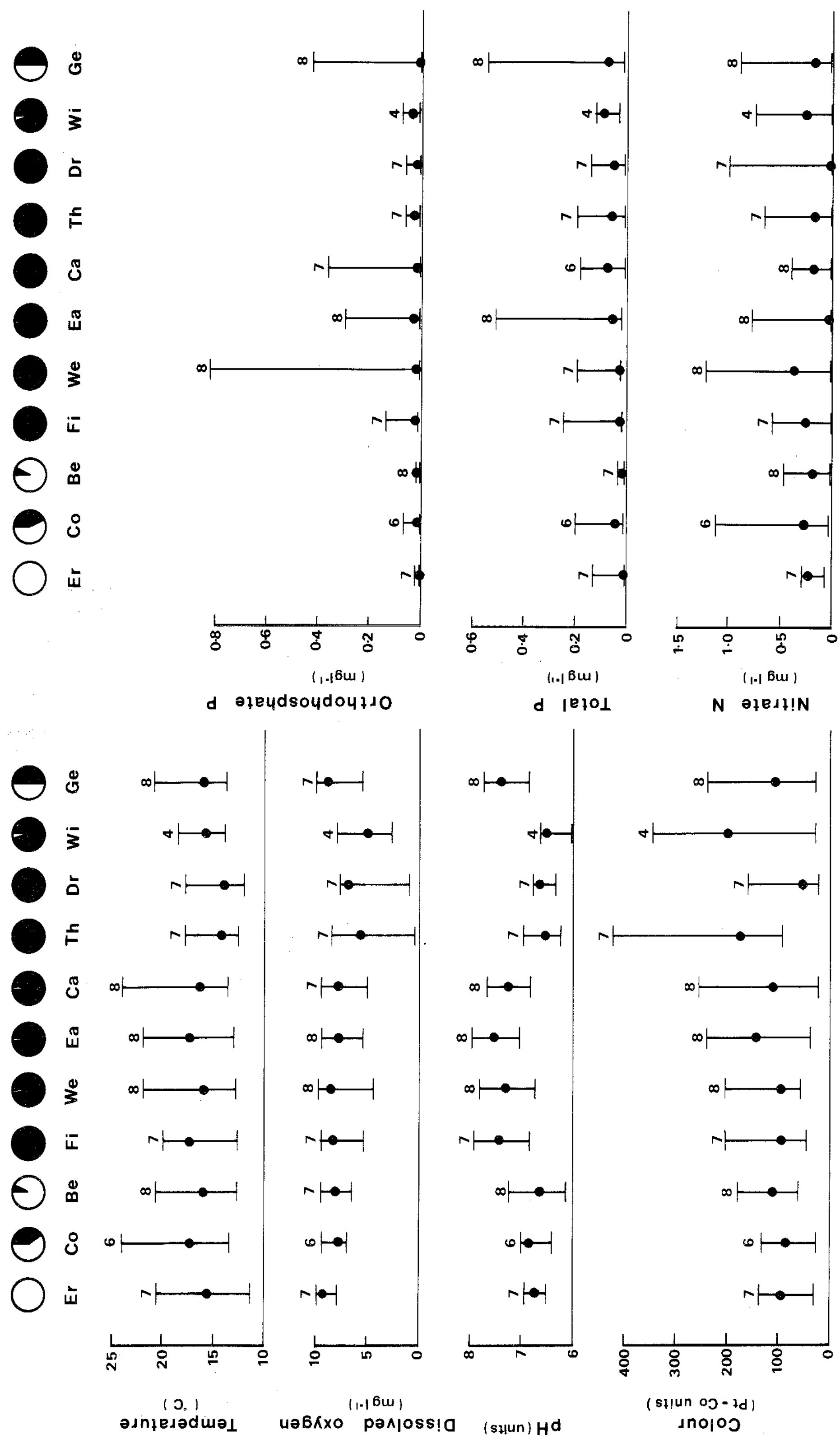
Table 2. Summary of analytical procedures

Indicator	Method/apparatus
Dissolved oxygen	Iodometric method with azide modification[A]
Colour	Hach DR-A colour meter
Turbidity	Hach 2100A turbidimeter
Suspended solids	Gravimetric determination after vacuum filtration over pre-weighed Whatman GF/C glass microfibre filters, followed by drying at 105°C and cooling under desiccation
Electrical conductivity	Philips PW 9505 conductivity meter with PW 9510 cell. Corrected to 20°C
Potassium	GBC SB900 atomic absorption spectrophotometer
Phosphorus	Ascorbic acid method[A] using Pye Unicam SP1800 spectrophotometer, with persulfate pre-digestion[A] for total phosphorus
Nitrate	Automated cadmium reduction method[A] using Technicon Auto Analyzer II
Nitrite	Diazotisation method[A] using Technicon Auto Analyzer II
Ammoniacal nitrogen	Automated phenate method[A] using Technicon Auto Analyzer II
Total Kjeldahl nitrogen	Macro-Kjeldahl method[A] using Buchi 315 distillation unit, followed by nesslerisation method[A] using Pye Unicam SP1800 spectrophotometer

[A] Anon. (1980).

Streamflow data were obtained mainly from continuous level recorders operated by the Rural Water Commission of Victoria at the gauging stations shown in Fig. 1. Most of these recorders have been rated only for relatively low discharges, and estimates of peak flows are therefore very approximate. In some cases, flows were measured directly at the time of sampling using an Ott model 10.002 current meter and standard hydrographic techniques. Where a sampling station was located near but not at a gauging station on the same stream, a time lag was allowed for in calculation of flows at the sampling point. This was estimated from the relationship between discharge and mean velocity at the gauging station.

