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REGIONAL FREQUENCY ANALYSIS OF LOW FLOWS IN NEW ZEALAND RIVERS

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ABSTRACT

Annual minimum low flow series (1-day, 7-day and 30-day mean flows) from nearly 500 catchments are used to investigate regional patterns and frequency distributions of low flows within New Zealand. Maps of logarithms of mean annual minimum 7-day specific mean flows demonstrate broad regional patterns and suggest estimation of this statistic from contour maps may be worthwhile for many regions. Catchment characteristics (rainfall, soil porosity, vegetation, slope, elevation, hydrogeology) are used to help explain regional variations. Probabilities of zero flows in annual minimum series are estimated using logistic regression on river catchment area and mean annual precipitation. L-moment ratios of non-zero low flow series are used to test homogeneity of regional and non-geographic groupings of river catchments, and to identify candidate statistical distributions for each group. Regional groupings based on Hutchinson's (1990) low flow regions are of varying homogeneity. A homogeneous Bay of Plenty / Rotorua sub-region is identified from the heterogeneous North Island central volcanic region. Most of the groupings analysed are heterogeneous so a wide range of frequency distributions is required to describe adequately New Zealand annual low flow series.

INTRODUCTION

On an annual basis, the cost of drought is on a par with the cost of flood damage in New Zealand (see e.g. Pearson 1992). Despite such a huge cost to the community, not enough is known yet about regional patterns and frequency of occurrence of New Zealand droughts.

Droughts are caused by sustained periods without significant rainfall. River catchments integrate the effects of rainfall over large areas, so analysis of low streamflows can advance knowledge of droughts, as well as provide critical information to river users. This study uses river flow records from almost 500 New Zealand catchments to investigate regional patterns and frequency distributions of low flows.

Background to low flow statistics

The impacts of droughts on river users can be expressed in terms of how often a river can supply a particular water demand. Demand flow is the total water requirement at a particular point on a river, such as water supply for domestic, industrial and agricultural uses, provision for hydroelectric power generation, and minimum flow required by fish. If the demand cannot be met satisfactorily by the river, how much water must be stored in order to meet any deficiency which might arise? To answer this question, frequency analyses of low flows and of water deficiency volumes are required.

The assumptions made in drought frequency analyses are similar to those for flood frequency, i.e. recorded data are assumed to have been drawn randomly from an unchanging statistical distribution, which will also apply in future.

Low flow statistics used in frequency analyses are usually annual minimum m-day mean flows, where m is often taken to be 7 days i.e., the week in a year with the lowest average flow.

The form of the probability distribution governing annual minimum flow series is that: minima are bounded below by some flow $q_0 > 0$, since negative river flows cannot occur; and skewness of annual minima series is most often positive (Matalas 1963). The true distribution of minima is always unknown and parametric distributions (or non-parametric approaches for that matter) are simply estimators of that unknown distribution. Statistical distributions used for low flows include the Weibull (Nathan and McMahon 1990) and log-normal distributions. Another possibility is the Extreme Value Type 1 (EV1) distribution; although it does not have a lower bound, the probability of its values being smaller than zero is usually much less than 0.1% when analysing hydrological data.

The return period (T) of minima is the reciprocal of F, the cumulative probability function for annual minima, i.e. $T = 1/F$ for minima. For a given design probability $1/T$ of failure (i.e. unable to meet water demand), if the value of a low flow quantile q_T is large in comparison to the demand flow, then the river can supply the demand satisfactorily. On the other hand if q_T is less than, or of the same order of magnitude as, the demand flow, then the river alone, without some form of regulation, could not adequately supply demand.

Low flows are usually quite small in comparison to the mean flow of the river. For example, the mean flow over 20 years for the Hutt River at Birchville near Wellington (site number 29818, drainage area 427 km^2, Walter 1990) is

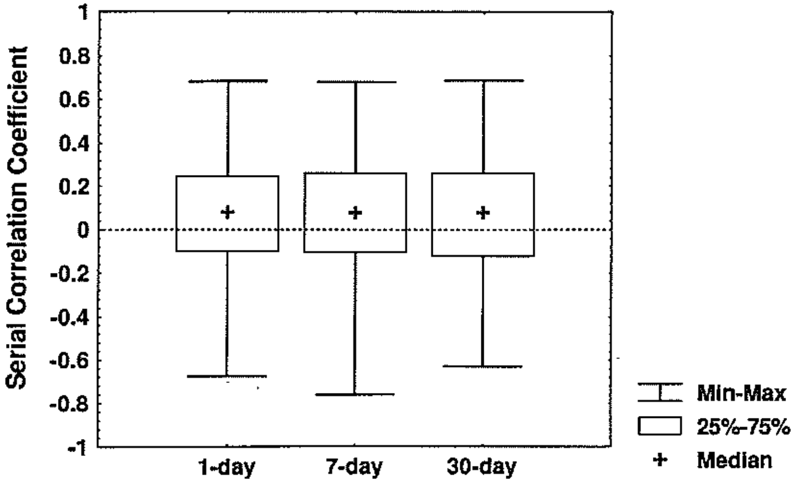

FIG. 1—Distribution of serial correlation coefficients for annual minimum low flows of three durations from almost 500 New Zealand catchments.

TABLE 1—Pearson correlation coefficients for 7-day low flow statistics (*LQA*, L_{CV}, L_{SK}, L_{KUR}), from catchments with 20 or more years of record, and catchment characteristics

Variable	*LQA*	L_{CV}	L_{SK}	L_{KUR}	*A*	*P*	*DWP*	*EL*	*BL*	*H*	*S*	*VEG*
LQA	1.00											
L_{CV}	-.79*	1.00										
L_{SK}	-.54*	.58*	1.00									
L_{KUR}	-.21*	.25*	.56*	1.00								
A	.21*	-.19*	-.10	-.13	1.00							
P	.58*	-.29*	-.30*	-.19*	.07	1.00						
DWP	.47*	-.31*	-.33*	-.21*	.06	.17	1.00					
EL	.42*	-.33*	-.30*	-.20*	-.01	.24*	.41*	1.00				
BL	.26*	-.14	-.17	-.14	-.00	.11	.20*	.83*	1.00			
H	.05	-.06	-.00	.01	.08	-.19*	.28*	-.34*	-.45*	1.00		
S	.28*	-.10	-.14	.02	-.02	.39*	.32*	.46*	.46*	-.52*	1.00	
VEG	.45*	-.35*	-.32*	-.15	.09	.39*	.31*	.01	-.18*	-.06	.40*	1.00

$^*p < 0.05$

TABLE 2—Logistic regression coefficient estimates (with standard errors) for probabilities of zero low flows of different durations.

Duration (days)	No. of Sites	*a*	*s.e.*	*b*	*s.e.*	*c*	*s.e.*
1	495	-11.6	3.2	1.63	0.19	4.28	1.05
7	495	-13.4	3.4	1.92	0.23	5.02	1.15
30	493	-12.7	2.8	1.86	0.20	4.90	0.93

22300 l/s, while estimated values of 7-day q_5, q_{10} and q_{20} are 1607, 1346 and 1155 l/s respectively (Pearson 1992). These vary from 7% to 5% of mean flow, which is a narrow range of variation. In contrast, design floods may range from 50 to 200 times the mean flow.

Regional Studies

If no gauging station exists at a river site, the knowledge available for other gauged sites must be applied to the ungauged site. Regional studies analyse recorded low flow series in a region and estimate minimum flows of some return period (q_T). These values are then applied to ungauged catchments. Methods previously used in New Zealand include:

* regression equations for low flows applied to catchments within distinct hydrological regions (e.g. Grant 1971), including flows obtained from simultaneous gauging of streams with and without records (e.g. McKerchar and Dymond 1981, Harrison 1988).

* regression equations for low flows based on catchment characteristics such as catchment area, mean rainfall, hydrogeology and slope (Whitehouse et al. 1983; Hutchinson 1990).

Hutchinson's (1990) study covered all of New Zealand, whereas the other studies focused on particular regions. Hutchinson used regression equations based on catchment characteristics to estimate $q5/A$ (7-day 5-year return period specific discharge), for 11 regions. Regions were identified using plots of $q5/A$ and catchment rainfall, where $q5$ was estimated subjectively, without investigating the underlying frequency distribution. This study explores more fully the nature of frequency distributions of annual minimum flows in New Zealand rivers. Annual minimum low flow series (1-day, 7-day and 30-day mean flows) from nearly 500 New Zealand catchments are used. Spatial patterns of mean annual minimum low flow (q) are investigated using contour maps and regressions on catchment characteristics. Statistics of the dimensionless annual series (divided by series q) are used to investigate frequency distributions. Regional estimation of both q and the dimensionless frequencies provides a complete regional model of annual low flow series.

