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Ian G. Jowett & Maurice J. Duncan

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# Flow variability in New Zealand rivers and its relationship to in-stream habitat and biota

IAN G. JOWETT
Freshwater Fisheries Centre
Ministry of Agriculture and Fisheries
P. O. Box 8324, Riccarton
Christchurch, New Zealand

MAURICE J. DUNCAN
Hydrology Centre
DSIR Marine and Freshwater
Department of Industrial and Scientific Research
P. O. Box 22 037, Christchurch, New Zealand

**Abstract** Flow variability indices were determined for 130 sites on New Zealand rivers and the sites were divided into groups based on these indices. Univariate and discriminant analyses were used to identify the catchment characteristics which contributed to flow variability. Climate, as determined by topography, geographic location, and the composition of the regolith (especially water storage capacity and transmissivity characteristics), accounted for a broad regional distribution of groups. Flow variability decreased with catchment size and area of lake and, to a lesser degree, with catchment slope. Relationships were found between flow variability, and morphological and hydraulic characteristics. The longitudinal variability of water depth and velocity increased with flow variability, indicating a more pronounced pool/riffle structure in rivers with high flow variability. Mean water velocity at mean annual low, median, and mean flow was higher in rivers of low flow variability than in rivers of high flow variability. There were strong associations with periphyton communities and trout distribution and abundance and a weak association with benthic invertebrate communities. Water velocity was the most important hydraulic variable; it could be linked to changes in water temperature, benthic invertebrate and periphyton community structure, and trout distribution and abundance.

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**Keywords** flow variability; hydrology; discriminant analysis; classification; in-stream habitat; community structure; benthic invertebrates; periphyton; trout ; morphology

## INTRODUCTION

Flow has an important influence on lotic flora and fauna, especially extreme flow conditions such as floods or drought (Hynes 1970; Minshall 1988; Townsend 1989). In New Zealand, flow variability is one of the major factors influencing the distribution and abundance of brown trout (*Salmo trutta*) and rainbow trout (*Oncorhynchus mykiss*, formerly *Salmo gairdneri*) (Jowett 1990). Flood flows have also been shown to severely reduce trout populations (Allen 1951; Jowett & Richardson 1989).

Benthic invertebrates are affected in a similar manner. Floods and droughts can affect the abundance of benthic macroinvertebrate fauna and can change community structures, although recovery is usually rapid (Extence 1981; Cowx et al. 1984; Sagar 1986; Scrimgeour et al. 1988; Quinn & Hickey 1990a). Algae and aquatic macrophytes can be scoured by floods especially when the substrate is moved or abraded (Hynes 1970; Scrimgeour et al. 1988; Biggs & Close 1989).

Flow variability is usually described by statistical parameters derived from the frequency distribution of the flow series (the flow duration curve). Parameters commonly used include the coefficient of variation, range, and skewness of the distribution (Chow 1964). The coefficient of variation of mean annual flows has been used for comparisons of flow variability (McMahon 1982).

Precipitation, catchment area, the character of the regolith (defined as surficial deposit covering bedrock, including soils and alluvium) and vegetation, and the presence of lakes influence flow variability (Chow 1964). The variability of natural river flow in New Zealand is primarily a result of variation in precipitation. Mean annual precipitation ranges from 350 mm and fewer than 125 precipitation days in Central Otago, to over 8000 mm and 200 precipitation days in the Southern Alps (Coulter 1975). Seasonal patterns vary from north to south, with higher winter rainfall in the north and lower in the south. The seasonal pattern is not marked and falling on relatively short, steep catchments, generates river flows which can rise and fall rapidly.

Regionalisation, either subjective or semi-quantitative, groups together rivers of similar hydrological characteristics by their location (e.g., Beable & McKerchar 1982). In New Zealand, most quantitative regionalisations have used only one or two hydrological variables for specific purposes, such as flood or water yield studies (e.g., Mosley 1981; Beable & McKerchar 1982). However, in Australia (Hughes 1987; Hughes & James 1989) and the United States (Poff & Ward 1989), a number of hydrological variables, primarily describing flow variability, have been used to define regions or stream types for studies of stream ecology. Whereas hydrological regionalisation has been shown to be generally applicable when climatic effects are dominant, differences in catchment size and the presence of lakes or springs can influence the flow regime of a river so that it differs from the flow regime of other rivers in the same region. McKerchar & Pearson (1989) recognised the difficulties of defining geographical boundaries, and adopted a procedure of mapping flood statistics instead.

The importance of flow variability to lotic biota and the utility of a hydrological river classification system to biological researchers has been emphasised (Hughes & James 1989; Poff & Ward 1989). However, neither study examines analytically the factors contributing to flow variability, the effect of flow variability on river characteristics (e.g., in-stream habitat, water velocity, and morphology), or the significance of their classifications to biological systems.

This study is part of a major multi-disciplinary and multi-agency project which describes and characterises a large number of New Zealand rivers according to their hydrology, water quality, and benthic invertebrate, periphyton, and trout communities (Biggs et al. 1990). The present paper:

(1) classifies New Zealand river sites according to indices describing flow variation, including the magnitude and variation of high and low flows;
(2) identifies the catchment characteristics which contribute to flow variability; and
(3) examines linkages between flow variability and hydraulic characteristics, in-stream habitat, water quality, periphyton, benthic invertebrates, and trout distribution and abundance; it incorporates the results of the other characterisation studies in this issue (Biggs 1990; Close & Davies-Colley 1990; Jowett 1990; Quinn & Hickey 1990a).

## METHODS

### Hydrological data

Hydrological data for 130 river sites (Fig. 1) were obtained in mid 1988 from the Water Resources Database (DSIR, Christchurch). The record length of hydrological data ranged from 5 to 55 years and averaged 17.8 years. Data from the majority of sites were validated by DSIR Water Resources Survey staff. Data and discharge ratings of sites showing unusual values or sequences of values were checked and poor-quality records were discarded.

Flows were analysed to obtain values for the mean annual flow, median flow, mean annual low flow, mean annual maximum flow, and coefficient of variation of flow (Table 1A). These statistics were selected because they are objective and readily obtainable. All statistics were calculated from records of instantaneous flow, usually recorded every 15 min. In addition, a baseflow index and coefficients of variation of the annual maxima and annual minima were calculated from daily mean flows. The baseflow index, expressed as a percentage, was the ratio of the volume of baseflow to the total volume of run-off, where baseflow was separated according to Hewlett & Hibbert (1967), using a separation slope of 0.004 $l\ s^{-2}\ km^{-2}$ (e.g., Fig. 2).