For the Bemm, Cann and Genoa Rivers, comparisons were drawn with monitoring data obtained for the same stations during 1978–79 (Anon. 1983). For flow-related variables, such comparisons were made by plotting concentration against instantaneous flow and calculating associated linear regression lines. The data were logarithmically transformed as appropriate. Since the 1978–79 sampling was at regular monthly intervals and missed major storm events, data for that period cover a much smaller range of flows than the 1983 data. Valid statistical testing of the significance of differences between 1978–79 and


Er
Co
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Temperature (°C)
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Total P (mg l-1)
Nitrate N (mg l-1)

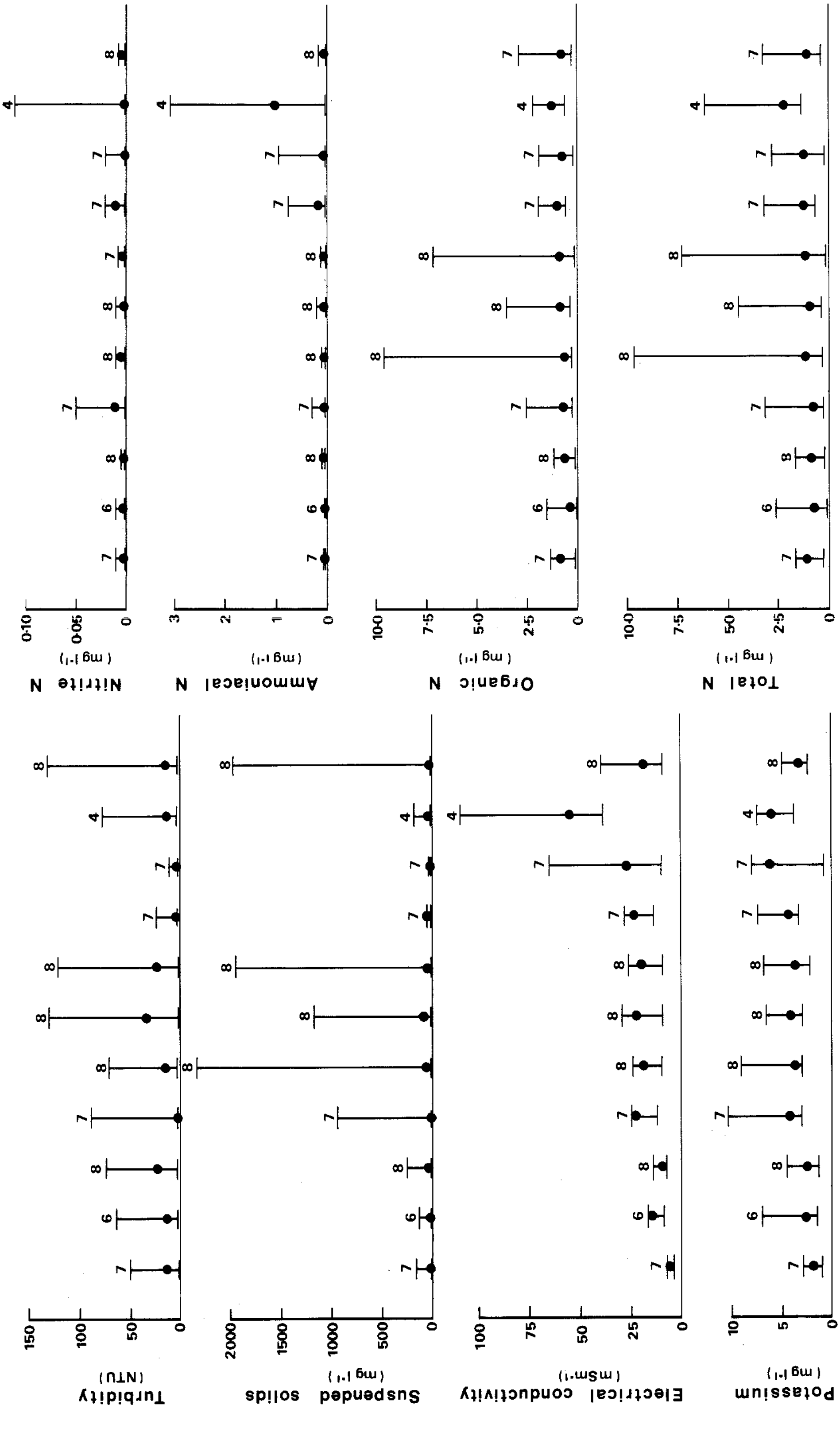


Fig. 4. Maximum, minimum and median values of water-quality indicators for all sampling stations. Numerals above symbols are sample sizes, and streams are identified by the first two letters of their names. Black sectors show the proportion of each catchment that was burnt.

1983 regression relationships was frequently prevented due to inequality of residual mean squares (F-test, $P < 0{\cdot}05$). Comparisons were therefore drawn subjectively.

Linear flow–concentration regressions for 1983 data were used to derive approximate estimates of exports of suspended and dissolved solids, potassium, phosphorus and nitrogen from the Bemm, Cann and Genoa catchments for the period mid February to mid May (corresponding approximately to the period of the study). Regressions were based on logarithmically transformed data for flow, suspended solids, phosphorus and nitrogen, and untransformed data for potassium. Electrical conductivity values (in mS m^{-1}) were not converted to logarithms but were multiplied by $6{\cdot}4$ to estimate dissolved solids (in mg l^{-1}). This conversion factor is an average of values determined by our laboratory for various rivers in Gippsland. Data obtained at flows below 1 Ml day^{-1} were not included in the regressions because they deviated widely from the general pattern. Discharge data for the gauging stations on the Bemm, West Cann, East Cann and Genoa Rivers (daily for flows below about 500 Ml day^{-1}; hourly for higher flows) were inserted into regression equations for the corresponding sampling stations to calculate estimated concentrations. These were then multiplied by the associated flows, and the loads so derived were summed to obtain totals for the period under consideration. The totals for the East and West Cann Rivers were combined to provide estimates for the Cann River as a whole. Catchment areas for each gauging station were obtained from Anon. (1982).

Results

River Flow

Overall, about a quarter of the samples were taken when the streams were rising, about 40% when they were falling, and the remainder when they were steady. The lowest flows were sampled in mid February, when only the Errinundra and Bemm Rivers had substantial discharges (>20 Ml day^{-1}). The East Cann, Thurra and Wingan Rivers were not flowing at the sampling points at this time, and discharges of the West Cann, Cann and Genoa Rivers and Fiddlers Green and Drummer Creeks were below 2 Ml day^{-1}. Maximum flows sampled were associated with the third storm at all stations. For those sampling stations located at or near gauging stations, these maxima are shown in Table 3. Instantaneous maximum flows occurring at each location during the study period are given for comparison.