DATA

Annual minimum series of 1-day, 7-day and 30-day mean flows were assembled for 495 gauged New Zealand catchments from the national Water Resources Archive. These flow data have been collected by central and local

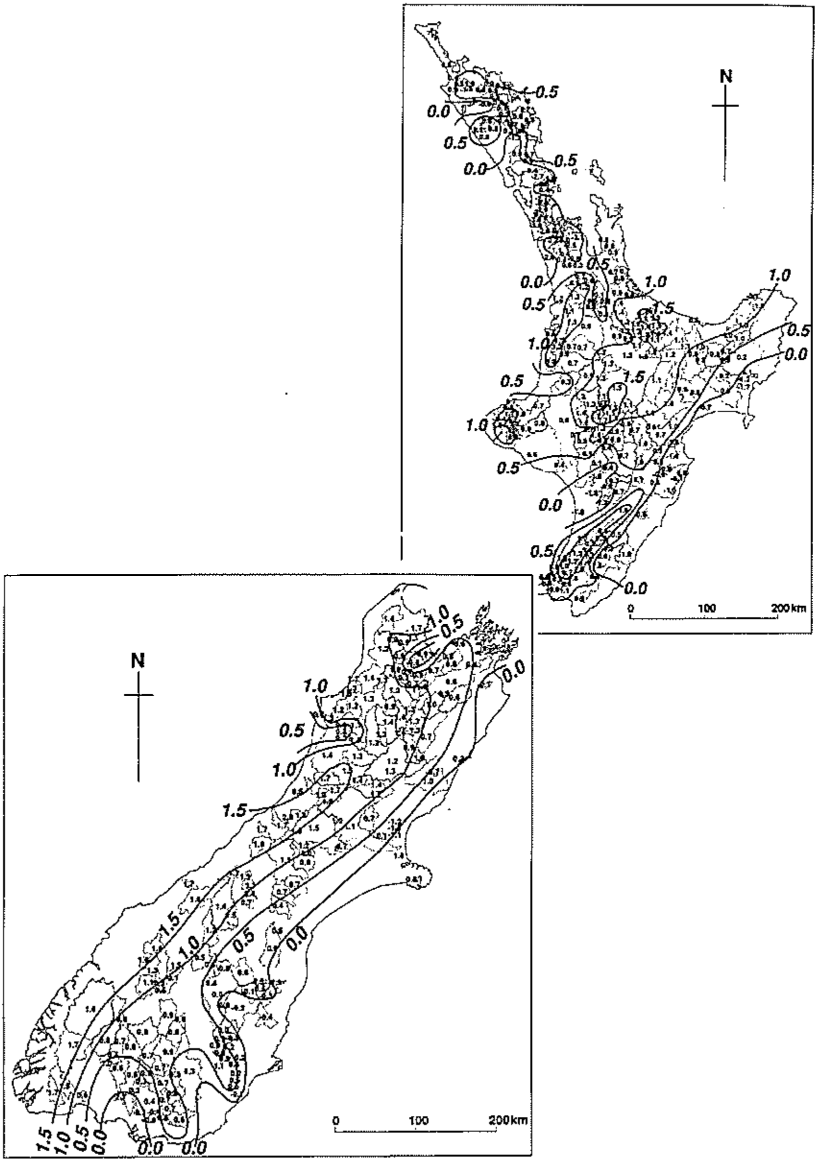

FIG. 2—Logarithms (base 10) of specific mean annual minimum 7-day discharge (*LQA*; in log[l/s/km^2] units) for 495 New Zealand catchments.

government field hydrologists. Each annual series had five or more values, and the average number was $n = 16$. The data set was therefore rich spatially, but sparse temporally. The main statistic analysed was the 7-day flow; the 1-day and 30-day flows were compiled to consider any differences in other durations. The calendar year was arbitrarily used in defining annual values, although a year beginning sometime in mid-winter (July), encompassing the austral summer (usual time of lowest flows), has been more commonly used. The effect of these definitions on low flow frequency estimates is not analysed.

Most annual minimum flow series did not include zero flows. There were 56, 53, and 45 annual series which had some zero flows (usually small catchments), and 14, 12, and 6 annual series which were all zero flows, for the 1, 7 and 30 day durations respectively. The number of zero flows in each annual series (n_z) was noted.

A number of characteristics were compiled for each catchment: catchment area (A; km^2), annual rainfall (P; mm), and catchment-average characteristics (some based on the national Land Resources Inventory): vegetation index (VEG; ranging from 1 for grass to 2 for native bush and forests), soil-depth-weighted porosity (DWP; %), elevation (EL; m), bare land (BL; %), slope (S; deg.), and hydrogeology index (H; ranging from 1 for low to 8 for high bedrock transmissibility). Approximately 30 catchments were too small (less than 0.1 km^2) to estimate automatically some of the Land Resources Inventory-based characteristics (using a geographic information system), and so they were not estimated for this study. More detail about the Land Resources Inventory characteristics is given by Hutchinson (1990) and McKerchar (1991).

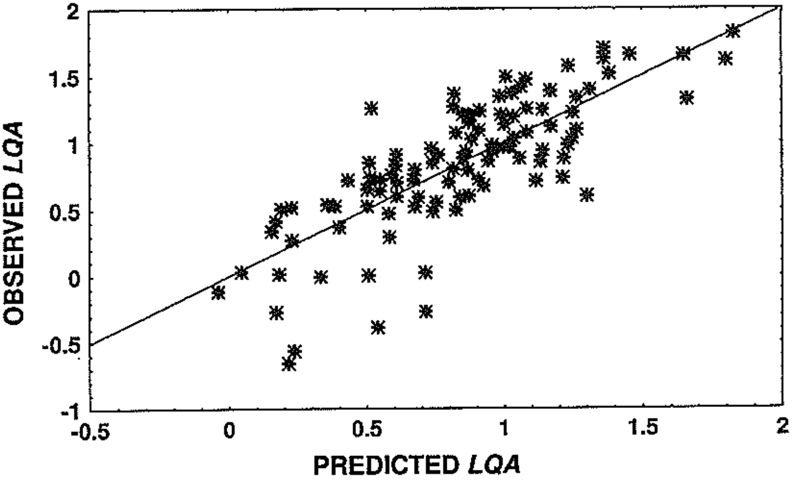

FIG. 3—Regression estimation of logarithms (base 10) of specific mean annual minimum 7-day discharge (LQA; in log[l/s/km^2] units) using catchment characteristics and 128 New Zealand catchments, each with 20 or more annual low flow values.

TABLE 3—L-moment ratios, homogeneity statistics (V_i), and Kappa q_{100}/q estimates for sites with 10 or more and 20 or more positive annual minimum flows of durations 1, 7 and 30 days.

Duration (days)	Min. No. positive ann. flows	No. of sites	Average L-moment ratios			Homogeneity tests			
			L_{CV}	L_{SK}	L_{KUR}	V_1	V_2	V_3	q_{100}/q
1	10	332	0.195	0.124	0.156	63	15	7.6	0.33
1	20	132	0.169	0.106	0.152	42	9.9	5.7	0.40
7	10	335	0.195	0.141	0.162	64	15	6.8	0.34
7	20	131	0.172	0.124	0.157	42	10	5.5	0.40
30	10	330	0.213	0.162	0.152	60	17	7.9	0.34
30	20	130	0.192	0.142	0.140	49	13	6.2	0.39

METHODS

Regional methods were used to investigate spatial patterns of low flow in New Zealand, and frequency distributions using the annual minimum low flow series (1-day, 7-day and 30-day mean flows) from almost 500 catchments. Serial correlations of these data were checked to satisfy the assumption of independence between years.

Mean Annual Minimum 7-day Flow

Estimation of an index low flow, mean annual minimum low flow (q), analogous to mean annual flood peak in "index flood" regional methods, was investigated using contour maps and regressions based on catchment characteristics. For each annual minimum 7-day low flow series, the arithmetic mean (q; in l/s) and the log specific discharge ($LQA = \log[q/A]$) were computed. Values of the log of the specific discharge were plotted at the centroid of each catchment on a map of New Zealand.

Zero Flows

Difficulties arise in the frequency analysis of low flows when the data include zero values. Nathan and McMahon (1990) addressed the problem by first analysing low flow frequencies for the non-zero flows, and then modifying this result by considering the probability of zero flows. The final (cumulative probability) distribution function G of low flows x is given by,

$$G(x) = 1 - [1 - p_z][1 - F(x)] \tag{1}$$

where p_z is the probability of a zero annual flow and $F(x)$ is the distribution function fitted to positive low flows. Probability p_z is estimated simply by n_z / n. Therefore $F(x)$ should be estimated first and then modified using the above relationship to obtain $G(x)$ when $p_z > 0$.

