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DISTRIBUTION OF HIGH INTENSITY RAINFALLS IN METROPOLITAN CHRISTCHURCH, NEW ZEALAND

George A Griffiths[1] and Charles P Pearson[2]

ABSTRACT

Rainfall depth-duration-return period relations are derived for metropolitan Christchurch from a database of nearly 3000 stationary and serially independent annual maxima of 8 durations ranging from 0.5 to 72 hours. Depth-return period relations at a rainfall station are modelled by Extreme Value Type I distributions. L-moment analysis shows that metropolitan Christchurch is a single homogeneous region and a 4-parameter Kappa distribution is used to model dimensionless depth-return period data in this region. The depth-duration relation has a constant spatial pattern for rainfalls up to about 12 hours duration but increasingly resembles the mean annual pattern for longer durations. Area reduction factors derived in the United Kingdom may be used in Christchurch. Theoretical envelopes for storm hyetograph shapes are determined, and formulae are presented to calculate changes in risk of exceedance of rainfalls in a design life when rainfall intensity is increased by climate change during that period. Examples are given of the calculation of design rainfalls of specified duration and return period for Christchurch.

INTRODUCTION

General procedures for estimating the areal and frequency distributions of potential storm rainfalls from point measurements made under constant climatic conditions are well established (Natural Environment Research Council, 1975; United States Water Resources Council, 1976; Institution of Engineers Australia, 1987). Within New Zealand these procedures have been applied at the national scale by Seelye (1947), Robertson (1963) and Tomlinson (1980); at the regional scale by Whitehouse (1985); and at the catchment scale by Jowett and Thompson (1977), Griffiths and McSaveney (1983), Thompson and McGann (1990) and Priestley (1992), amongst others, for flood estimation or as part of general hydrological studies. There is growing demand for potential or design rainfalls, particularly as input to rainfall-runoff routing models used in floodplain management studies (Griffiths, et al, 1989) and in the design of engineering structures. Additionally, this information is vital to models which forecast the productive or economic performance of water-dependent agriculture, horticulture or industry.

[1] Canterbury Regional Council, P O Box 345, Christchurch

[2] NIWA — Freshwater, P O Box 8602, Christchurch

The calculation of design rainfalls commonly involves up to six steps. First, continuous depth-duration-return period (or intensity-duration-frequency) relations are derived for each rainfall station in the area. Second, methods are deduced for interpolating information between stations. Third, point-to-area relations are derived to predict the areal distribution of rainfalls in potential storms. Fourth, procedures for specifying the temporal sequence of rainfall within a storm or the shape of the design hyetograph are worked out. Finally, guidelines are given for dealing with future climate change.

In this study we adopt the above methods while introducing some new procedures to complete certain steps. For the first two steps, a regional frequency method is employed which is new to studies of rainfall distribution in New Zealand, if not for the analysis of floods (McKerchar and Pearson, 1989). In step four, envelope curves of cumulative storm rainfall are put forward to aid solution of the hyetograph problem.

This study illustrates the use of some robust statistical methods (Kuczera, 1982) in the calculation of potential high-intensity rainfalls for a region having a good coverage of rainfall stations. The purpose is to provide design rainfalls for both general use and for assessing potential damage arising from future flooding of rivers in metropolitan Christchurch.

THEORY

Regional Frequency Analysis

Regional frequency analysis was employed to obtain rainfall depth-return period relations, P(T), for any location in Christchurch using rainfall data from stations within the metropolitan area. The first step was to model P(T) for all stations for a range of durations from 0.5 hr to 72 hrs. Following Tomlinson (1980) the Extreme Value Type I (EV1) cumulative density function was adopted — a distribution successfully used for annual maximum flood peaks in New Zealand (McKerchar and Pearson, 1989). Of all the distributions that might be utilised, EV1 has the strongest theoretical basis (Fisher and Tippet, 1928). Moreover, a 2-parameter function is preferable because its sampling error, although high for small samples, is less than the sampling errors of 3 or more parameter distributions.