Table 3. Maximum flows at times of sampling compared with maximum flows for the study period at selected stations

Station No.	Stream	Instantaneous maximum flow sampled (Ml day^{-1})	Instantaneous maximum flow recorded (Ml day^{-1})
2	Combienbar River	2700	7540
3	Bemm River	16 600	17 800
5	West Cann River	9700	11 400
6	East Cann River	8200	13 200
11	Genoa River	47 200	57 900

Temperature

Measured water temperatures ranged from 11 to 24°C (Fig. 4). There was no obvious relationship between temperature and either altitude or proportion of catchment burnt. The highest maxima were recorded from the Combienbar and Cann Rivers, which had relatively exposed channels. Lowest maximum and median values were obtained from the Thurra River and Drummer Creek, where some riparian forest survived the fires.

Dissolved Oxygen

The total range of dissolved oxygen concentrations varied greatly between stations (Fig. 4). In the Bemm River and tributaries, measured values were never below 6 mg l^{-1}, but in the Cann River system relatively low concentrations of 4–6 mg l^{-1} were found before and during the first storm. In the Thurra and Wingan Rivers, oxygen levels were very low under zero-flow conditions (0–2 mg l^{-1}) but rose after the first storm. In Drummer Creek,

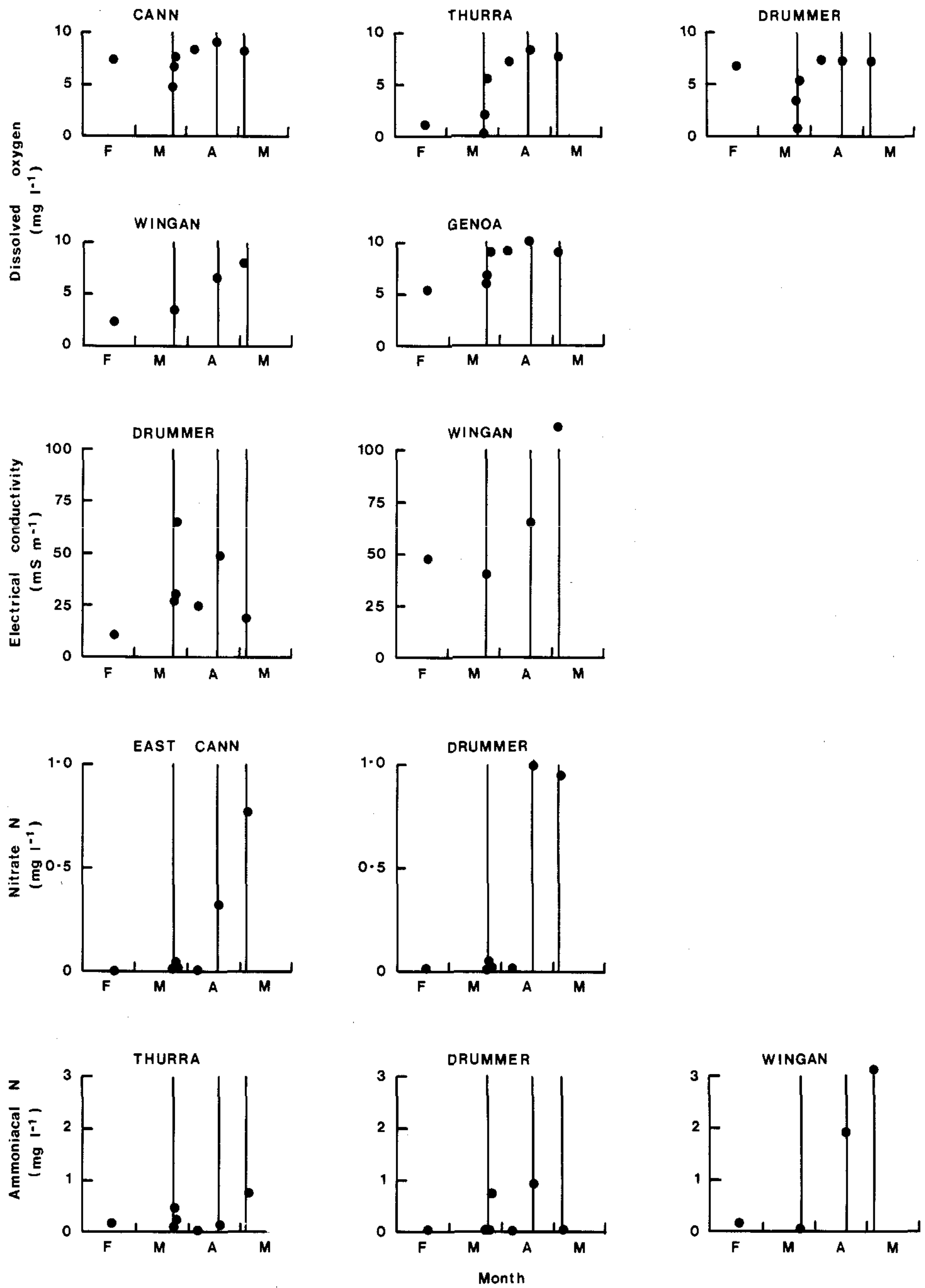
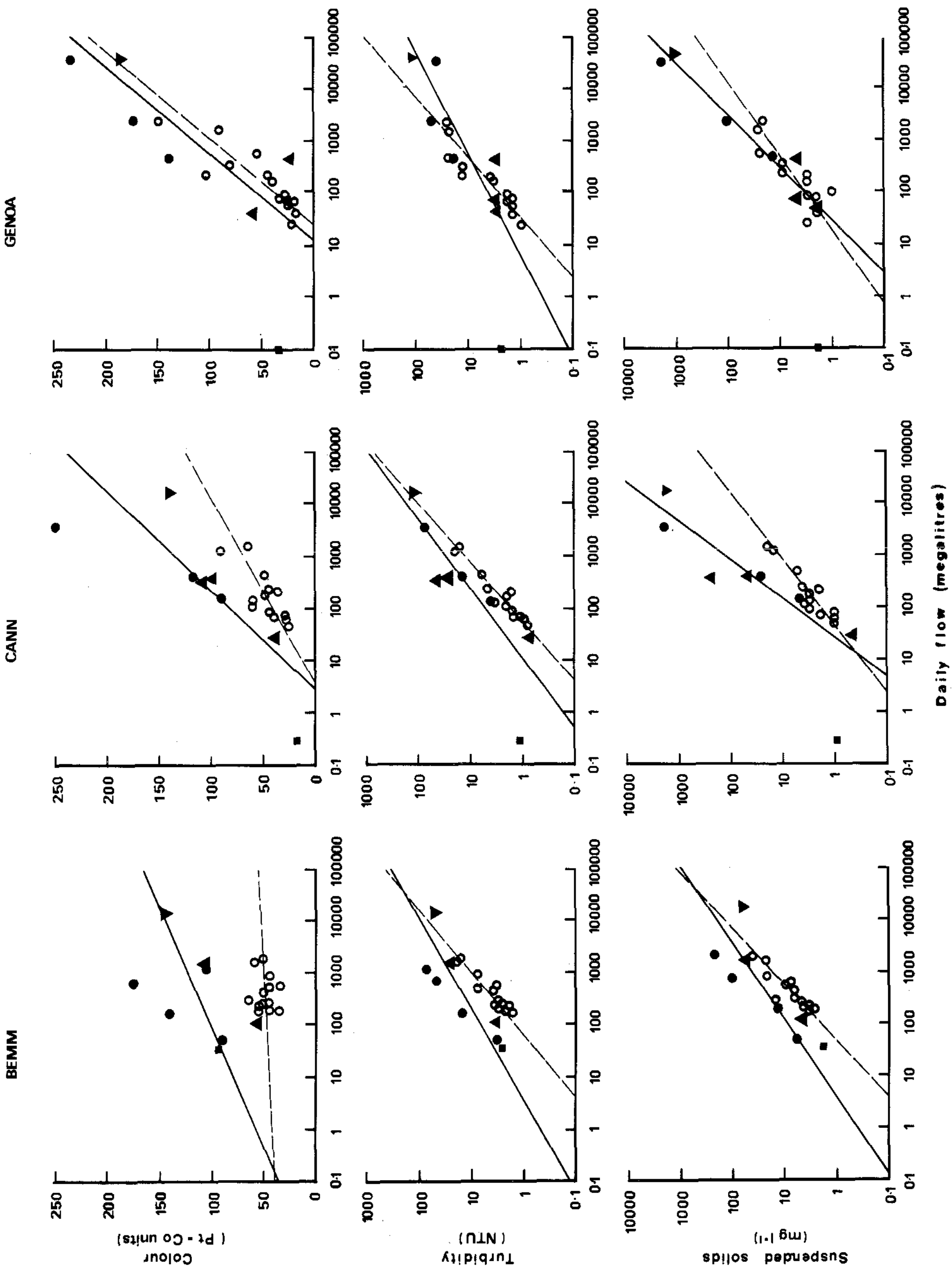