Seven indices of flow variability were used. The overall variability of the flow was described by three indices, the baseflow index, the coefficient of variation of flow, and the ratio of mean to median flow (a measure of the skewness of the flow frequency distribution). Indices of the range of flow fluctuation were calculated by dividing the mean annual maxima and mean annual minima by the median flow. Variability of the annual extremes was represented by their coefficients of variation. Median flow was used to form indices because it is less likely to be affected by extreme flow estimation errors than mean flow.

### Catchment and environmental data

The hydrogeological character of the regolith was represented by three indices. These were the

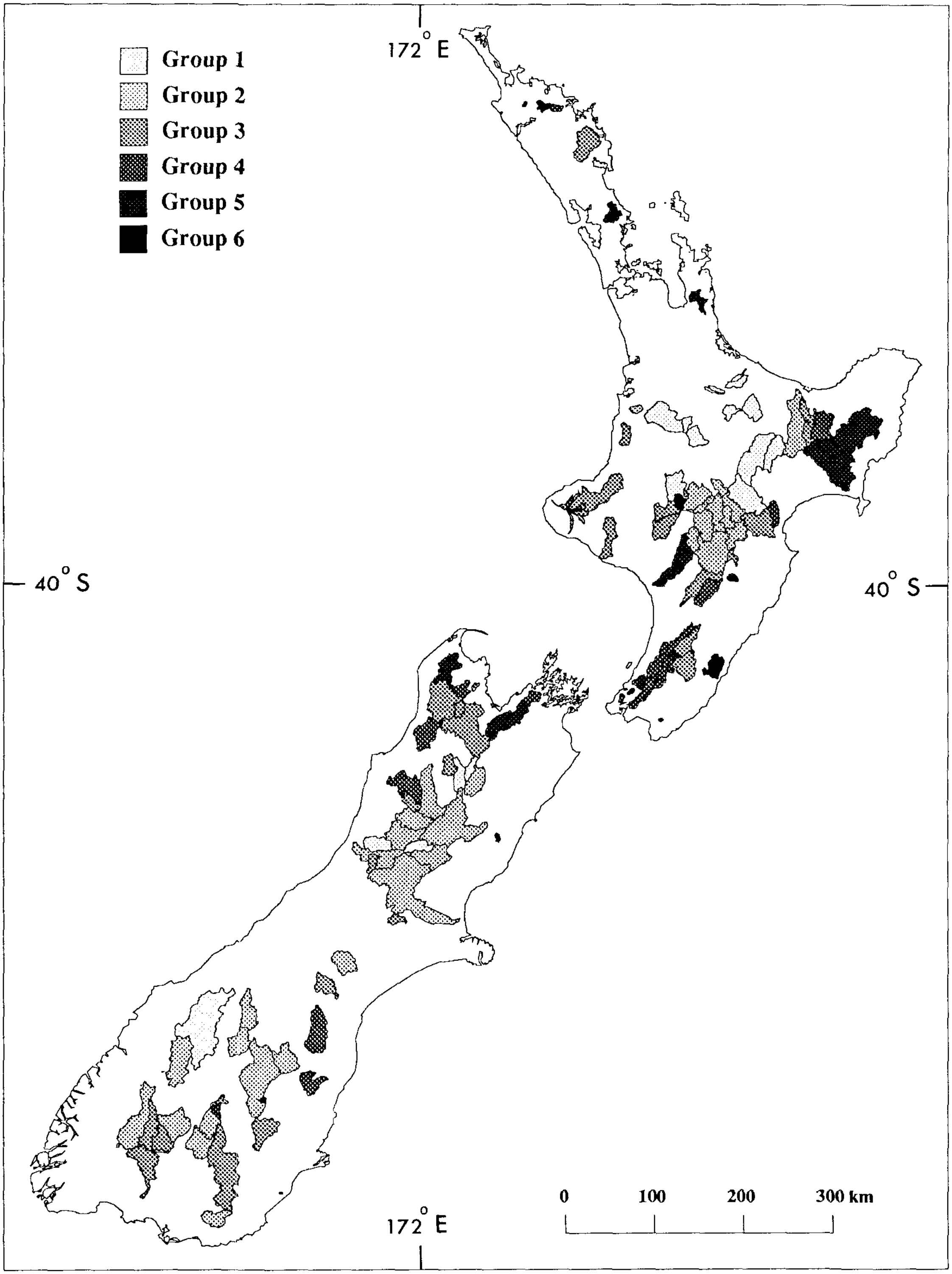



**Fig. 1** Flow recording site catchments in New Zealand and their flow variability classification.

**Table 1** Definition of variables used in analyses.

**A. Hydrological** (flow in $m^3 s^{-1}$)

| | |
|---|---|
| BFI | Baseflow index (baseflow as % of total flow volume) |
| CVFLOW | Coefficient of variation of flow |
| CVMAF | Coefficient of variation of mean annual maximum flow |
| CVMALF | Coefficient of variation of mean annual minimum flow |
| MAF | Mean of annual maximum flow |
| MALF | Mean of annual minimum flow |
| MEANF | Mean annual flow |
| MEDIANF | Median flow (exceeded 50% of time) |
| RUNOFF | Mean annual flow/catchment area expressed in metres |

**B. Catchment**

| | |
|---|---|
| AREA | Catchment area ($km^2$) |
| ELEV_C | Mean catchment elevation above msl (m) |
| ELEV_S | Elevation of site above msl (m) |
| GSLOPE | Average ground slope (areal weighted mean of ROLL, STEEP, and FLAT) |
| SLOPE_R | Mean river slope from top of catchment to site (%) |
| SLOPE_S | Local river gradient |

Catchment (% over catchment)

| | |
|---|---|
| ALLUVIUM | % alluvium |
| DEVEL | % developed pasture, crop, or horticulture |
| FLAT | % flat slope (< 4°) |
| FOREST | % native or exotic forest cover |
| HARDSED | % hard sedimentary rock |
| IGNEOUS | % igneous rock |
| LAKE | % lake area |
| LIME | % limestone |
| LOESS | % loess soil |
| NISTEEP | % North Island steepland soils |
| ROLL | % rolling slope (8–20°) |
| SCHIST | % schist |
| SCRUB | % native scrub, gorse, or broom cover |
| SIALP | % South Island alpine soils |
| SOFTSED | % soft sedimentary rock |
| STEEP | % steep slope (> 20°) |
| TUSSOCK | % undeveloped grassland or tussock |
| VOLCANIC | % volcanic ash |
| WSTOR_H | % regolith with high water storage and transmissivity |
| WSTOR_L | % regolith with low water storage and transmissivity |
| WSTOR_M | % regolith with medium water storage and transmissivity |