The second step was to assign stations to regions, where a region is a set of stations whose dimensionless rainfall frequency distributions are similar (Hosking and Wallis, 1991). The L-moments technique (Wallis, 1989; Hosking, 1990; Hosking and Wallis, 1993; Pearson, 1991) provides a robust and accurate method for identifying homogeneous regions, selecting frequency distributions for describing regional data and estimating the parameters of the chosen regional distributions. As L-moments are linear functions of the data, they are less affected by data variability. The first L-moment (L_1) is the usual mean, the second (L_2) is a measure of spread, the third (L_3) of skewness and the fourth (L_4) of kurtosis. L-moment ratios (L_2/L_1, L_3/L_2, L_4/L_2) are analogous to, but more statistically powerful than, the corresponding conventional coefficients of variation, skewness and kurtosis.

The third step, once regions were defined, was to select P(T) for each region. For mathematical simplicity and to accommodate L_4 variation (Pearson, 1992) we chose the 4-parameter Kappa distribution whose cumulative density function, F, is given by (Mielke, 1973)

$$F = 1 - (1/T) = \left\{1 - h\left\{1 - \left[k[(P/\bar{P}) - u]/\alpha\right]\right\}^{1/k}\right\}^{1/h} \qquad (1)$$

in which P is rainfall depth; $\bar{P}$ is mean annual maximum rainfall depth; and h, k, u and α are parameters. With 4-parameter distributions the behaviour of average annual storms has less influence on the estimation of rarer annual storms than it has with 2 or 3-parameter distributions.

Maximum Rainfalls

Estimates of maximum rainfall or probable maximum precipitation (Hansen, 1986) have been used for more than 50 years in calculating probable maximum floods for the design of hydraulic structures. As probable maximum precipitation cannot theoretically be exceeded, its return period is infinite. The estimate thus truncates the distribution of annual maxima; it is also independent of design life. Doubts about the philosophic basis of probable maximum precipitation and the assumptions and procedures used to estimate it, however, have prompted a move to risk-based approaches to engineering design (National Research Council, 1988). Calculation of the magnitude and frequency of the near maximum rainfalls required for risk analysis, using probabilistic, as opposed to deterministic, methods of storm transposition, has been made by Foufoula-Georgiou (1989) and Laurenson and Pearse (1991) but much remains to be done. Estimation of maximum rainfalls is not reported herein.

Area Reduction Factors

Design storm rainfall values at a station or point commonly are converted to corresponding areal values by using area reduction factors. The point rainfall of specified duration and return period is multiplied by the appropriate factor to give the magnitude of the areal rainfall with the same duration and return period. These factors are small for short durations over large areas, but tend to unity as area decreases and duration increases. The standard area reduction factors for temperate zone climates (Fig. 1) from the Natural Environment Research Council (1975) were recommended for use in New Zealand by Tomlinson (1980). They were estimated empirically from a large number of storms recorded in the United Kingdom. Contour maps of storm depth were drawn using data for annual maximum storms of given area and duration. Point rainfalls from these maps were divided by annual maximum point rainfalls measured at stations within the storm area. These ratios were then averaged both for the relevant stations and over time to yield the area reduction factor for this area and duration.

Storm Hyetographs

Tomlinson (1978) found that rainfall sequences in New Zealand storms classified by season, return period of peak rainfall and duration of storm had the greatest variation in profiles between storms, as opposed to within storms, for any classification. Variations with respect to return period, storm duration and storm areal size were relatively insignificant. Similar behaviour has been observed in the United Kingdom (Natural Environment Research Council, 1975). Pearson (1992) noted that cumulative temporal patterns for recorded storms in Christchurch are quite variable between storms but consistent between rainfall stations within storms, particularly for storms longer than 6 hours. While the selection of storm profiles or hyetograph shapes for a metropolitan area is