For ungauged catchments, p_z can be estimated by finding and applying a relationship between p_z and catchment characteristics for gauged catchments. Tasker (1989) used logistic regression for this purpose for 55 Florida (USA) streams using drainage area, catchment slope and soil infiltration characteristics as independent variables.

Tasker's (1989) regression approach was used for the New Zealand 1, 7 and 30-day low flows, using catchment area (A; km^2) and annual precipitation (P; mm) as independent variables. The logistic regression equation is,

$$p_z = 1 / \{1 + \exp[a + b\log A + c\log P]\} \tag{2}$$

where a, b and c are coefficients to be estimated, and logarithms are to base 10. Land Resource Inventory variables were not used in equation (2) since their indices were not available for small catchments (e.g. Moutere, Nelson). Deleting these sites from the analysis of zero flows would have introduced substantial bias in the resulting equations. Future work to extend equation (2) to include Land Resource Inventory variables would first require manual estimation of the indices for small catchments.

Frequency Methods

Regional frequency methods are used to analyse statistics of annual flow series from a number of sites, to identify groups of sites with the same frequency

TABLE 4—Expected and observed numbers of acceptances of the EV1 distribution versus EV2, EV3 alternatives, using the Hosking et al (1985) two-sided test at the 95% level for sites with 10 or more and 20 or more positive annual minimum flows of durations 1, 7 and 30 days.

Duration (days)	Min. No. positive ann. flows	No. of sites	Expected no. of sites for EV1 distribution:			Actual no. of sites for annual low flows:		
			EV1	EV2	EV3	EV1	EV2	EV3
1	10	332	314	9	9	261	17	54
1	20	132	124	4	4	98	6	28
7	10	335	317	9	9	269	23	43
7	20	131	123	4	4	103	8	20
30	10	330	314	8	8	265	31	34
30	20	130	124	3	3	108	9	13

distribution. Combining information from many sites with relatively short records can allow inferences to be made about longer return period events. Each site's statistics are treated as a sample of the same frequency distribution and the averaged statistics over the sites are used to estimate the parameters of this distribution. How to select groups of sites which may have the same distribution, test if this is a realistic assumption, identify and fit an appropriate distribution, is covered below.

Methods based on L-moment ratios (Hosking 1990) have been recommended for hydrological regional frequency analyses (e.g. Hosking and Wallis 1993, Stedinger et al 1993, Vogel and Fennessey 1993). Sample estimators of L-moment ratios are superior to those of conventional moment ratios. Studies using L-moments for regional low flows have been reported by Alila et al (1992), by Thomas and Olson (1992), and by Werick et al (1994) in the construction of a United States National Drought Atlas.

L-moment ratios (L_{CV}, L_{SK}, L_{KUR} - Hosking 1990, Hosking and Wallis 1993, Pearson 1991a), analogous to conventional moment ratios (coefficients of variation, skewness and kurtosis), were used to test for frequency distribution homogeneity of Hutchinson's (1990) regions, and to test other groups of catchments based on catchment characteristics; best regional or group dimensionless frequency curves (q_T/q) were then estimated for each group of catchments. L-moment ratios are dimensionless and defined as,

$$L_{CV} = l_2/l_1 \qquad (3)$$

$$L_{SK} = l_3/l_2 \qquad (4)$$

$$L_{KUR} = l_4/l_2 \qquad (5)$$

where $l_1, \ldots, l_4$ are the first four L-moments ("L" for linear functions of the low flow observations). l_1 is the usual sample mean, l_2 is a linear measure of spread, l_3 is a linear measure of skewness, and l_4 is a linear measure of kurtosis.

Hosking and Wallis (1993) statistical tests are based on the amount of scatter or cohesion of the L-moment ratios of each group of annual low flow series. Statistics V_i, i=1,2,3, measure the extent of the dispersion. V_1 is based on L_{CV} only, V_2 on L_{CV} and L_{SK}, and V_3 on L_{SK} and L_{KUR}. Values of V_i greater than two for a group indicate heterogeneity (too much scatter); values less than one indicate homogeneity (acceptably random scatter). Group average L-moment ratios are compared with known ratios for different distributions (Hosking 1990) to assess the best distribution for the group. Two-parameter distributions plot as single points in the L_{KUR}-L_{SK} plane (e.g. the Extreme Value Type I, EV1, distribution has $L_{SK} = 0.17$, $L_{KUR} = 0.15$), three-parameter distributions are curves and four- (or more) parameter distributions are areas. Hosking and Wallis (1993) goodness-of-fit tests were used to examine which of five three-parameter distributions can match a group's average L_{KUR}. The five distributions are (in order of descending L_{KUR}, for a given L_{SK}): the Generalised Logistic (GLO), Generalised Extreme Value (GEV), Generalised Normal (GNO), Pearson Type III (PE3) and Generalised Pareto (GPA). The four-parameter Kappa distribution (KAP; Mielke 1973) was necessary whenever regional average L_{KUR} was unacceptable for the three-parameter distributions. These distributions cover a wide region in the L_{KUR}-L_{SK} plane and algorithms linking their parameters with L-moment ratios are available (Hosking 1990).

The Weibull distribution, used by Nathan and McMahon (1990) for low flows, is related to the GEV distribution: if a random variable X is EV3, then -X is Weibull. Therefore the Weibull curve in the L_{KUR}-L_{SK} plane is the mirror image of the GEV curve, reflected through the L_{KUR} axis. Its applicability to New Zealand low flows was examined graphically. The GEV distribution is the limiting distribution of largest extremes; the Weibull as defined is the limiting distribution of smallest extremes.

Catchment characteristics were used to define non-geographic groups, and their homogeneity and best distributions were examined using Hosking and Wallis tests. Acreman and Wiltshire (1989) reviewed regional flood frequency approaches, including using groups of catchments that are physically similar but not necessarily in the same geographic regions. Pearson (1991c) used this approach for regional flood frequency of small New Zealand catchments. It entailed using a method proposed by Wiltshire (1985) to monitor the effects on flood frequency of splitting catchments into physically similar groupings. Wiltshire's method was modified to use L-moment ratios to monitor the flood frequency behaviour.

This approach was used for low flows using catchment characteristics. Low flow frequency variability was monitored as the group of positive low flow catchments was split into two using a partitioning value of one catchment characteristic, or into four using two catchment characteristics simultaneously. Partitioning is optimal when low flow frequency variability is minimum. The method is more fully described in Pearson (1991c).

The low flow frequency variability measure (*SSL*) for each catchment grouping was the sum of squares of deviations of individual catchment L-moment ratios L_{CV} and L_{SK} from their group record-length-weighted average points,

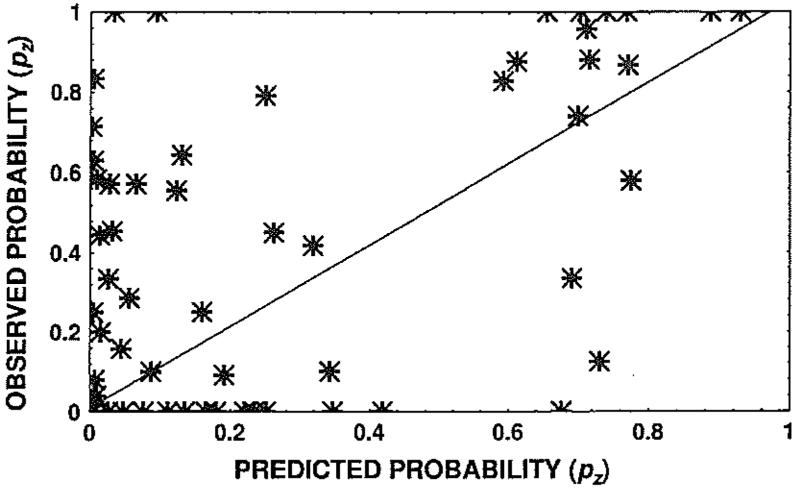

FIG. 4—Observed (estimated by $p_z = n_z / n$) versus predicted probabilities of zero 7-day low flow (p_z) for 495 New Zealand catchments using equation (2).

summed over each group. This is equivalent to the summation over all groups of squared Euclidean distances between individual points and group averages in the L_{CV}-L_{SK} plane. This measure is similar to Hosking and Wallis's (1993) second L-moment ratio statistic for testing homogeneity (V_2). Pearson (1991c) used L_{SK} and L_{KUR} for *SSL*, but recommended L_{CV} and L_{SK} for future use.