**C. Environmental**

Temperature (°C)

| | |
|---|---|
| MAXTEMP | Maximum annual sinusoidal temperature (maximum annual) |
| MINTEMP | Minimum annual sinusoidal temperature (minimum annual) |
| RANGTEMP | Mean annual temperature amplitude |
| TEMP | Mean annual temperature |

In-stream habitat

| | |
|---|---|
| BEDROCK | % bedrock substrate |
| BOULDER | % boulder (> 264 mm) substrate |
| COARSEGRAVEL | % gravel (10–64 mm) substrate |
| COBBLE | % cobble (64–264 mm) substrate |
| COVER | In-stream trout cover grade (1–9) |
| EROSION1 | % catchment area with severe and very severe erosion |
| EROSIONSB1 | % catchment area with streambank erosion |
| FINEGRAVEL | % fine gravel (2–10 mm) substrate |
| MANNING | Mean Manning's *n* (friction coefficient) for reach |
| SAND | % sand (0.06–2 mm) substrate |
| SILT | % silt (< 0.06 mm) substrate |
| SUBSTRATE | Mean substrate size (mm) calculated from percentage compositions |
| VEGETATION | % in-stream vegetation/debris |

For the following in-stream habitat parameters, three suffixes are used to denote the flow for which the particular variable is derived: 1 at MALF, 2 at MEDIANF, 3 at MEANF.

| | |
|---|---|
| DEPTH | Mean depth (m) |
| RBS | Relative bed stability (ratio of water velocity to velocity which will just move substrate, calculated for each measurement point and averaged for reach) |
| VDEPTH | Standard deviation of mean cross-section depths |
| VEL | Mean velocity ($m s^{-1}$) |
| VVEL | Standard deviation of mean cross-section velocities |
| WUABTA | Weighted usable area % for adult brown trout (Bovee 1978) |
| WUABTF | Weighted usable area % for brown trout feeding (Shirvell & Dungey 1983) |
| WUABTS | Weighted usable area % for brown trout spawning (Shirvell & Dungey 1983) |
| WUAFP | Weighted usable area % for food production (Waters 1976) |
| WUARTA | Weighted usable area % for adult rainbow trout (Bovee 1978) |

Water quality—mean of three values taken at low to median flow

| | |
|---|---|
| COND25 | Total conductivity at 25° C ($mS m^{-1}$) |
| DRP | Dissolved reactive phosphorus ($mg m^{-3}$) |
| pH | pH |
| TIN | Total inorganic nitrogen ($mg m^{-3}$) |
| TKN | Total Kjedahl nitrogen ($mg m^{-3}$) |

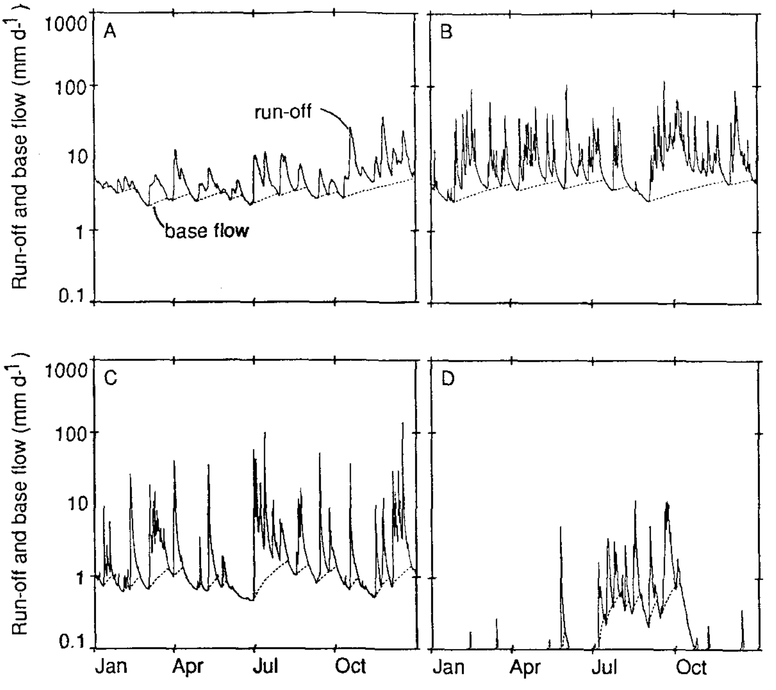



**Fig. 2** Examples of annual run-off and baseflow hydrographs of rivers with low flow variability (Groups 1 and 2) and high flow variability (Groups 5 and 6).

**A** Group 1, Buller River at Lake Rotoiti, 1984, catchment area 195 km$^2$, CVFLOW 0.76;

**B** Group 2, Ahaura River, 1981, catchment area 790 km$^2$, CVFLOW flow 1.06;

**C** Group 5, Wairoa River, 1984, catchment area 464 km$^2$, CVFLOW flow 2.24;

**D** Group 6, Whareama River, 1984, catchment area 398 km$^2$, CVFLOW flow 3.37.

percentage of catchment area containing rock types with high, medium, or low water storage capacity and transmissivity. Ash, alluvium, colluvium, peat, glacial till, and unconsolidated sediments were considered to have high water storage and transmissivity. Weakly indurated sedimentary rocks (mudstone, siltstone, sandstone), crushed argillite, loess, and conglomerates had medium water storage and transmissivity, whereas indurated sedimentary rocks (argillite, greywacke, limestone, sandstone, conglomerate), igneous rocks (excluding ash), and metamorphic rocks had low water storage and transmissivity (Hutchinson in press).

Catchment characteristics were obtained from the New Zealand Land Resource Inventory, and the preparation of basic data used in this study is described by Close & Davies-Colley (1990). In-stream measurements of water depth, velocity, and substrate were made following the general in-stream flow incremental methodology (IFIM) (Bovee 1982) and using survey and hydraulic modelling procedures detailed by Jowett (1989). The modified Wentworth particle size scale (Bovee & Milthous 1978) was used for substrate except that gravel was subdivided into fine gravel (2–10 mm) and gravel (10–64 mm).