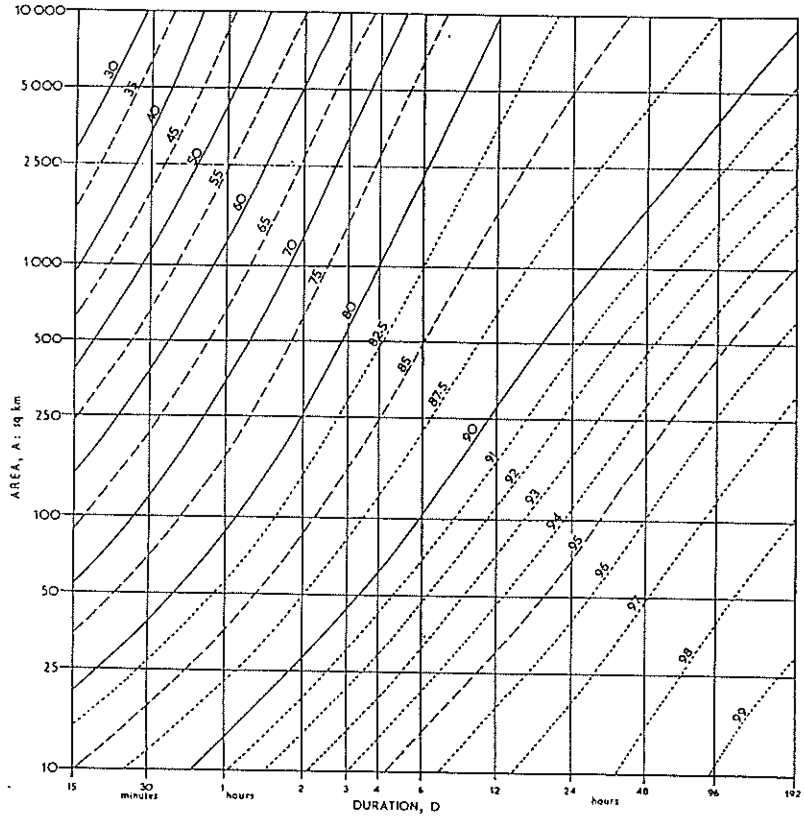

FIG. 1—Area reduction factors (as percentages) after Natural Environment Research Council (1975).

arbitrary, there are theoretical bounds to shape, and it is useful to prescribe an envelope to the choice of possible profiles.

Ball (1992) showed that triangular hyetographs, with maximum rainfall intensity occurring at either the beginning or the end of a storm, represent design extremes. Integration of each extreme with respect to time, t, yields two parabolic cumulative profiles, one concave and the other convex (Fig. 2). Midway between the two is a linear cumulative pattern equivalent to uniform storm rainfall. To calibrate these profiles we assume that triangular hyetographs apply to storms having return periods of 10 years or longer, that hyetographs become more uniform as return period increases and that, for simplicity, profiles apply to effective rainfall (catchment losses assumed zero). For these conditions a suitable but arbitrary choice of exponent for the 10-year events is $1 + (1/\log_{10}T)$ which for $T = 10$ is parabolic, and for infinite T is unity. If P/P_s is dimensionless storm rainfall, where P_s is total depth of storm rainfall, and t/D_s is dimensionless