RESULTS

Serial Correlation

Serial correlations (between successive years) were examined for each catchment's low flow series. Series which had all zero flows (serial correlation of unity) were not included. Figure 1 summarises the distribution of serial corre-

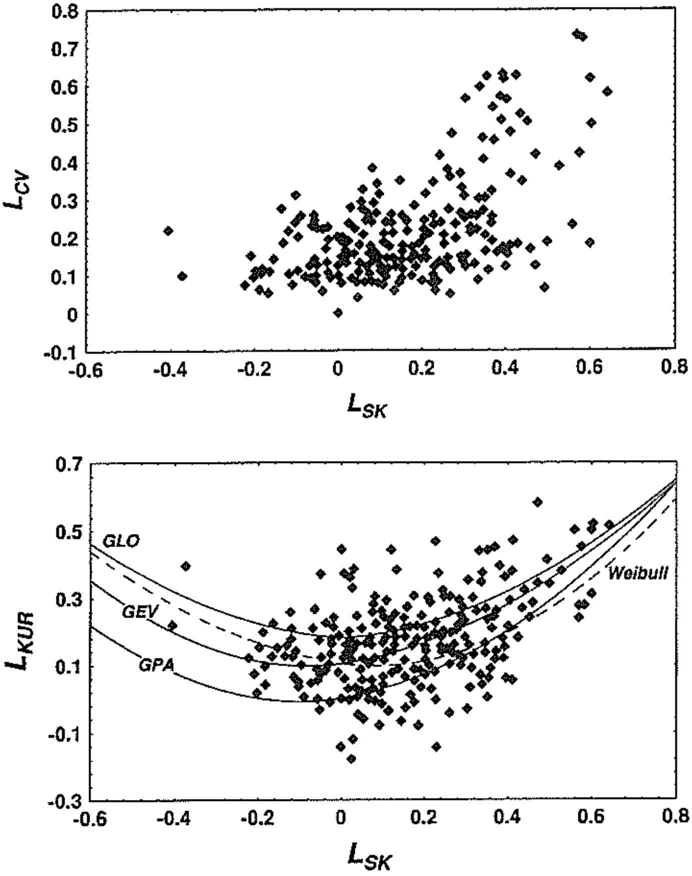

FIG. 5—L-moment ratios (L_{CV}, L_{SK}, L_{KUR}) for positive annual minimum 7-day low flow series with ten or more values.

lation coefficients for each series and flow duration. There is no difference between the durations. The correlations appear normally distributed with median values between 0 and 0.1. Weighted averages for the serial correlations, according to the length of each flow series, were 0.129 for 1- and 7-day flows and 0.111 for 30-day duration flows. The sampling distribution of the serial correlation coefficient for random series of length 16 years is symmetrical about zero with standard error of 0.25, i.e., similar to the distributions in Figure 1. Therefore serial correlations for New Zealand annual low flow series are negligible. Further, the choice of the calendar year for annual minima sampling does not lead to serially correlated series.

Mean Annual Minimum 7-day Flow

The log specific discharge ($LQA = \log[q/A]$) is presented in Figure 2. Logarithms (base 10) were used, as values of q/A range over two orders of magnitude and linear interpolation between logarithmic contours could be made. Contours of equal values of LQA were drawn by hand. Lowest LQA values (less than zero) occur broadly on the east coast of both islands, and in smaller regional pockets elsewhere (Auckland, western Manawatu, southern Southland). Highest LQA values (greater than 1.5) occur in the central North Island, including Taranaki, and on the West Coast of the South Island. Specific low flow means appear to vary continuously and smoothly in space for many New Zealand regions, as there is a high degree of spatial correlation between adjacent rivers. Contour maps could be useful for estimation of discharges of ungauged catchments (analogously to flood maps of McKerchar and Pearson, 1989, 1990). Completely gauged regions, particularly in dry areas, are being analysed to test whether low flow statistics such as log specific discharge vary smoothly or remain constant within a region.

Explanation of the regional variability of log specific discharge (Fig. 2) was sought using catchment characteristics. Table 1 presents the Pearson correlation coefficients between log specific discharge and the catchment characteristics for the subset of 128 catchments with 20 or more years of record. Significant ($p < 0.05$) positive correlations were found for log specific discharge with annual rainfall (P), soil-depth-weighted porosity (DWP; %), elevation (EL), bare land (BL; %), slope (S, degrees), and vegetation index (VEG). The best multiple regression for log specific discharge was,

$$LQA = -5.20 + 1.64 \log(\mathrm{P}) + 0.03DWP + 0.02\,BL - 0.02S + 0.34VEG \quad (6)$$

The coefficient of determination was $r^2 = 61\%$ and the standard error of estimate was 0.30 $\log(\mathrm{l/s/km^2})$ units. The relationship between observed and predicted log specific discharge for this regression is shown in Figure 3.

Zero Flows

Table 2 gives the results of fitting Tasker's (1989) logistic regression (equation 2) to New Zealand data; Figure 4 shows the fit for the 7-day low flows. The correlation between predicted and observed values is 0.75. This level of correlation is inflated by the large number of points clustered near zero-zero. However, for each low flow duration the regression is well-defined. The coefficients in Table 2 indicate that the predicted probability p_z increases as area A and precipitation P decrease, as we would expect - zero flows are more likely in small catchments in low rainfall regions. These relationships can be used to provide approximate p_z estimates for ungauged New Zealand catchments. For example, for an ungauged catchment with A = 1.0 km^2 and P = 1000 mm, approximate probabilities of zero annual minimum 1-, 7- and 30-day mean flows are 0.22, 0.17 and 0.12 respectively. For A = 10 km^2 and P = 1000 mm, the same regional estimates of pz are 0.05, 0.03 and 0.02 respectively. The wide scatter (Fig. 4) implies that these estimates are approximate.

Frequency Distributions of Positive Low Flows

L-moment ratios were estimated for positive low flows from the 1-, 7- and 30-day annual minimum series, for series with 10 or more and 20 or more positive values. The number of sites in each category is summarised in Table 3. The L-moment ratios (L_{CV}, L_{SK}, L_{KUR}) for each site are given in Figure 5 for 7-day low flows with ten or more positive values. Table 3 gives record-length-weighted average L-moment ratios for each category. On average the annual low flow

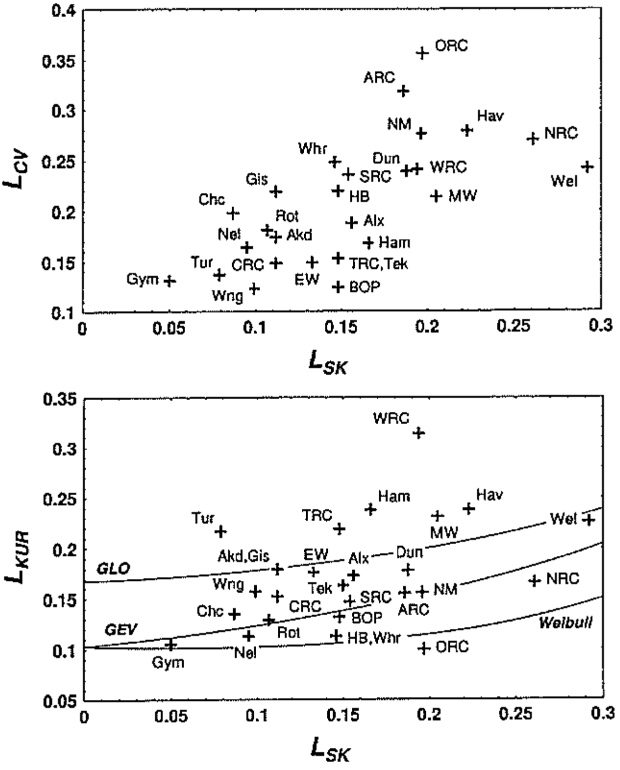

FIG. 6—Weighted average L-moment ratios (L_{CV}, L_{SK}, L_{KUR}) for positive annual minimum 7-day low flow series with ten or more values from various data collection agencies.

series tend to be positively skewed, as with annual flood series. There is considerable scatter about the means of individual site L-moment ratios (Fig. 5). This scatter is greater than that found in L-moment ratios for New Zealand annual maximum flood series (Pearson 1991a). In that study, dry regions such as South Canterbury were at one extreme of the L_{KUR}-L_{SK} plot and wet regions such as West Coast were at the opposite side. Hosking and Wallis homogeneity test results (Table 3) (all V_i values exceed two) confirm that this extent of scatter is not acceptable for a homogeneous group.