Environmental data and classifications based on that data were not available at all 130 river sites. Classification of 86 sites based on water quality data is described by Close & Davies-Colley (1990), 82 sites based on periphyton data by Biggs (1990), 78 sites based on invertebrate data by Quinn & Hickey (1990a), and 85 sites based on trout data by Jowett (1990),

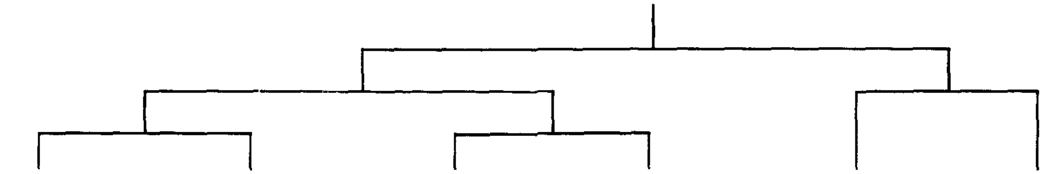
Water temperature data were either obtained from Mosley (1982) or from more recent measurements using the same method (sine curves fitted to water temperatures sampled throughout the year). Mean annual temperature, amplitude, and extremes were calculated from the average annual sinusoidal water temperature variation.

## Analysis

Variables were divided into two groups: catchment and environmental (Table 1B and 1C). Catchment characteristics, represented by 27 topographical, lithological, and land-use variables, can affect flow variability, whereas environmental variables may be affected by flow variability. These two sets of data were analysed in three main steps:

(1) Rivers were classified into six groups of similar flow variability (based on the flow variability indices) using two-way indicator species analysis (TWINSPAN, Hill 1979).

(2) Univariate analysis of variance between groups was used to identify which of the 27 catchment variables (Table 1B) showed significant differences



| Group 1 | Group 2 | Group 3 | Group 4 | Group 5 | Group 6 |
|---|---|---|---|---|---|
| Arnold R. | Ahaura R. | Aparima R. | Atiwhakatu Stm | Akatarawa R. | Nobles Stm |
| Buller R. | Ahuriri R. | Awakino R. | Esk R. | Aorere R. | Ruakokopatuna R. |
| Clutha R. | Grey R. | Baton R. | Fraser R. | Dovedale Ck | Stanton R. |
| Gowan R. | Hautapu R. | Inangahua R. 2 | Hakataramea R. | Hangaroa R. | Whakapapa R. |
| Hurunui R. 1 | Hurunui R. 2 | Irthing Stm | Hutt R. | Hoteo R. | Whareama R. |
| Mangorewa R. | Lindis R. | Karamea R. | Inangahua R. 1 | Kauaeranga R. | |
| Mangakino Stm | Manuherikia R. | Kaupokonui Stm | Kakanui R. | Mangamuka R. | |
| Mohaka R. | Mararoa R. | Makaroro R. | Kerikeri R. | Pakuratahi R. | |
| Rangitaiki R. | Marokopa R. | Mangatainoka R. | Maerewhenua R. | Pauatahanui Stm | |
| Tahunatara Stm | Maruia R. | Mangawhero R. | Mangahao R. | Pelorus R. | |
| Tarawera R. | Mataura R. | Manganuioteao R. | Mokihinui R. | Ruamahanga R. 1 | |
| Tongariro R. 2 | Moawhango R. | Manganui R. 1 | Ohau R. | Tairua R. | |
| Waiari Stm | Ngaruroro R. 1 | Manganui R. 2 | Otaki R. | Tukipo Stm | |
| Waihou R. | Ngaruroro R. 2 | Mangles R. | Pohangina R. | Turakina R. | |
| Waimakariri Stm | Orari R. | Motueka R. | Porirua Stm | Waipaoa R. | |
| Waipapa R. | Otematata R. | Opihi R. | Rai R. | Waipapa Stm | |
| Wanganui R. 2 | Rangitikei R. 1 | Oreti R. | Takaka R. | Wairoa R. | |
| Whirinaki R. | Rangitikei R. 2 | Oroua R. | Tauherenikau R. | Wairoa R. | |
| | Shotover R. | Patea R. | Waingawa R. | | |
| | Taramakau R. | Pomahaka R. | Wainuiomata R. | | |
| | Taruarau R. | Riwaka R. | Waioeka R. | | |
| | Tauranga-Taupo R. | Ruamahanga R. 2 | Waiohine R. | | |
| | Tongariro R. 1 | Selwyn R. | Waiwakaiho R. | | |
| | Waiau R. | Stony R. | Whakatiki Stm | | |
| | Waikaia R. | Taieri R. | | | |
| | Waimakariri R. | Taipo R. | | | |
| | Waipa R. | Tutaekuri R. | | | |
| | Wairau R. | Waimana R. 1 | | | |
| | Wanganui R. 1 | Waimana R. 2 | | | |
| | Whakatane R. | Waingongoro R. | | | |
| | Wyndham Stm | Waiongona Stm | | | |
| | | Wairua R. | | | |
| | | Waitara R. | | | |
| | | Whenuakura R. | | | |

**Fig. 3** Dendrogram listing 130 hydrological sites grouped in order of increasing flow variability. Where there are two sites on the same river, Site 1 is up stream and 2 down stream.

between groups. This subset of catchment variables was then used to investigate the catchment variables which best discriminated between groups of rivers with differing flow variability. Three sites, (Whakapapa River below a diversion structure, Wanganui River at Piriaka, and Tongariro River at Turangi), were excluded because flows are artificially controlled and do not reflect catchment characteristics.

(3) The effect of flow variability on biota, hydraulic, and in-stream habitat was examined for the sites where data were available, including the three sites previously excluded. Variables related to

flow variable were identified if they showed a significant correlation with flow variability and significant differences between groups. The univariate analysis of variance, used to identify group differences, was similar to that made for catchment variables, except group division was made at a higher level so that there were only three groups, increasing the number of sites in each group and making significance testing more valid.

## RESULTS

### Classification of sites

All 130 sites were classified into six groups based on flow variability (Fig. 3). Coefficients of variation of annual extremes were not used in classifying sites because they showed little relationship to other flow variability indices or catchment characteristics. These indices are affected by the probabilistic nature of extreme flows and the uncertainty in extreme flow estimation using stage-discharge rating curves.

The primary division (Fig. 3) separated Groups 5 and 6 from the rest because of their high ratios of mean annual flood to median flow and mean to median flow, and large coefficient of variation of flow. Flow variability for all indices, except the coefficient of variation of annual maxima, increased from Group 1 to Group 6 (Table 2). Differences between all groups were significant (Tukey test $P < 0.001$) for one index, the coefficient of variation of flow. However, differences between groups were not always significant for the other indices.