Fig. 5. Time series of various indicators at selected stations. Vertical lines indicate the time of the first, second and third major storms.


BEMM
CANN
GENOA
Colour (Pt - Co units)
Turbidity (NTU)
Suspended solids (mg l-1)
Daily flow (megalitres)

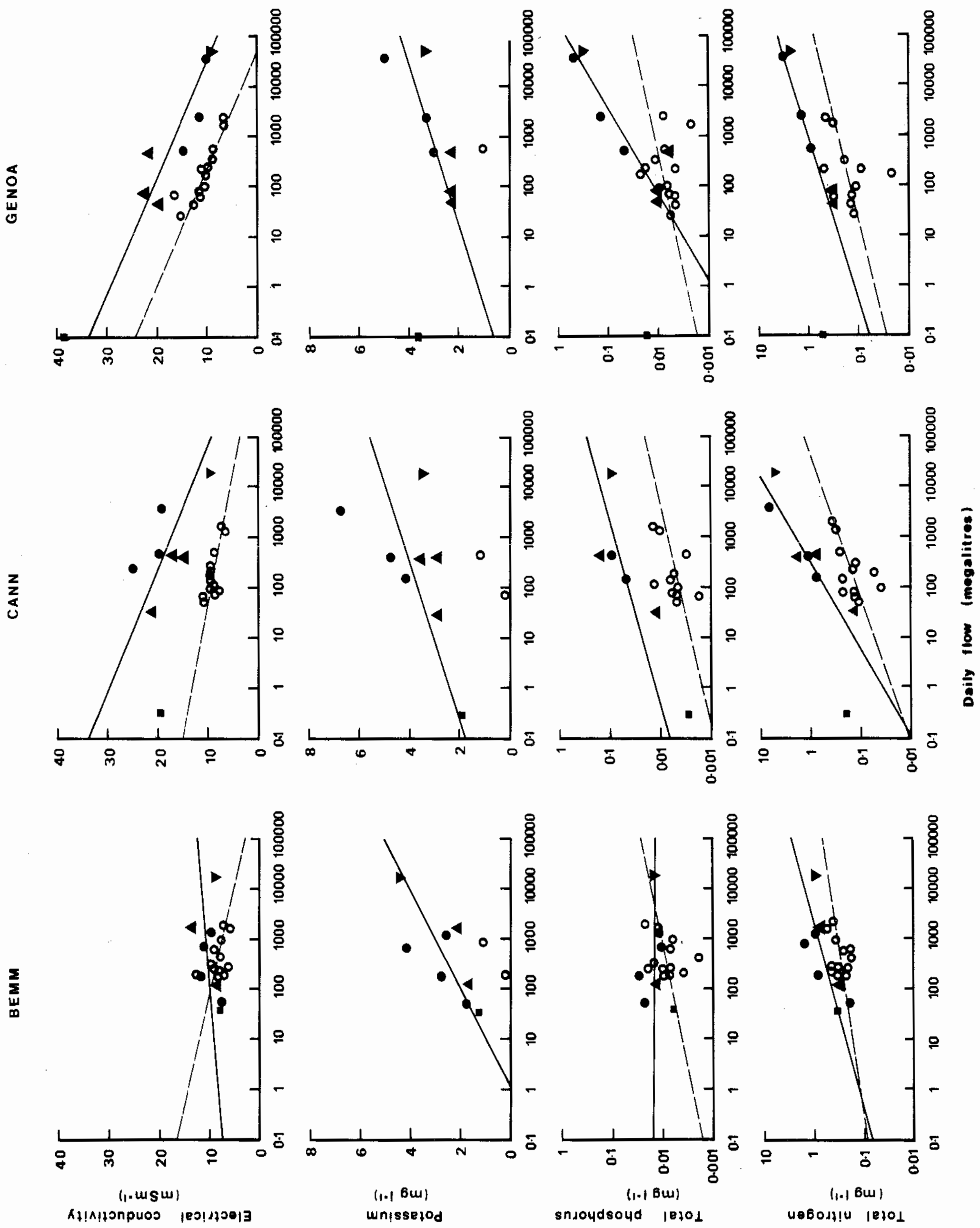


Fig. 6. Flow–concentration plots for selected indicators for the Bemm, Cann and Genoa river stations. Regression lines (solid for 1983 data, dashed for 1978–79 data) are based on results for flows greater than 1 Ml day^{-1}. Data for zero flow are not shown. ○ 1978–79. ■ February 1983. ● March 1983. ▲ April 1983. ▼ May 1983.

oxygen concentration was high in mid February but dropped sharply during the first storm, with subsequent recovery. The lowest oxygen concentration in the Genoa River (5 mg l^{-1}) was recorded under drought conditions in February. Time-series plots for selected stations are given in Fig. 5.

pH

On the basis of pH readings (Fig. 4), the streams could be divided into a generally alkaline group (the Cann River and its tributaries and the Genoa River) and a generally acidic group (the Bemm and Thurra Rivers and their tributaries and the Wingan River). Values for the Bemm, Cann and Genoa Rivers were not significantly different from those recorded from the same streams in 1978–79 (*t*-tests, $P > 0{\cdot}05$).

Colour

The total range of colour values measured was 20–420 Pt–Co units (Fig. 4). Highest readings were for zero-flow samples from pools of the Thurra (380–420 units) and Wingan (320–340 units) Rivers. After initial flushing, colour levels in these rivers were positively correlated with flow as they were in all other streams. At most localities, samples giving the highest colour readings were associated with the first storm (Table 4), although the greatest flows sampled resulted from the third storm. Comparisons between 1978–79 and 1983 data are presented in Fig. 6. In the Bemm and Cann Rivers, colour levels were clearly greater in 1983 than in 1978–79, but in the Genoa River there was little obvious difference.

Table 4. Storm events producing the highest measured values, for each stream, of those variables generally positively correlated with flow

Streams are identified by the first two letters of their names and storms as 1 (March), 2 (April) and 3 (May)

Variable	Storm event producing highest value in:										
	Er	Co[A]	Be	Fi	We	Ea	Ca	Th	Dr	Wi	Ge
Colour	3	1	1	1	1	1	1	1[B]	3	1[B]	1
Turbidity	2 = 3	1	1	3	3	3	3	3	3	3	3
Suspended solids	1	1	1	3	3	2	1	1	3	3	1
Potassium	1	1	3	1	1	1	1	1	1	1[B]	1
Orthophosphate	1	1	3	1	1	1	1	3	3	3	1
Total phosphorus	3	1	1	1	1	1	1[C]	1	2	1[B]	1
Nitrate	1	1	1	1	1	3	2	1	2	3	3
Nitrite	1	1	1	2	3	1 = 3	3	1 = 3	3	3	3
Ammoniacal nitrogen	2 = 3	3	3	3	3[D]	3	3	3	2	3	3
Organic nitrogen	3	1	1	1	1	3	1	1	3	3	1
Total nitrogen	3	1	1	1	1	3	1	1	3	3	1

[A] Not sampled during second storm.
[B] At time of first storm, but river not flowing.
[C] Highest specific measurement of total phosphorus was for second storm, but was exceeded by orthophosphate for first storm (see text).
[D] Equivalent concentration also recorded under low-flow conditions in February.

Turbidity

Highest turbidities were recorded from the Cann River and its tributaries and the Genoa River, whereas levels in the Thurra River and Drummer Creek were always low (Fig. 4). At most stations, maximum recorded turbidities were produced by the third storm (Table 4). In the Bemm and Cann Rivers, turbidities were higher in 1983 than at similar flows in 1978–79 (Fig. 6), but in the Genoa little change was apparent.

Suspended Solids

As for turbidity, the highest suspended-solids concentrations were recorded from the Cann River and its tributaries and the Genoa River (Fig. 4). Maxima ranged from 2300 mg l^{-1} in the West Cann River to 11 mg l^{-1} in Drummer Creek, and the greatest value obtained for the Thurra River was also low (38 mg l^{-1}). The Errinundra River, with an entirely unburnt catchment, yielded a maximum of 163 mg l^{-1}. Samples giving the highest readings were usually associated with either the first or third storm (Table 4). Concentrations were generally higher than at similar flows in 1978–79 for the Bemm and Cann Rivers but not for the Genoa (Fig. 6).

Table 5. Product-moment correlations for the relationships between various variables and the logarithm of flow in the Bemm, West Cann, East Cann and Genoa Rivers

$^*P < 0\cdot05$; $^{**}P < 0\cdot01$; others not significant

Variable	Correlation			
	Bemm	West Cann	East Cann	Genoa
Suspended solids[A]	0·81*	0·91**	0·92**	0·97**
Electrical conductivity	0·34	−0·52	−0·87*	−0·89**
Potassium	0·77*	0·37	0·39	0·81*
Total phosphorus[A]	−0·02	0·54	0·51	0·91**
Total nitrogen[A]	0·76*	0·84**	0·94**	0·98**

[A] Logarithmically transformed.