From the L-moments (Fig. 5), it is clear that a two-parameter distribution (with implicitly fixed L_{SK} and LK_{UR}) will not suffice to describe all New Zealand annual low flow series. The EV1 distribution would be suitable for many of the low flow series since its population L-moment ratios ($L_{SK} = 0.15$, $L_{KUR} = 0.17$) are near the centre of the sample values. However the EV1 distribution is not satisfactory for the catchments away from its point in the L_{KUR}-L_{SK} plane. Hosking et al's (1985) test was used to check whether this distribution can be used in individual cases. Results of this test (also used by McKerchar and Pearson 1989 for annual flood series) in Table 4 show that, although overall the EV1 distribution is unsuitable, there is a surprisingly large number of sites for which the EV1 distribution would be satisfactory. No three-parameter distribution is satisfactory for the New Zealand low flow data as a whole either. Average values of q_{10d}/q from the Kappa distribution for the different data-sets range between 0.33 and 0.40 (Table 3). There is no difference in q_{10d}/q between low flow durations, but longer records have higher values and are probably a better indicator of true q_{10d}/q values. These, however, are only group average values, and q_{10d}/q for individual catchments take on a much wider range of values.

As a prelude to investigating Hutchinson's (1990) low flow regions, we show average L-moment ratios of positive annual minimum 7-day low flow series (of 10 or more values) for agencies involved in regional data collection (Fig. 6 and Table 5). In many cases the regions in which these agencies operate are not homogeneous (e.g. the Buller, Nelson and Marlborough regions covered by NIWA Nelson field team, Pearson 1991b). This is reflected in the Hosking and Wallis (1993) homogeneity test V_i values (Table 5). The most homogeneous group of catchments was that managed by Southland Regional Council. The best fitting three-parameter distribution for the mean L-moment ratios of each group was the GLO distribution (8 agencies), followed by GEV (6), GNO (3), PE3 (3), and GPA (1), with six agencies not suiting any of these distributions. The three-parameter Weibull distribution could be used for Greymouth, Hawkes Bay, Nelson, and Otago catchments (Fig. 6).

The 27 agency average L-moment ratios gives some indications of where clusters exist (Fig. 5). The regions for which L_{CV} values in Table 4 are clearly above 0.2 (more variable annual low flow series) are Northland, Gisborne, Hawkes Bay, Manawatu, Wellington, Otago and Southland. The regions for which L_{CV} values in Table 5 are clearly below 0.2 (less variable annual low flow series) are Waikato, Bay of Plenty, Taranaki, Wanganui, West Coast and Canterbury. The proximity of geographic regions appears to be reflected to some degree in the L-moment ratio plots: West Coast and Nelson; Wellington, Manawatu, and Taranaki; Otago and Southland.

TABLE 5—Average L-moment ratios, homogeneity statistics (V_i), best distribution, and q_{100}/q estimates for positive annual minimum 7-day low flow series (of 10 or more values) for regional data collection agencies.

Data Collection Agency		No. Sites	Average L-moment ratios: L_{CV}	L_{SK}	L_{KUR}	Homogeneity tests V_1	V_2	V_3	Best Dist.	q_{100}/q
NIWA Field Teams										
Whangarei	Whr	16	0.248	0.146	0.113	15	5.2	2.8	PE3	0.27
Auckland	Akd	5	0.174	0.112	0.179	1.4	-1.5	-1.1	GLO	0.36
Hamilton	Ham	11	0.168	0.166	0.238	2.4	2.7	2.2	KAP	0.44
Rotorua	Rot	31	0.181	0.107	0.129	41	11	4.7	GEV	0.39
Gisborne	Gis	6	0.219	0.112	0.181	1.6	-0.2	0.2	GLO	0.19
Havelock	Hav	13	0.279	0.223	0.238	10	4.0	1.1	KAP	0.16
Turangi	Tur	10	0.137	0.079	0.217	7.8	1.4	0.0	KAP	0.46
Wanganui	Wng	21	0.123	0.099	0.157	8.3	0.2	-1.0	GLO	0.53
Wellington	Wel	11	0.242	0.292	0.226	5.5	0.7	-0.6	GLO	0.36
Nelson	Nel	18	0.164	0.095	0.113	22	3.4	3.3	GEV	0.44
Greymouth	Gym	22	0.131	0.050	0.105	10	1.6	0.6	GEV	0.52
Christchurch	Chc	10	0.198	0.087	0.135	14	3.9	1.6	GNO	0.31
Tekapo	Tek	9	0.151	0.150	0.163	7.2	1.5	0.5	GLO	0.48
Alexandra	Alx	9	0.188	0.156	0.173	4.5	1.4	0.6	GLO	0.36
Dunedin	Dun	13	0.239	0.188	0.178	15	6.0	2.5	GLO	0.23

TABLE 5—(contd)

Data Collection Agency		No. Sites	Average L-moment ratios: L_{CV}	L_{SK}	L_{KUR}	Homogeneity tests V_1	V_2	V_3	Best Dist.	q_{100}/q
Regional Councils										
Northland	NRC	8	0.270	0.261	0.166	4.3	0.2	-0.8	GNO	0.32
Auckland	ARC	12	0.318	0.186	0.155	4.4	3.0	1.3	GEV	0.06
Waikato	EW	21	0.149	0.133	0.176	8.0	0.3	0.6	GLO	0.47
Bay of Plenty	BOP	5	0.124	0.148	0.132	10	3.2	2.9	PE3	0.63
Hawkes Bay	HP	7	0.220	0.148	0.115	8.6	3.8	2.0	PE3	0.35
Taranaki	TRC	12	0.153	0.148	0.219	1.7	0.4	-0.4	KAP	0.47
Man-Wang.	MW	9	0.214	0.205	0.231	3.8	1.6	1.0	KAP	0.33
Wellington	WRC	12	0.241	0.194	0.314	6.0	4.1	2.8	KAP	0.24
Nel. & Marl.	NM	10	0.276	0.196	0.156	7.9	3.8	2.4	GEV	0.20
Canterbury	CRC	13	0.148	0.112	0.152	3.4	0.1	-0.4	GNO	0.51
Otago	ORC	5	0.356	0.197	0.100	3.6	3.1	2.3	GPA	0.18
Southland	SRC	16	0.236	0.154	0.147	1.0	1.7	0.7	GEV	0.27

Low Flow Regions

The results of Hosking and Wallis (1993) homogeneity tests for Hutchinson's (1990) low flow regions (shown in Figure 7) are presented in Table 6. Figure 8 shows the degree of scatter of L-moment ratios for each region, for 7-day duration annual minimum flow series with 20 or more annual values.

The degree of homogeneity for these regions varies according to the number of sites per region (determined by restricting the region to sites with either 10+ or 20+ annual values) and the low flow duration (1, 7 or 30 days). Region E (Mt Taranaki catchments) was consistently homogeneous (2 out of 3 test passes) in each of the six groups in Table 6. Regions A and C (North Island's east coast medium- to high-rainfall catchments), and H and J (South Island's east coast medium- to high-rainfall catchments) were reasonably homogeneous, particularly for sites with 20 or more annual series. These regions may be considered homogeneous for regional frequency studies (some heterogeneity can be accommodated, Lettenmaier et al. 1987).

The most heterogeneous region was region B (North Island volcanic catchments). This region had the most sites, including all Waikato River catchments, and needs to be broken down into a number of smaller, homogeneous regions. A brief analysis was conducted using Bay of Plenty and Rotorua catchments as a subregion of B. Sites used were 14610, 14614, 14627, 14628, 14601, 14624, 14625, 15302, 15341, 15408, 15410, 15412, 15432, 15453 (Walter 1990). Regional average L-moment ratios for 1-day flows were: $L_{CV} = 0.10$, $L_{SK} = 0.04$, $L_{KUR} = 0.14$. All catchments had 10 or more annual low flows. The annual low flow series from this subregion therefore had less inter-annual variability and skewness compared with all of region B (Table 6). There was little variation of individual catchment L-moment ratios about the subregion averages, which was reflected in all three homogeneity tests. Best three-parameter distribution was GEV, with 100-year dimensionless regional 1-day low flow estimated to be $q_{100}/q = 0.63$. This value is higher than the estimate for all of region B in Table 6 (0.44), and indicates that Bay of Plenty and Rotorua extreme low flows remain higher, as a ratio to their mean annual low flow q, than equally extreme low flows elsewhere in region B. The defined subregion would be one step toward breaking heterogeneous region B into a number of distinct homogeneous subregions.