There was no way of deciding a "best" flow variability index and all were highly correlated except the coefficient of variation of annual maximum flows (Table 3). In general, as flow variability increased, so did the variation in baseflow, the magnitude of flow fluctuations above baseflow, and the flow recession rates (Fig. 2).

### Univariate analysis of variance of catchment characteristics between groups

Significant (Kruskal-Wallis test $P < 0.05$: Zar 1984) differences between groups were found for 20 catchment variables (Table 4). Several variables were highly correlated. Catchment area was correlated with mean ($r = 0.71$) and median flow ($r = 0.71$). The high water storage/transmissivity index was correlated with

**Table 2** Means and standard deviations of flow variability indices for the six groups determined by TWINSPAN analysis (Hill 1979).

| | Group 1 *n*=18 | Group 2 *n*=31 | Group 3 *n*=34 | Group 4 *n*=24 | Group 5 *n*=18 | Group 6 *n*=5 |
|---|---|---|---|---|---|---|
| Overall flow variability | | | | | | |
| BFI | 77.7 ± 14.8 | 58.2 ± 9.0 | 47.4 ± 11.6 | 41.6 ± 12.6 | 39.0 ± 8.4 | 27.8 ± 5.1 |
| CVFLOW | 0.55 ± 0.25 | 1.05 ± 0.12 | 1.48 ± 0.2 | 1.80 ± 0.23 | 2.33 ± 0.33 | 3.29 ± 0.37 |
| MEANF/MEDIANF | 1.1 ± 0.10 | 1.43 ± 0.10 | 1.67 ± 0.13 | 1.79 ± 0.15 | 2.15 ± 0.23 | 4.00 ± 2.12 |
| Low flow variability | | | | | | |
| MALF/MEDIANF | 0.62 ± 0.21 | 0.34 ± 0.08 | 0.30 ± 0.10 | 0.25 ± 0.11 | 0.23 ± 0.10 | 0.15 ± 0.10 |
| CVMALF | 0.17 ± 0.06 | 0.27 ± 0.14 | 0.31 ± 0.17 | 0.37 ± 0.19 | 0.39 ± 0.19 | 0.99 ± 0.52 |
| High flow variability | | | | | | |
| MAF/MEDIANF | 8.5 ± 6.5 | 18.8 ± 4.9 | 35.9 ± 10.6 | 60.8 ± 14.4 | 101.4 ± 32.8 | 244.8 ± 96.6 |
| CVMAF | 0.41 ± 0.21 | 0.42 ± 0.11 | 0.39 ± 0.14 | 0.45 ± 0.25 | 0.43 ± 0.19 | 0.55 ± 0.13 |

**Table 3** Correlation matrix (Spearman rank correlation) of flow variability indices (abbreviations listed in Table 1). $^{***}P < 0.001$.

| | MEANF/MEDIANF | CVFLOW | MALF/MEDIANF | CVMALF | MAF/MEDIANF | CVMAF |
|---|---|---|---|---|---|---|
| MEANF/MEDIANF | 1.00 | | | | | |
| CVFLOW | 0.91*** | 1.00 | | | | |
| MALF/MEDIANF | −0.67*** | −0.62*** | 1.00 | | | |
| CVMALF | 0.47*** | 0.53*** | −0.72*** | 1.00 | | |
| MAF/MEDIANF | 0.88*** | 0.96*** | −0.56*** | 0.47*** | 1.00 | |
| CVMAF | 0.04 | 0.16 | −0.16 | 0.37*** | 0.09 | 1.00 |
| BFI | −0.81*** | −0.70*** | 0.54*** | −0.30*** | −0.73*** | 0.16 |

percentage of volcanic ash ($r = 0.89$) and negatively correlated with low water storage/transmissivity index ($r = -0.80$). The medium water storage/transmissivity index was correlated with the percentage of soft sedimentary rock ($r = 0.90$). Percentage of flat land was correlated with the percentage of developed land ($r = 0.61$) and negatively correlated with average ground slope ($r = -0.88$). Differences in group means can result from the characteristics of a single group (e.g., forest area within a catchment for Group 6), or from a linear relationship between the variable and flow variability over all groups. There were significant correlations ($P < 0.02$) between flow variability, as measured by the coefficient of variation of flow, and all variables in Table 4, except average ground slope, percentage flat land, mean river slope, percentage of forest, and percentage of tussock grassland.

### Discriminant modelling with catchment characteristics

Stepwise discriminant analysis (Klecka 1980) selected eight significant ($P < 0.01$) variables (Table 5). This model correctly classified 65% or 82 of the 127 sites. The first four discriminant functions were significant ($P < 0.02$). Group centroids plotted against the first two discriminant functions (Fig. 4) showed Function 1 was related to flow variability, and Function 2 was related to flow variability for Groups 2 to 6, but separated Group 1.

Correlations between variables and the discriminant function (structure coefficients) reveal how closely the variables and function are related (Table 5). The percentage of catchment area with high water storage and transmissivity was most closely related to Function 1, but the area of lake in the catchment and elevation of the flow recorder site were also important. Function 2 was most closely related to the area of lake in the catchment, the catchment area, and the elevation of the recorder. The area of lake in the catchment was the variable which separated Group 1 from the other groups in Function 2 (Fig. 4 and Table 5).

Functions 3 and 4 were not obviously related to flow variability. In Function 3, the percentage of land with a flat slope separated Group 3 and in Function 4,

**Table 4** Group means and standard deviations for catchment variables which show significant ($P < 0.05$) difference between groups (abbreviations listed in Table 1). ***$P < 0.001$.