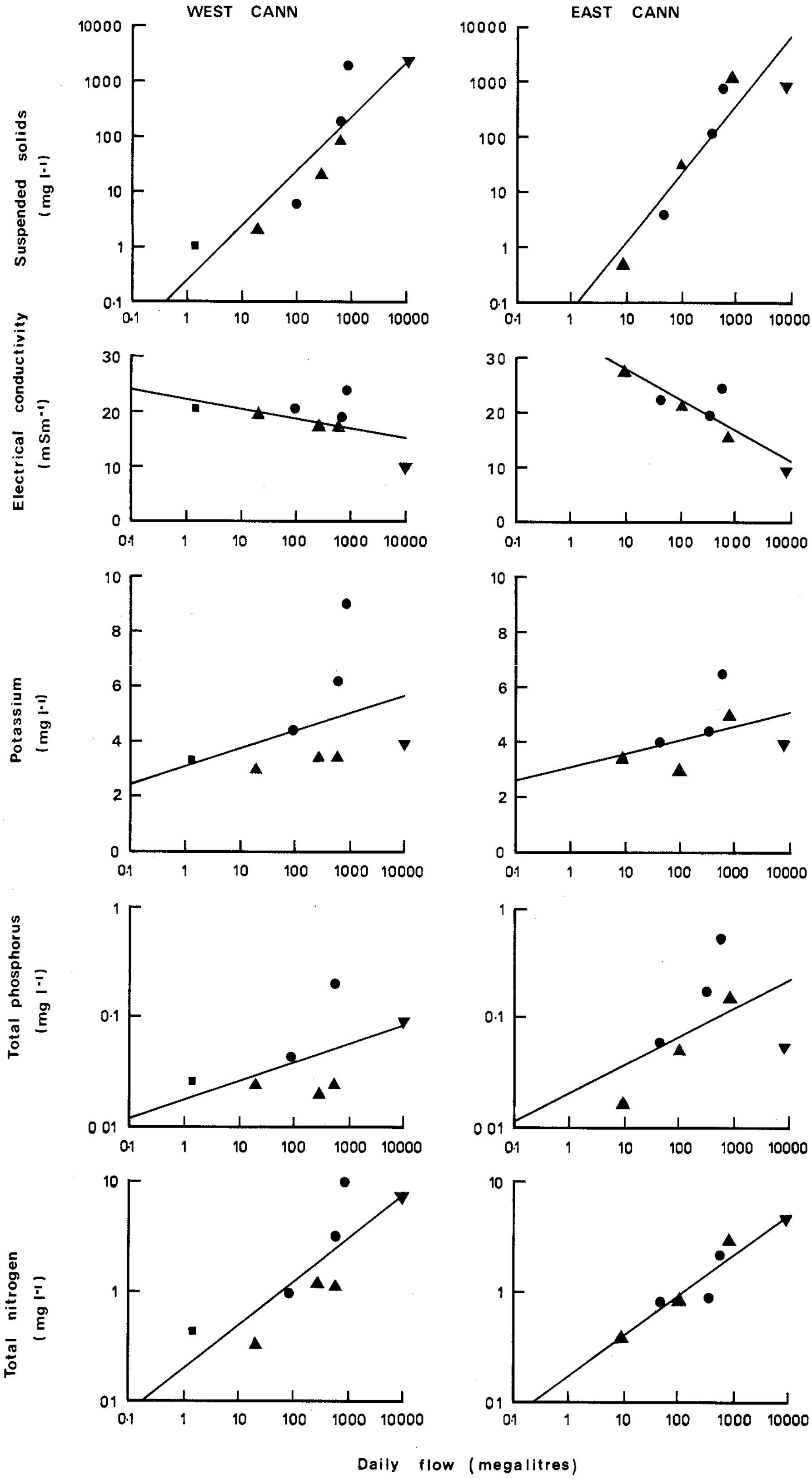
Correlations between the logarithms of discharge and suspended-solids concentration were high for the Bemm, West and East Cann and Genoa Rivers (Figs 6 and 7 and Table 5); values of r ranged from 0·81 to 0·97 for 1983 data. Estimated sediment exports per unit area were six to nine times higher for the Cann and Genoa catchments than for the virtually unburnt Bemm Catchment (Table 6).

Table 6. Estimated sediment, solute and nutrient exports from the Bemm, Cann and Genoa catchments for the period 15 February to 15 May 1983

Variable	Export (kg km^{-2})		
	Bemm	Cann	Genoa
Suspended solids	13 000	113 000	73 000
Dissolved solids	5800	8000	7200
Potassium	290	380	360
Phosphorus	1	7	27
Nitrogen	100	280	230

Electrical Conductivity

Electrical conductivity (EC) varied considerably between localities, with the highest maxima and widest ranges being recorded for the Wingan and Genoa Rivers and Drummer Creek (Fig. 4). Quite different temporal trends were observed for these three streams (Figs 5 and 6). Peak EC occurred at the time of the first storm for Drummer Creek, the third storm for the Wingan River, and the February low-flow period for the Genoa River. In the Cann and Genoa Rivers, conductivities were clearly greater than for equivalent flows in 1978–79, whereas for the Bemm River there was little difference (Fig. 6).



WEST CANN
EAST CANN
Suspended solids (mg l-1)
Electrical conductivity (mSm-1)
Potassium (mg l-1)
Total phosphorus (mg l-1)
Total nitrogen (mg l-1)
10000
1000
100
10
1
0·1
30
20
10
0
10
8
6
4
2
0
1
0·1
0·01
10
1
0·1
0·1 1 10 100 1000 10000
Daily flow (megalitres)

EC was usually, but not always, negatively correlated with discharge and the correlations were often weak (Figs 6 and 7 and Table 5). Estimated solute exports per unit area from the catchments of the Bemm, Cann and Genoa Rivers differed only slightly (Table 6).