The best fitting three-parameter distribution in Table 6 for Hutchinson's regions was the GLO (20 data-sets), followed by GEV (13), GNO (12), PE3 (3), GPA (0). The four-parameter Kappa distribution (KAP) was necessary whenever regional average L_{KUR} was unacceptable for the three-parameter distributions used (18 data-sets). This usually coincided with a heterogeneous region (e.g. regions B and K). For monthly low flows, three-parameter distributions were satisfactory for all but one region (K).

Regardless of homogeneity, q_{100}/q estimates from the best distributions for each region are useful for summarising a region's low flow characteristics. Regions G and I (North and South Island low rainfall east coast regions respectively) have very low q_{100}/q estimates, indicating highly variable river flows (these results are from positive low flows only and so true q_{100}/q estimates will be lower - mainly for smaller catchments - after adjustment for zero flows). Regions A, C and F (northern and central non-volcanic North Island regions) have medium q_{100}/q estimates, and the remaining regions (B, D, E, H, J and K) have high q_{100}/q estimates (well-sustained flows).

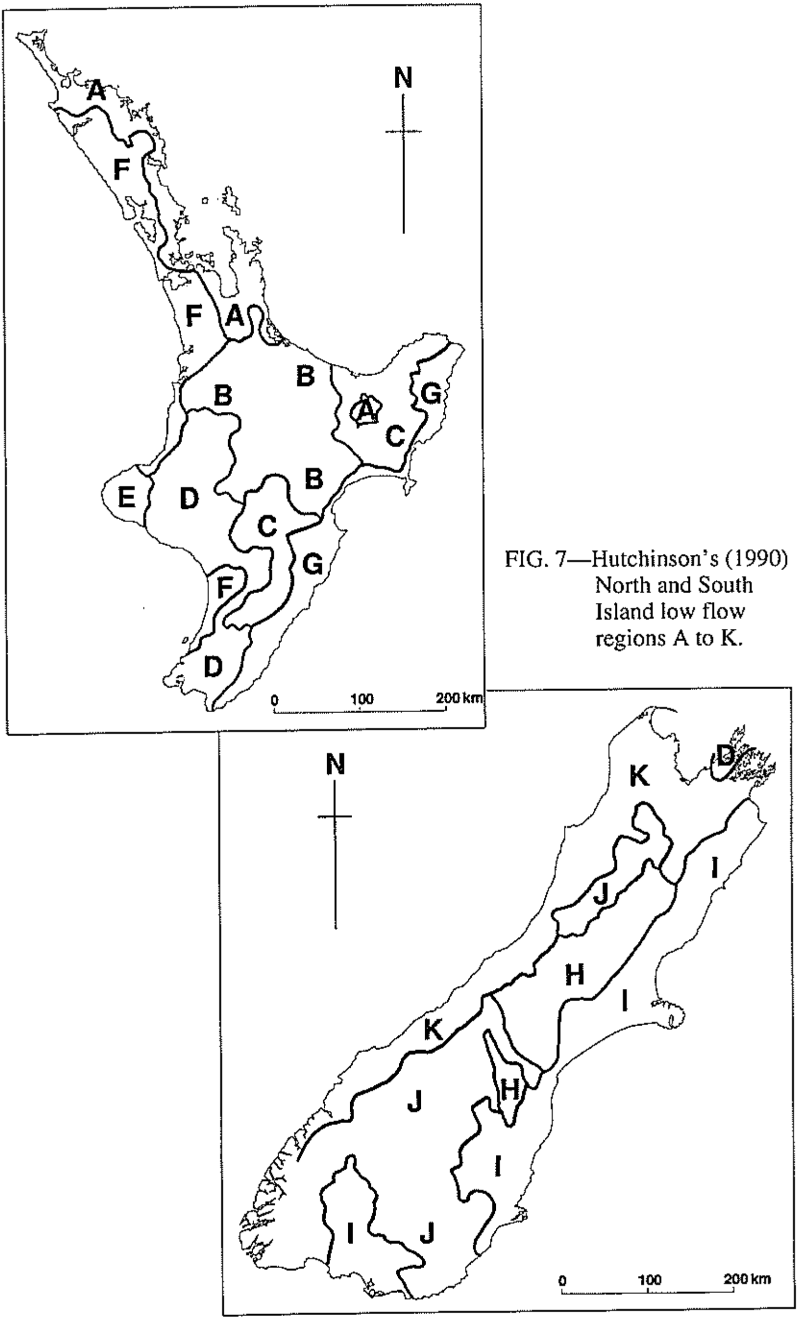

FIG. 7—Hutchinson's (1990) North and South Island low flow regions A to K.

Groups of "Similar" Low Flow Catchments

For each catchment characteristic partitioning point, defining two distinct groups of sites for that catchment characteristic, the L-moment ratio variability statistic *SSL* was calculated using the 7-day 20+ years set of low flows (128 sites with full catchment characteristic information). By varying the partitioning point, and hence group composition, a minimum SSL value was found for each characteristic, representing the best two-group low flow frequency homogeneity. For each characteristic, minimum *SSL* values are given in brackets: *VEG* (3.62), *DWP* (3.79), *EL* (3.82), *P* (3.83), *A* (3.98), *BL* (4.11), *S* (4.11), and *H* (4.13). Therefore, the best single characteristic (two-group) results were for vegetation index, depth-weighted porosity and elevation (Fig. 9). These catchment characteristics were, along with annual rainfall, the most highly correlated with L_{CV} and L_{SK} (Table 1). None of the groups defined were homogeneous (Table 7). The results using the vegetation index and depth-weighted porosity simultaneously to define four groups are summarised in

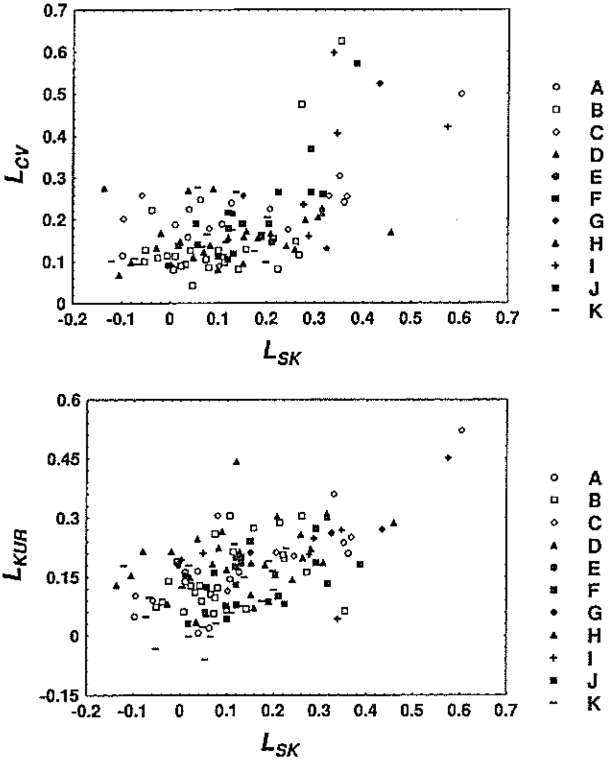

FIG. 8—L-moment ratios (L_{CV}, L_{SK}, L_{KUR}) for positive annual minimum 7-day low flow series with 20 or more values from Hutchinson's (1990) low flow regions A to K.

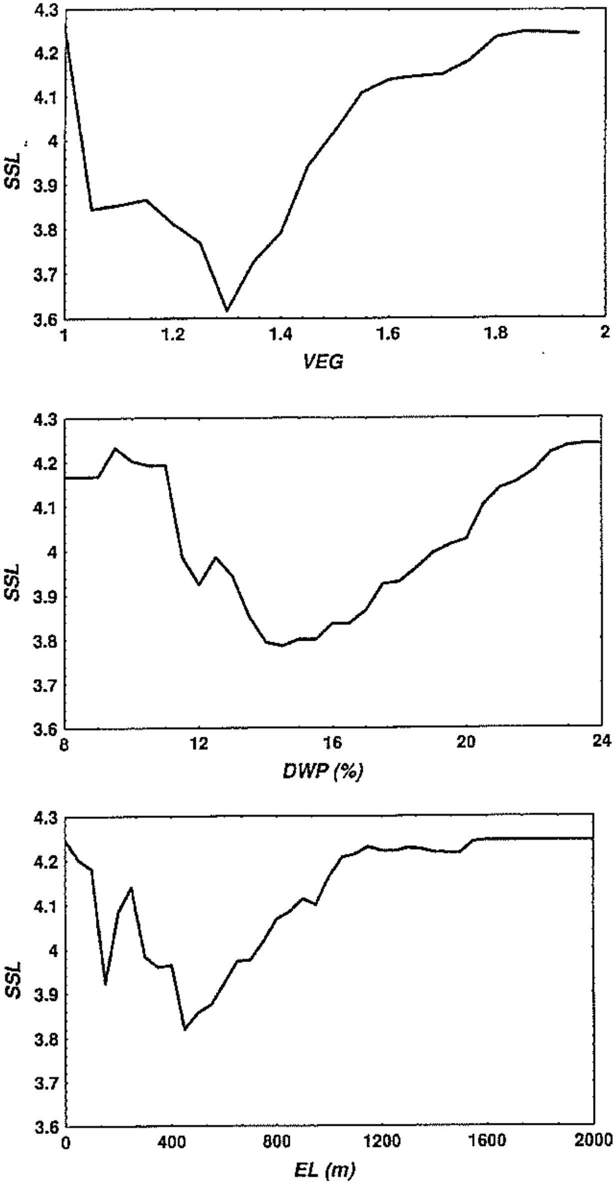

FIG. 9—Variation of low flow L_{CV}-L_{SK} group proximity measure (*SSL*) for catchment groups based on catchment characteristics: vegetation index (*VEG*), soil depth-weighted porosity (*DWP*), and elevation (*EL*).