| Group | AREA*** | DEVEL | ELEV_C | ELEV_S*** | FLAT*** |
|---|---|---|---|---|---|
| 1 | 482 ± 636 | 9.6 ± 12.4 | 353 ± 358 | 258 ± 186 | 10.9 ± 14.0 |
| 2 | 900 ± 749 | 9.7 ± 13.9 | 513 ± 460 | 308 ± 211 | 13.4 ± 7.9 |
| 3 | 511 ± 493 | 30.7 ± 27.8 | 440 ± 316 | 154 ± 124 | 27.9 ± 22.9 |
| 4 | 259 ± 224 | 12.6 ± 17.9 | 207 ± 290 | 110 ± 73 | 10.8 ± 14.4 |
| 5 | 406 ± 527 | 19.8 ± 26.6 | 246 ± 306 | 100 ± 123 | 5.4 ± 7.0 |
| 6 | 117 ± 189 | 34.3 ± 45.6 | 138 ± 168 | 133 ± 108 | 4.3 ± 5.1 |
| | FOREST | GSLOPE | LAKE*** | LOESS | MEANF |
| 1 | 51.5 ± 22.3 | 21.0 ± 4.0 | 2.5 ± 3.8 | 0.0 ± 0.0 | 26.1 ± 46.1 |
| 2 | 29.1 ± 26.9 | 22.1 ± 3.0 | 0.1 ± 0.4 | 1.9 ± 8.2 | 37.0 ± 38.3 |
| 3 | 33.0 ± 27.1 | 18.5 ± 6.6 | 0.0 ± 0.0 | 5.4 ± 10.5 | 20.0 ± 23.7 |
| 4 | 47.6 ± 33.5 | 23.0 ± 4.9 | 0.1 ± 0.4 | 5.8 ± 11.4 | 14.2 ± 18.7 |
| 5 | 41.8 ± 34.3 | 24.4 ± 3.3 | 0.0 ± 0.0 | 6.3 ± 14.8 | 15.1 ± 20.0 |
| 6 | 3.3 ± 5.3 | 22.7 ± 6.0 | 0.0 ± 0.0 | 5.8 ± 11.5 | 2.0 ± 3.1 |
| | MEDIANF*** | NISTEEP | SIALP | SLOPE_R | SOFTSED |
| 1 | 22.7 ± 41.2 | 16.6 ± 20.8 | 1.5 ± 4.3 | 2.76 ± 2.12 | 0.1 ± 0.5 |
| 2 | 25.9 ± 26.4 | 18.3 ± 26.2 | 0.9 ± 2.2 | 2.23 ± 0.93 | 5.9 ± 17.0 |
| 3 | 11.9 ± 13.9 | 15.7 ± 23.9 | 0.2 ± 0.8 | 3.94 ± 3.09 | 11.9 ± 18.6 |
| 4 | 7.7 ± 9.7 | 38.7 ± 36.4 | 0.0 ± 0.0 | 4.20 ± 2.17 | 6.0 ± 15.3 |
| 5 | 7.0 ± 9.5 | 43.0 ± 33.3 | 0.0 ± 0.0 | 2.82 ± 1.66 | 21.6 ± 33.9 |
| 6 | 0.3 ± 0.4 | 24.8 ± 32.7 | 0.0 ± 0.0 | 4.21 ± 3.42 | 24.3 ± 28.4 |
| | TUSSOCK | VOLCANIC | WSTOR_H*** | WSTOR_L*** | WSTOR_M*** |
| 1 | 21.8 ± 21.2 | 57.9 ± 43.9 | 68.2 ± 36.9 | 27.1 ± 33.6 | 1.8 ± 6.8 |
| 2 | 46.5 ± 30.8 | 25.1 ± 34.4 | 38.9 ± 29.4 | 55.9 ± 32.8 | 4.6 ± 9.3 |
| 3 | 24.9 ± 21.9 | 29.8 ± 36.4 | 42.9 ± 30.3 | 36.8 ± 31.8 | 16.9 ± 21.0 |
| 4 | 26.8 ± 29.2 | 5.4 ± 16.5 | 13.2 ± 19.4 | 78.4 ± 27.6 | 7.5 ± 14.2 |
| 5 | 24.5 ± 28.8 | 9.4 ± 18.1 | 11.4 ± 13.7 | 60.1 ± 42.9 | 28.6 ± 33.2 |
| 6 | 48.0 ± 38.4 | 0.0 ± 0.0 | 4.3 ± 4.9 | 58.0 ± 37.4 | 38.5 ± 33.7 |

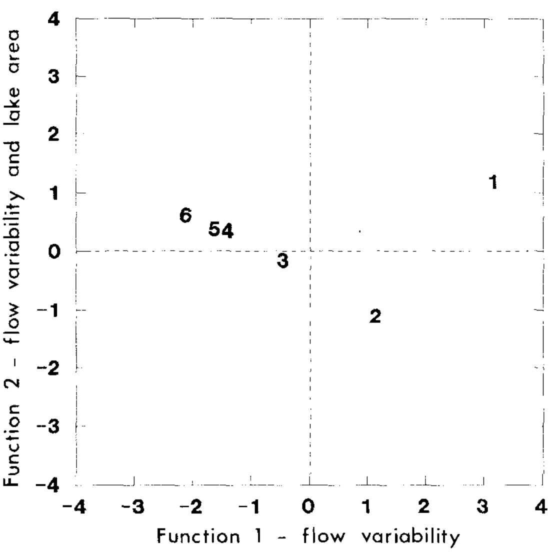



**Fig. 4** Group centroids (Groups 1–6 inclusive) for the first and second discriminant functions of the flow variability discriminant model using catchment variables.

medium water storage and transmissivity index discriminated Groups 4 and 6 from the others (Table 5).

The incorrectly classified sites showed no obvious geographical pattern, and 37 of 45 sites (82%) were classified into a group which was adjacent to the correct classification.

## Univariate analysis of variance of environmental variables between groups

To avoid small sample sizes, flow variability groups were formed at a higher level, i.e., Groups 1 and 2, Groups 3 and 4, and Groups 5 and 6.

Significant ($P < 0.05$) Spearman rank correlations with the coefficient of variation of flow and significant (Kruskal-Wallis test $P < 0.05$: Zar 1984) differences between the three flow variability groups were found for 22 environmental variables (Table 6).

Strong positive correlations ($P < 0.001$) were found between the coefficient of variation of flow and the maximum annual water temperature and annual water temperature amplitude. Mean water velocity and relative bed stability were negatively correlated with the coefficient of variation of flow at median and mean annual low flow. Variation in stream geometry, as measured by standard deviation of mean cross-section depth and velocity, increased with flow variability.

Weighted usable area for both adult brown and rainbow trout at median and mean flow increased with flow variability. However, the most significant group differences ($F = 12.0$, $P < 0.001$) were for *weighted usable area for food production at mean* annual low flow which decreased with flow variability. Optimum water velocities used to calculate adult trout habitat were between 0 and 0.43 m $s^{-1}$ whereas optimum velocities for food production were 0.64–0.85 m $s^{-1}$.

Water quality, as indicated by conductivity and total Kjedahl nitrogen, improved as flow variability decreased. However, there were no significant relationships between flow variability and pH, inorganic nitrogen, or dissolved phosphorus.