Potassium

Concentrations of potassium ranged from 0·7 mg l^{-1} in Drummer Creek to 10·2 mg l^{-1} in Fiddlers Green Creek. Median values were greatest for Drummer Creek and the Wingan River and lowest for the Bemm River and its tributaries (Fig. 4). The first storm produced the highest measured concentrations in all streams except the Bemm and Wingan Rivers (Table 4). Data for 1978–79 are few but indicate much lower concentrations than in 1983 (Fig. 6). Estimated exports per unit area were similar for the Bemm, Cann and Genoa catchments (Table 6).

Phosphorus

Due to interference from other substances present, total phosphorus could not be determined satisfactorily in all instances before samples were exhausted. Consequently, the highest orthophosphate measurement exceeded the maximum for total phosphorus in two streams (the West Cann and Cann Rivers). The Bemm River had notably low phosphorus concentrations (Fig. 4), and the highest maxima were recorded for the Cann River system and the Genoa River. Generally, maxima occurred at the time of the first storm (Table 4).

Comparisons with 1978–79 data (Fig. 6) suggested that phosphorus levels had changed little in the Bemm River since that time, but had increased in the Cann. Some increase also appears to have occurred in the Genoa, but interpretation is difficult because of the data scatter. For 1983 data, the correlations between discharge and total phosphorus were generally weak (Figs 6 and 7 and Table 5). Estimated catchment exports per unit area were much greater for the Cann and Genoa Rivers than for the Bemm (Table 6).

Nitrogen

Results are presented as total combined nitrogen and the constituents nitrate, nitrite, ammoniacal nitrogen and organic nitrogen (calculated as total Kjeldahl nitrogen less ammoniacal nitrogen). Nitrate concentrations varied widely in all streams (Fig. 4), being generally positively correlated with discharge. Highest levels were mostly measured for samples associated with the first storm (Table 4), but in some streams concentrations remained very low until the second or third storms (Fig. 5). With a total range of <0·001–1·2 mg N l^{-1}, nitrate concentrations greatly exceeded those of nitrite. The latter were recorded at 0·05 mg N l^{-1} and 0·11 mg N l^{-1} in Fiddlers Green Creek and the Wingan River, respectively, but otherwise did not exceed 0·02 mg N l^{-1} (Fig. 4).

Ammoniacal nitrogen reached much higher levels in the Thurra River (0·77 mg N l^{-1}), Drummer Creek (0·94 mg N l^{-1}) and the Wingan River (3·1 mg N l^{-1}) than in other streams (Fig. 4). Maxima for the Bemm River and its tributaries did not exceed 0·06 mg N l^{-1} and corresponding values for the Cann River system and the Genoa River were 0·27 and 0·12 mg N l^{-1}, respectively. Highest levels were recorded as a result of the third storm in most streams (Table 4). However, in the Thurra and Wingan Rivers and Drummer Creek, concentrations were also high at the time of the first or second storm (Fig. 5).

Organic nitrogen concentrations reached the greatest maxima in the Cann River system and the Genoa River (Fig. 4). Being the dominant nitrogen form, organic nitrogen followed a generally similar pattern to that of total nitrogen. However, the Wingan River had a greater total nitrogen maximum than the Genoa because of its high content of ammoniacal nitrogen. The first and third storms produced the highest concentrations of total nitrogen for the various

Fig. 7. Flow–concentration plots for selected indicators for the West and East Cann river stations. Conventions as in Fig. 6.

streams (Table 4). In comparison with 1978–79 data, total nitrogen concentrations were high during 1983 for the Bemm, Cann and Genoa Rivers.

Total nitrogen concentrations in 1983 were well correlated with discharge (Figs 6 and 7 and Table 5), and estimated catchment exports per unit area were two to three times greater for the burnt Cann and Genoa basins than for the basically unburnt Bemm basin (Table 6).

Discussion

The severity of wildfire impact on stream water quality is governed by a number of factors including fire intensity, catchment topography, geology and soils, post-fire climate and revegetation patterns (Boughton 1970; Brown 1974; Anderson *et al.* 1976; Langford and O'Shaughnessy 1977). In the present study, quality differences between streams were considerable. These differences were most likely due to variations in catchment characteristics and fire extent and intensity. Post-burn rainfall patterns were broadly similar across the study area, and sampling was completed before significant revegetation of burnt areas.

Peak turbidities and concentrations of suspended solids and phosphorus were much greater in the Cann River and tributaries and the Genoa River than in other streams. This probably reflects the importance of surface runoff and associated erosional processes in the regimes of these two rivers. They have upper catchments dominated by soils of only moderate permeability, and substantial overland flow was observed in burnt areas of both catchments during the study. Flows of both rivers responded rapidly to the onset of storms. For example, flow in the West Cann River at Weeragua on 21 March rose from 4 Ml day^{-1} at 0100 h to 34 Ml day^{-1} at 1400 h and 1990 Ml day^{-1} at 1600 h. On the same day, the Genoa River at the Wangarabell Gorge had no flow until 1100 h. At 2000 h, the flow was 101 Ml day^{-1} and by 2300 h this had increased to 29 500 Ml day^{-1}.

By contrast, some other streams with burnt catchments, the Thurra River, Drummer Creek and the Wingan River, responded only slowly to catchment rainfall. After the first storm, the Wingan at the Princes Highway had still not started flowing by the morning of 25 March, and the Thurra did not flow until late on 22 or early on 23 March. Drummer Creek maintained a low flow (<1 Ml day^{-1}) at the end of the drought, and was not observed flowing strongly (>5 Ml day^{-1}) until the time of the second storm. Subsurface flow was probably relatively more important in the water budgets of these streams for which low suspended-solids maxima, but some high solute peaks (in Drummer Creek and the Wingan River, indicated by the electrical conductivity), were recorded. As noted previously, soils in the upper Thurra basin are generally more permeable than those in the Cann and Genoa catchments. Low topography, including swampy areas, may also have played a role in mitigating or attenuating suspended-sediment losses in the Thurra and Wingan basins.