Table 7. One group was reasonably homogeneous (Group 3: high *VEG*, low *DWP*), whereas the other three were not. The L-moment ratios for these groups (Fig. 10) were dispersed widely, except for Group 3.

The results in Table 7 show some interesting patterns. The low *VEG*, *DWP* and *EL* groups have low average q_{10d}/q values. For soil-depth-weighted porosity catchments having lower porosity, soils will have less storage for water during extreme droughts, and hence their river flows will drop to lower values, than catchments with more storage capacity. For vegetation index and elevation, both positively correlated with rainfall (*P*, Table 1), catchments with low vegetation and/or in low lying regions are likely to be in drier climates and hence their river flows will be more variable.

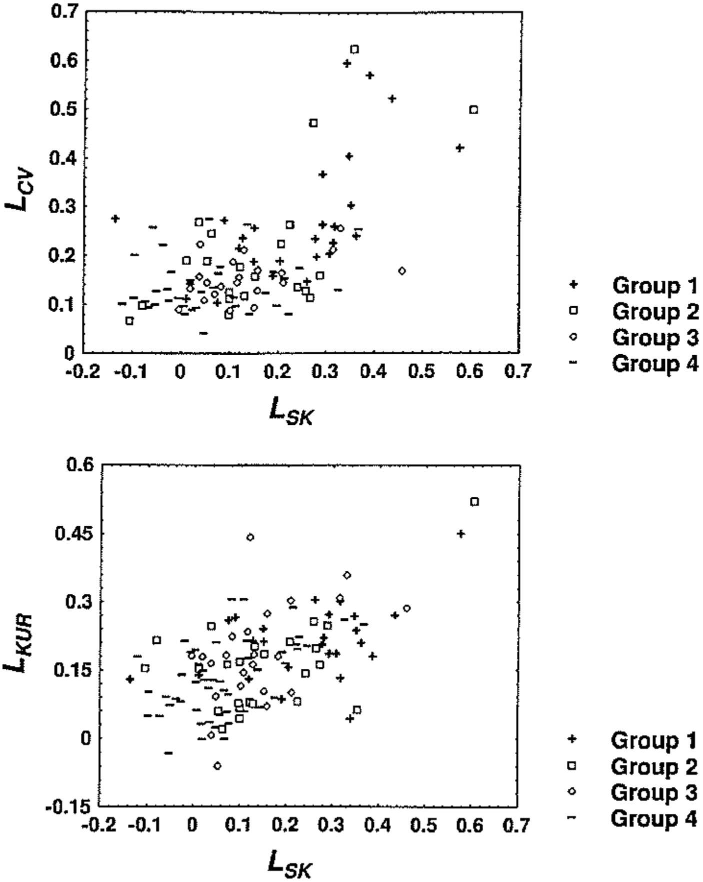

FIG. 10—L-moment ratios (L_{CV}, L_{SK}, L_{KUR}) for positive annual minimum 7-day low flow series with 20 or more values from non-geographic low flow groups 1 to 4 (Table 7).

DISCUSSION

Flow data are available from a sufficient number of sites to allow specific mean annual 7-day low flow (*LQA*) to be contoured for New Zealand, but because records are short, frequency measures are highly variable, and annual low flow frequencies are less well defined. Long-term hydrometric data collection at a number of river locations around New Zealand is needed for future low flow frequency analyses. The regional variability of *m*-day duration annual low flow frequency distributions may be inherently high. Frequency distributions of other drought flow statistics (such as annual maximum drought volumes under a threshold, Clausen and Pearson 1994) may vary less regionally.

Approximate estimates for log specific discharge *LQA* are available from the contour maps in Figure 2 and the regression relationship (equation 6). For catchments with some annual low flow data, plotting the data on probability paper (either Gumbel, logarithmic or normal) can be used to estimate approximate frequencies. The regional estimators of q_{100}/q given in Tables 5 and 6 provide approximate guidelines for expected low flow behaviour. For catchments without data on annual low flows, regional *LQA* and q_{100}/q can be combined to estimate q and q_{100}. A homogeneous group of catchments with low flow data, either surrounding the catchment of interest or having similar catchment characteristics, should be formed and the group's dimensionless frequency distribution for q_T/q used with *LQA* for frequency estimates.

Example

The Waiairi River at Muttons (site number 14627, Walter 1990) in the Bay of Plenty region has a catchment area of $A = 69.9$ km^2. Catchment characteristics are: $P = 2290$ mm, $DWP = 20.0\%$, $BL = 3.7\%$, $S = 20.6$ deg., $VEG = 1.64$.

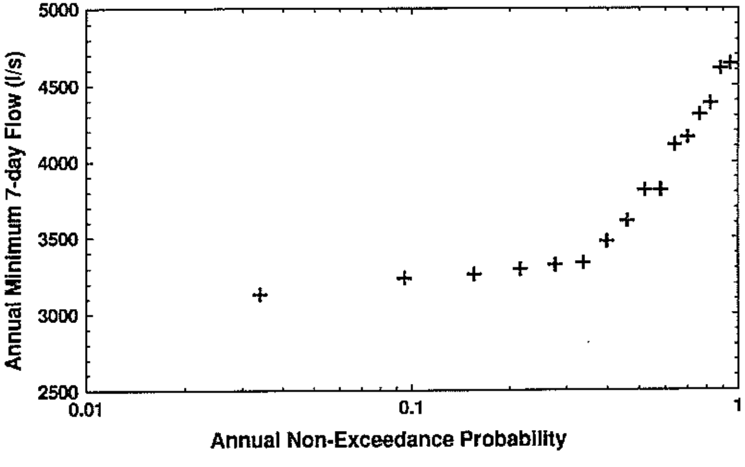

FIG. 11—Low flow probability plot for 7-day annual minimum flow series from Waiairi River at Muttons (14627), Bay of Plenty.

Sixteen annual minimum 7-day mean flow values recorded at this catchment are presented in a frequency plot (Fig.11). Sample mean is q = 3780 l/s. The frequency plot indicates that q_{100} = 3000 l/s (approximately). In fact the annual series distribution is acceptably EV1 by Hosking et al's (1985) test. This distribution gives q_{100} = 2860 l/s.

If there had been no data available at this site, q could be estimated regionally: LQA = 1.6 (Fig. 2) and LQA = 1.83 (Equation 6), so that q = 2780 l/s and 4730 l/s respectively. A regional q_{100}/q estimator is available from a homogeneous geographic group of Bay of Plenty/Rotorua catchments: $q_{100}/q = 0.63$. Therefore regional estimators of q_{100} range from 1750 l/s to 2980 l/s.

CONCLUSIONS

The map of log specific 7-day mean annual low flow (*LQA*; Fig. 2) summarises regional patterns of low flows in New Zealand. The patterns correspond broadly to patterns on maps of annual rainfall. Higher *LQA* values occur in higher rainfall regions, and in the volcanic region of central North Island. Lower *LQA* values tend to occur in the drier eastern areas of New Zealand. This map presents the spatial patterns of average drought flows in New Zealand rivers, and it may be useful for estimation of log specific discharge. The alternative approach of estimating log specific discharge by regression on catchment characteristics could be improved, beyond that presented in this paper, by deriving regional equations.