**Table 5** Correlations between variables and discriminant functions (structure coefficients) for significant functions ($P < 0.02$) of the discriminant model (abbreviations listed in Table 1).

| Variable | Function 1 | Function 2 | Function 3 | Function 4 |
|---|---|---|---|---|
| AREA | 0.147 | –0.456 | –0.052 | –0.128 |
| ELEV_S | 0.284 | –0.364 | –0.154 | –0.094 |
| FLAT | 0.008 | –0.216 | 0.883 | 0.077 |
| LAKE | 0.296 | 0.505 | –0.058 | 0.011 |
| NISTEEP | –0.163 | 0.173 | –0.401 | 0.206 |
| SLOPE_R | –0.136 | 0.181 | 0.331 | 0.276 |
| WSTOR_H | 0.390 | 0.042 | 0.536 | –0.106 |
| WSTOR_M | –0.228 | 0.117 | 0.060 | –0.884 |

## Relationships between flow variability classification and classifications based on biological and water quality criteria

When sites were tabulated by flow variability and trout classifications (Table 7A), there was a significant relationship between flow variability and trout species and abundance classifications ($\chi^2 = 22.2$, $P = 0.014$). Rainbow trout rivers were predominantly those with low flow variability ($\chi^2 = 12.74$, $P = 0.002$), but there was no significant relationship between brown trout abundance and flow variability ($\chi^2 = 7.29$, $P = 0.121$).

Periphyton communities, formed into three groups (Table 7B), showed a significant association with flow variability ($\chi^2 = 15.7$, $P = 0.003$). Periphyton Group 1, dominated by filamentous algae, was associated with rivers of high flow variability. Groups 2 and 3 were associated with rivers of low and moderate flow variability.

There were significant differences in flow variability between the two major invertebrate community groups ($\chi^2 = 7.49$, $P = 0.024$)(Table 7C). The first group, described by Quinn & Hickey (1990a) as "clean water" fauna dominated by mayflies and caddisflies, was more common in rivers with low flow variability. The second group, characterised by molluscs, chironomids, or oligochaetes, was more common in rivers with more variable flows. To a degree, differences may have been masked by the invertebrate sampling strategy, which was to take samples from similar water depths and velocities in each river.

There was no significant relationship between water quality and flow variability classifications (Table 7D). The majority of sites fell into one water quality group, clean rivers with low nutrients or ionic strength, and were most commonly associated with rivers of low to moderate flow variability. The other group, with higher nutrients and ionic concentrations, showed no association with any particular flow variability group. Two sites, affected by sewage or geothermal input, were excluded. However, two water quality variables (conductivity and total Kjedahl nitrogen) were related to flow variability (Table 6), suggesting that the water quality classification was dominated by different water quality variables.

## DISCUSSION

### Flow variability

There was no clear-cut distinction between hydrological indices and, apart from the coefficient of variation of annual maxima, all were highly correlated. Although TWINSPAN was used to form groups based on all indices, very similar groupings result from ordered arrangements based on one flow variability index, especially the coefficient of variation of flow. However, other indices may be more appropriate for particular studies, such as mean annual maxima in flood studies (e.g., McKerchar & Pearson 1989), or the baseflow index in biological studies.

As expected, rivers which drained lakes or were fed from springs or similar groundwater sources were rivers with the least flow variation. More surprisingly, the adjacent group, with slightly more flow variation, was formed of rivers whose catchments were subject to regular, but not constant, precipitation—resulting in relatively constant baseflow (e.g., Fig. 2B). West Coast rivers fell into this category, generally agreeing with Beable & McKerchar (1982) who found this region had the lowest coefficient of variation of annual maxima of any region in New Zealand. Greatest flow variation occurred in rivers which were subject to irregular precipitation, with correspondingly greater variation in run-off and baseflow (e.g., Fig. 2C and 2D). Water quality varied in accordance with this, with "better" quality water in rivers with a constant supply of water and "poorer" quality water in rivers with less regular flow.

**Table 6** Group means and standard deviations for environmental variables which show significant ($P < 0.05$) difference between groups and significant ($P<0.05$) correlations with the coefficient of variation of flow (abbreviations listed in Table 1). Scc, Spearman correlation coefficient, ***$P < 0.001$, **$P < 0.01$.

| | Flow variability | | | |
|---|---|---|---|---|
| | Low | Medium | High | Scc |
| MAXTEMP | 16.1 ± 2.0 | 18.2 ± 2.3 | 19.2 ± 3.2 | 0.443*** |
| RANGTEMP | 4.6 ± 1.4 | 5.6 ± 1.0 | 5.8 ± 1.6 | 0.402*** |
| TEMP | 11.5 ± 1.8 | 12.6 ± 2.0 | 13.4 ± 2.2 | 0.237** |
| RBS(1) | 0.30 ± 0.10 | 0.24 ± 0.10 | 0.16 ± 0.06 | 0.449*** |
| RBS(2) | 0.39 ± 0.10 | 0.34 ± 0.12 | 0.25 ± 0.08 | −0.330 |
| VDEPTH(1) | 0.39 ± 0.17 | 0.48 ± 0.15 | 0.64 ± 0.13 | 0.418*** |
| VEL(1) | 0.48 ± 0.14 | 0.32 ± 0.11 | 0.21 ± 0.08 | −0.618*** |
| VEL(2) | 0.66 ± 0.17 | 0.53 ± 0.15 | 0.40 ± 0.08 | −0.569*** |
| VEL(3) | 0.73 ± 0.18 | 0.64 ± 0.16 | 0.54 ± 0.09 | −0.395** |
| VVEL(1) | 0.33 ± 0.15 | 0.42 ± 0.14 | 0.72 ± 0.28 | 0.569*** |
| VVEL(2) | 0.22 ± 0.09 | 0.26 ± 0.08 | 0.43 ± 0.15 | 0.487*** |
| VVEL(3) | 0.21 ± 0.08 | 0.24 ± 0.08 | 0.35 ± 0.14 | 0.331 |
| WUABTA(2) | 0.18 ± 0.09 | 0.19 ± 0.07 | 0.31 ± 0.09 | 0.445*** |
| WUABTA(3) | 0.17 ± 0.08 | 0.19 ± 0.07 | 0.28 ± 0.08 | 0.454*** |
| WUABTF(1) | 0.10 ± 0.06 | 0.14 ± 0.06 | 0.13 ± 0.03 | 0.331 |
| WUABTF(2) | 0.06 ± 0.04 | 0.11 ± 0.06 | 0.12 ± 0.03 | 0.448*** |
| WUABTF(3) | 0.06 ± 0.03 | 0.10 ± 0.05 | 0.10 ± 0.03 | 0.382** |
| WUAFP(1) | 0.33 ± 0.13 | 0.24 ± 0.08 | 0.12 ± 0.07 | 0.491*** |
| WUARTA(2) | 0.16 ± 0.07 | 0.20 ± 0.09 | 0.25 ± 0.05 | 0.391** |
| WUARTA(3) | 0.15 ± 0.06 | 0.20 ± 0.08 | 0.25 ± 0.06 | 0.398** |
| COND25 | 8.4 ± 7.7 | 9.4 ± 5.2 | 17.5 ± 11.2 | 0.334** |
| TKN | 95 ± 55 | 132 ± 76 | 525 ± 1473 | 0.359** |