Water-quality impacts of the fires were much intermingled with the after-effects of the preceding drought. Comparison of 1978–79 and 1983 water-quality data showed appreciable increases in colour, turbidity, suspended solids, potassium and nitrogen levels in the Bemm River, which was only marginally affected by the fires. However, the Cann and Genoa Rivers, with burnt catchments, underwent substantial increases in conductivity and phosphorus concentrations as well. Marked depletion of dissolved oxygen was unique to streams with burnt catchments, but resulted from stagnant conditions during the drought as well as oxygen demand of fire-generated materials washed into the streams at the time of the first storm. Similarly, the highest colour levels occurred in pools of the Thurra and Wingan Rivers under zero-flow conditions, although colour was generally positively correlated with discharge.

The first storm produced the highest measured levels of many indicators in many streams (Table 4), although the greatest flows occurred as a result of the third storm. Rapid depletion of mobile materials accumulated during the drought, or liberated as a result of the fires, may account for this. Reduced inorganic nitrogen species (nitrite and ammoniacal nitrogen) were exceptions to the general pattern, generally peaking at the time of the third storm.

Perhaps these high levels resulted from nitrite and ammonia generation due to decomposition after the first or second storm, with subsequent mobilization as a result of the third storm.

The estimates of catchment exports (Table 6) illustrate some overall impacts of the fires. They should be considered as indicative only, given the often low correlations between concentration and discharge and the known inaccuracies of rating-curve techniques of load calculation (Walling 1977*a*, 1977*b*, 1978; Olive *et al.* 1980; Geary 1981; Rieger *et al.* 1982). Refinements such as the use of different rating curves for rising and falling stages (Loughran 1976, 1977) were not used because of the small number of observations for each stream. The use of daily rather than hourly flow data to calculate loads at low flows probably introduced little error, because only a very small proportion of total exports was transported under low-flow conditions.

The estimated sediment and solute exports from the Bemm catchment (equivalent to 52 and 23 t km^{-2} $year^{-1}$, respectively) are within the range reported for unburnt catchments in Australia (see review by Olive and Walker 1982). In contrast, the sediment values for the almost wholly burnt Cann catchment (converting to 452 t km^{-2} $year^{-1}$) and the half-burnt Genoa catchment (292 t km^{-1} $year^{-1}$) are exceeded only by annual values for streams near Broken Hill (Abrahams 1972) and a stream in a north-east Queensland rainforest (Douglas 1966). However, rainfall during the 3-month period used for computation of exports from the East Gippsland catchments was 30–50% of the average annual total for most localities in the region. The highest suspended-solids concentration recorded for the East Gippsland rivers (2300 mg l^{-1} in the West Cann) is well below those reported by Brown (1972) in his investigation of the effects of an uncontrolled fire in the Yarrangobilly River and Wallace's Creek catchments in the Snowy Mountains, N.S.W. There, suspended-sediment concentrations following intense rainfall 7 months after the fire reached the maxima of 112 000 mg l^{-1} in the river and 143 000 mg l^{-1} in the creek. The highest records before the fire were 334 and 7052 mg l^{-1}, respectively. Other studies of Australian streams have found much lower suspended-sediment maxima following catchment wildfire. Midgley (1973) recorded a maximum of only 47 mg l^{-1} in a small stream draining a basin burnt by wildfire in the Cotter River catchment, A.C.T. He noted that rainfall following the fire was only of low intensity. Burgess *et al.* (1980, 1981) reported changes in suspended sediment in tributaries of the Wallagaraugh River, N.S.W., following a severe, uncontrolled fire. Little rain fell in the 2 months following the blaze, but thereafter heavy falls resulted in suspended-sediment concentrations as high as 283 mg l^{-1}. Condina *et al.* (1984) recorded suspended-solids concentrations up to 120 mg l^{-1} in Stoney Creek, an intermittent tributary of Cardinia Creek, Victoria, following the Ash Wednesday fires of February 1983. The absence of severe erosion was attributed to the low intensity of the first rains after the fire, which resulted in little surface runoff and promoted the growth of grasses.

Compared with values for other Australian streams summarized by Cullen and O'Loughlin (1982), phosphorus exports from the Bemm catchment (equivalent to 0·04 kg ha^{-1} $year^{-1}$) are low and those from the Cann and Genoa catchments (0·28 and 1·08 kg ha^{-1} $year^{-1}$) are intermediate and high, respectively. Even so, the Genoa phosphorus export for the post-fire trimester (0·27 kg ha^{-1}) represents only 0·03% of the estimated phosphorus stores in vegetation, litter and soil of a mixed eucalypt forest (Leitch *et al.* 1983). The highest concentration of phosphorus recorded for the East Gippsland rivers (0·82 mg l^{-1} in the West Cann) exceeds maxima measured following wildfire for New Chums catchment in the Cotter River basin, A.C.T. (0·74 mg phosphate l^{-1} = 0·24 mg phosphorus l^{-1}: Anon. 1975) and the Little River, N.S.W. (0·07 mg l^{-1}: Smalls 1978). However, it is below the highest value given by Condina *et al.* (1984) for Stoney Creek, Victoria (1·2 mg l^{-1}). The greatest nitrate-nitrogen concentration for the East Gippsland rivers (1·2 mg l^{-1} in the West Cann) lies between maxima for the Little River (0·02 mg l^{-1}) and Stoney Creek (2·7 mg l^{-1}). The highest ammoniacal nitrogen value in East Gippsland (3·1 mg l^{-1} in the Wingan River) exceeds maxima for New Chums catchment (1·9 mg l^{-1} as NH_4^+), the Little River (0·44 mg l^{-1}) and Stoney Creek (0·24 mg l^{-1}).

Overall, water-quality impacts of the East Gippsland fires were not as severe as might have been expected given the ensuing heavy rainfall, and the high flows that were sampled. For many indicators, fire effects were scarcely distinguishable from those of the preceding drought. By the middle of May, some recovery in quality was already distinguishable. Longer-term post-fire trends in the Cann River system are being monitored by the Rural Water Commission of Victoria.

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