The frequency results for the positive annual low flow series demonstrated the wide range of low flow distributions in New Zealand. The large variability of low flow L-moment ratios meant that most groups of catchments analysed were heterogeneous, with no unique dimensionless frequency distribution. This applied to groupings based on data collection agencies, on Hutchinson's (1990) low flow geographic regions, and on non-geographic groups defined by catchment characteristics. The most promising approach for future studies might be to further subdivide Hutchinson's low flow regions until homogeneity is achieved, as was illustrated for the Bay of Plenty / Rotorua subregion of heterogeneous region B (North Island central volcanic region).

ACKNOWLEDGEMENTS

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TABLE 6—Average L-moment ratios, homogeneity statistics (V_i), best distribution, and q_{100}/q estimates for Hutchinson's (1990) New Zealand low flow regions

Reg.	No. Sites	Av. L-moment ratios			Homogeneity statistics			Best dist.	q_{100}/q
		L_{CV}	L_{SK}	L_{KUR}	V_1	V_2	V_3		
1-day low flows, 10+ values									
A	30	0.25	0.09	0.14	9.8	5.0	2.4	GNO	0.13
B	66	0.15	0.10	0.15	40	6.6	2.9	KAP	0.44
C	25	0.22	0.15	0.19	3.9	2.5	1.4	GLO	0.24
D	39	0.18	0.16	0.22	12	2.7	1.8	KAP	0.40
E	14	0.14	0.12	0.20	2.9	-0.1	0.9	GLO	0.49
F	25	0.24	0.16	0.16	14	3.6	1.7	GEV	0.26
G	8	0.40	0.36	0.25	7.8	3.9	-0.2	GNO	0.05
H	21	0.15	0.07	0.15	4.4	2.4	1.2	GLO	0.39
I	24	0.30	0.22	0.18	13	6.5	3.2	GLO	0.08
J	39	0.16	0.09	0.12	14	3.2	2.0	GEV	0.45
K	41	0.18	0.10	0.11	28	6.6	3.0	KAP	0.41
1-day low flows, 20+ values									
A	8	0.19	0.01	0.12	1.1	1.7	1.8	GEV	0.24
B	29	0.14	0.07	0.15	34	2.8	0.5	KAP	0.48
C	10	0.23	0.17	0.22	3.6	3.1	1.6	KAP	0.26
D	17	0.17	0.13	0.20	6.4	2.0	1.4	KAP	0.40
E	2	0.15	0.07	0.12	5.4	1.1	0.2	GEV	0.45
F	7	0.26	0.25	0.19	9.7	2.2	0.1	GEV	0.31
G	3	0.27	0.30	0.23	6.2	2.0	-0.5	GLO	0.29
H	11	0.15	0.09	0.15	4.0	1.8	1.0	GNO	0.42
I	6	0.21	0.20	0.25	8.8	3.9	1.9	KAP	0.33
J	14	0.15	0.10	0.12	12	1.6	0.9	PE3	0.50
K	25	0.16	0.07	0.09	16	3.0	1.9	KAP	0.49
7-day low flows, 10+ values									
A	29	0.24	0.14	0.14	10	3.1	1.2	GNO	0.24
B	69	0.16	0.12	0.15	41	7.9	3.7	KAP	0.45
C	25	0.23	0.18	0.21	5.9	3.7	2.6	KAP	0.24
D	39	0.18	0.17	0.23	11	3.7	2.4	KAP	0.41
E	14	0.14	0.12	0.21	3.2	0.3	-1.0	KAP	0.48
F	26	0.23	0.16	0.14	16	3.9	1.4	GNO	0.30
G	8	0.40	0.36	0.24	8.1	3.6	-1.0	GLO	0.06
H	21	0.16	0.10	0.16	4.0	2.1	0.5	GLO	0.40
I	24	0.30	0.22	0.21	11	6.2	2.1	GLO	0.11
J	39	0.16	0.11	0.13	11	1.8	0.2	GEV	0.46
K	41	0.18	0.10	0.10	27	5.8	3.1	KAP	0.43

TABLE 6—(contd)

Reg.	No. Sites	Av. L-moment ratios			Homogeneity statistics			Best dist.	q_{100}/q
		L_{CV}	L_{SK}	L_{KUR}	V_1	V_2	V_3		
7-day low flows, 20+ values									
A	8	0.20	0.09	0.12	2.4	1.8	1.5	GEV	0.32
B	28	0.13	0.08	0.15	33	3.6	1.4	GNO	0.50
C	10	0.24	0.20	0.23	5.5	4.0	2.6	KAP	0.25
D	17	0.17	0.14	0.22	5.4	1.9	1.5	KAP	0.41
E	2	0.15	0.06	0.18	3.9	0.4	-0.5	GLO	0.38
F	7	0.26	0.24	0.15	11	2.9	0.0	GNO	0.29
G	3	0.28	0.31	0.25	5.5	2.0	-0.5	GLO	0.27
H	11	0.15	0.12	0.17	3.6	1.6	0.4	GLO	0.45
I	7	0.25	0.23	0.23	9.7	4.8	2.0	GLO	0.25
J	14	0.15	0.12	0.14	9.7	0.6	-1.0	GNO	0.51
K	24	0.15	0.07	0.08	12	1.8	2.1	KAP	0.51
30-day low flows, 10+ values									
A	27	0.28	0.19	0.14	9.8	3.8	1.5	PE3	0.25
B	68	0.16	0.12	0.14	40	9.6	4.6	GNO	0.46
C	25	0.24	0.18	0.16	1.4	-0.3	-0.3	GEV	0.28
D	39	0.21	0.16	0.17	16	6.2	4.5	GLO	0.30
E	14	0.17	0.13	0.20	2.3	-1.0	-1.1	GLO	0.38
F	26	0.24	0.23	0.18	11	2.4	0.9	GEV	0.33
G	8	0.42	0.40	0.30	6.0	3.5	1.1	GLO	0.09
H	21	0.16	0.09	0.13	3.0	2.1	1.1	GNO	0.43
I	24	0.31	0.23	0.20	11	5.5	1.8	GLO	0.09
J	36	0.17	0.15	0.14	5.7	1.5	0.3	GEV	0.46
K	42	0.23	0.15	0.10	28	7.5	3.2	KAP	0.37
30-day low flows, 20+ values									
A	7	0.22	0.15	0.14	2.8	1.2	0.3	GEV	0.32
B	27	0.14	0.09	0.12	33	5.7	2.5	GEV	0.53
C	10	0.23	0.15	0.16	2.2	0.4	0.4	GLO	0.20
D	18	0.22	0.15	0.17	13	4.5	3.9	GLO	0.26
E	2	0.18	0.11	0.21	3.0	-0.2	-1.2	GLO	0.31
F	7	0.26	0.23	0.15	7.6	1.4	0.4	PE3	0.34
G	4	0.34	0.32	0.20	7.9	3.7	0.3	GNO	0.24
H	9	0.16	0.12	0.15	2.2	1.0	0.8	GNO	0.47
I	7	0.25	0.22	0.21	10	4.7	1.8	GLO	0.23
J	14	0.16	0.15	0.15	6.4	0.3	-0.8	GEV	0.50
K	25	0.20	0.13	0.09	22	4.6	2.2	KAP	0.42

TABLE 7—Average L-moment ratios, homogeneity statistics (V_i), best distribution, and q_{100}/q estimates for non-geographic low flow groups based on catchment characteristics

Group	No. catchments	Av. L-moment ratios L_{CV}	L_{SK}	L_{KUR}	Homogeneity tests: V_1	V_2	V_3	Best Dist.	q_{100}/q
Vegetation									
1. VEG < 1.3	50	0.232	0.204	0.185	23	6.9	1.8	GLO	0.28
2. VEG >1.3	78	0.143	0.080	0.141	17	3.4	3.2	KAP	0.47
Depth-Weighted-Porosity									
1. DWP < 14.5%	33	0.249	0.216	0.197	13	4.6	0.9	GLO	0.24
2. DWP > 14.5%	95	0.152	0.096	0.145	34	6.4	4.6	KAP	0.45
Elevation									
1. EL < 450 m	49	0.217	0.173	0.181	27	9.3	3.7	GLO	0.29
2. EL > 450 m	79	0.149	0.095	0.142	16	3.4	3.0	GNO	0.47
VEG & DWP									
1. VEG < 1.3 DWP < 17%	25	0.274	0.249	0.211	9.8	3.6	0.1	GLO	0.22
2. VEG < 1.3 DWP > 17%	25	0.189	0.157	0.157	23	4.8	1.5	GEV	0.41
3. VEG > 1.3 DWP < 17%	23	0.157	0.139	0.183	3.5	-0.6	-0.6	GLO	0.45
4. VEG > 1.3 DWP > 17%	55	0.138	0.059	0.127	18	3.3	2.7	GNO	0.49

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