### Catchment characteristics

A broad geographical pattern was evident in the classification of river sites according to flow variability (Fig. 1). Group 1 and 2 sites were generally located in the central portions of the North and South Islands, Group 6 on the east coasts of both islands, Group 4 sites around Mount Taranaki, the Tararua Ranges, and the Nelson region, and Group 3 and 5 sites in intermediate locations. Six of the seven lake-fed rivers in the study were in Group 1. The composition of the regolith was the most important determinant of flow variability. The variable which best described the regolith was the percentage of rock in the catchment with high water storage and transmissivity, which, in turn, was closely related to the percentage of volcanic ash in the catchment.

In this study, there were no specific variables describing climatic zones based on exposure to prevailing airflows and topography. The importance of climate could only be inferred from the geographical distribution of flow variability and from variables which were themselves geographically distributed. In areas exposed to prevailing airflows and especially where topography increases rainfall, such as the Southern Alps, rainfall is frequent and flow variability is low. Variables such as mean and median flow, site and catchment altitudes, and percentage of alpine and steepland soil were important discriminators of this type of climate. In areas away from prevailing airflows, such as the east coast, rainfall is less frequent and flows more variable. The percentage of soft sedimentary rock, as commonly occurs on the east coast of the North Island, was a discriminator of this climatic zone. Mosley (1981) concluded that climate had a dominant influence on flood hydrology and the regions he identified have a broad correspondence with those identified here and those used by Beable & McKerchar (1982) in their regional flood study.

However, as Mosley (1981) pointed out, not all rivers within a geographically contiguous region have the same hydrological characteristics. Catchment area and the area of lake in the catchment both influenced flow variability. An increase in either factor decreased flow variability by storage of water in lake, river, and regolith. Flow variability also increased with catchment slope, but this was secondary to the effect of climate, regolith, catchment area, and lakes.

### Environmental characteristics

Flow variability can influence environmental river characteristics. Mean annual water temperature, the annual variation in water temperature, and the average summer temperature all increased with flow variability whereas mean water velocity decreased. Generally, water temperature increases as solar radiation and air temperature increase, and as water velocity decreases (Theurer 1982). The increase in water temperature

**Table 7** Number of river sites with high, medium, and low flow variability tabulated by biological and water quality classifications.

| | Flow variability | | |
|---|---|---|---|
| | Low | Medium | High |
| **A** Trout species and abundance classification | | | |
| 1. Brown trout, low biomass | 3 | 20 | 2 |
| 2. Brown trout, moderate biomass | 8 | 8 | 2 |
| 3. Brown trout, high biomass | 3 | 5 | 0 |
| 4. Brown and rainbow trout, moderate biomass | 10 | 6 | 1 |
| 5. Brown and rainbow trout, high biomass | 5 | 1 | 0 |
| 6. Rainbow trout only | 7 | 2 | 2 |
| **B** Periphyton community classification by dominant taxa | | | |
| 1. *Cladophora glomerata*/*Rhizoclonium* sp. and *Spirogyra* spp. | 1 | 4 | 7 |
| 2. *Oedogonium* spp./*Melosira varians* and diatom | 13 | 16 | 2 |
| 3. *Ulothrix zonata*/*Stigeoclonium* sp., *Audouinella hermanii* and *Lyngbya* spp. | 17 | 14 | 8 |
| **C** Benthic invertebrate classification by dominant taxa | | | |
| 1. "Clean-river" mayflies and stoneflies | 19 | 18 | 6 |
| 2. Oligochaetes, molluscs, or chironomids | 6 | 18 | 11 |
| **D** Water quality classification | | | |
| 1. "Clean-river" low nutrient or ionic strength | 25 | 28 | 11 |
| 2. High nutrient or ionic strength | 6 | 8 | 7 |

with increased flow variability is a result of the decrease in water velocity, and is aggravated by the higher air temperatures and levels of solar radiation which occur on the east coast.

Stream morphology varied with flow variability. Variation of mean cross-section depth and velocity indicated that rivers with less flow variation were longitudinally more uniform, particularly at low flows, than rivers with high flow variability. Field observations also confirmed stable flow rivers tended to be confined to well-defined channels and lacked the characteristic pool/riffle structure of gravel bed rivers. The difference may be related to the physical processes of scour and fill which help maintain the pool/riffle structure of a gravel bed river during floods (Andrews 1979). Substrate was relatively more stable at low to median flow in rivers of high flow variability than in rivers of low flow variability because of lower water velocities in rivers of high flow variability. Similarly, water velocity determined how weighted usable area varied with flow variability. Weighted usable areas with lower optimum velocities tended to increase with flow variability, whereas weighted usable area with a higher optimum velocity decreased.

Jowett (1990) identified flow variability as one of the major factors influencing trout distribution and abundance. This study confirms the association of rainbow trout with rivers of low flow variability. He also associated weighted usable area for food production and standard deviation of mean cross-section depth with trout abundance. The same two variables were associated with flow variability in this study.

Environmental factors, such as water quality and substrate composition, have a major effect on the periphyton and invertebrate community types that develop in a river (e.g., Biggs 1990; Quinn & Hickey 1990a), whereas flow variability, particularly floods, affects biomass (e.g., Sagar 1986; Scrimgeour et al. 1988; Quinn & Hickey 1990b). Benthic invertebrates considered indicative of "clean rivers" (Quinn & Hickey 1990a) were more common in rivers of low flow variability where water quality was "better". In addition, relationships between invertebrate and periphyton community classifications and flow variability suggest that water velocity influences community structure. Aquatic taxa with a preference for low water velocities (e.g., filamentous algae and molluscs) were more common in rivers of high flow variability, whereas taxa with higher velocity preferences (e.g., diatoms and stoneflies) were more common in rivers with less flow variability.

Of the environmental factors related to flow variability, water velocity appeared to be the most important. It influenced water temperature, relative bed stability, and weighted usable area and was a determinant of the structure of the aquatic community.

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