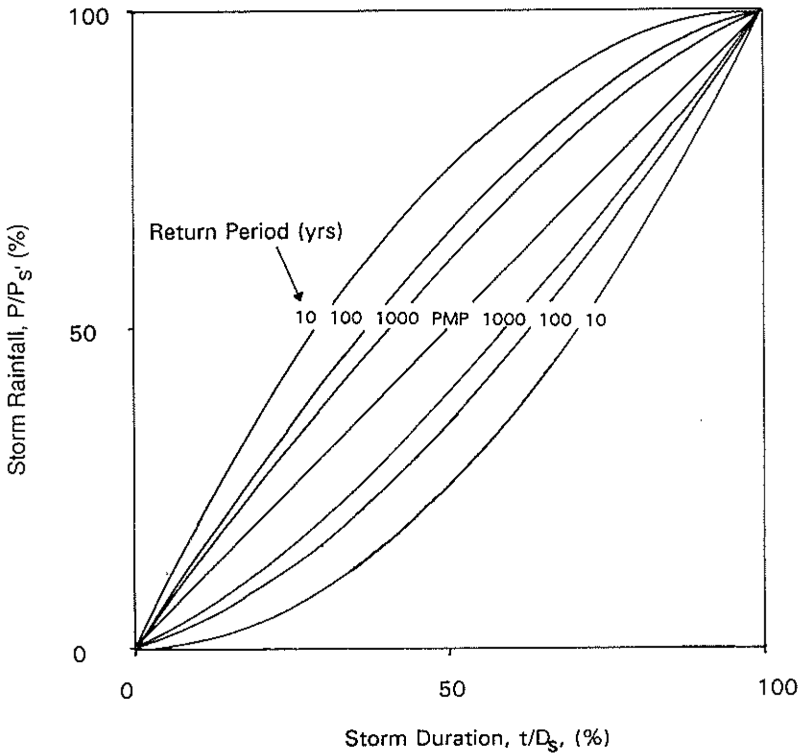

FIG. 2 Dimensionless cumulative storm profile envelopes for various return periods.

storm duration, where D_s is total storm duration, the required design envelopes are given by (Fig. 2):

Upper bound

$$P/P_s = (t/D_s)^{1+(1/\log T)} \quad (2)$$

Lower bound

$$P/P_s = 1 - [1-(t/D_s)]^{1+(1/\log T)} \quad (3)$$

$$0 \leq P/\bar{P}_s, t \leq 1$$

with a mid line of

$$P/P_s = t \quad (4)$$

The user can select an appropriate profile within the envelope; Institution of Engineers Australia (1987) offers further guidance on this matter.

TABLE 1—Automatic raingauge stations, mean annual maximum rainfalls for 8 durations and mean annual rainfall

Station	Station Number (Walter, 1990)	Years of Record	Location (Figure 3)	Mean Annual Maximum Rainfall (mm)								Mean Annual Rainfall (mm)
				0.5hr	1hr	3hr	6hr	12hr	24hr	48hr	72hr	1 Year
Burwood	323710	1962–90	2438	10.6	15.0	25.0	34.8	46.1	60.0	69.8	78.6	590
Airport	324501	1961–86	1337	11.1	14.1	22.5	32.4	45.9	58.9	70.2	78.3	632
Gardens	325612	1962–90	1932	10.8	15.1	24.4	36.2	49.2	61.6	73.6	82.8	646
Riccarton	325613	1965–90	1532	10.6	13.9	24.5	35.8	47.1	57.8	69.0	78.8	626
Belfast	325614	1982–90	2142	11.4	12.4	20.6	28.7	37.2	45.3	52.5	56.6	522
Halswell Junction Road	326511	1980–90	1228	12.4	15.0	23.3	34.4	43.5	53.5	64.4	73.7	653
Hoon Hay Valley	326610	1962–85	1923	—	14.8	23.9	36.5	50.4	63.1	77.9	91.4	626
Sparks Road	326611	1968–90	1828	10.7	14.4	23.9	35.4	48.5	62.5	78.5	88.7	685
Tunnel Road	326710	1962–90	2629	9.5	14.1	24.8	36.8	51.1	67.3	82.1	89.4	651
Huntsbury	326711	1969–90	2227	9.9	13.8	24.8	36.6	50.5	68.1	82.8	94.5	755
Sumner	326810	1968–90	3027	9.7	12.4	21.5	31.8	42.6	58.7	70.4	77.6	590
Bryndwr	327610	1981–90	1836	14.0	15.4	21.9	29.5	39.0	47.1	54.7	64.2	602
Cashmere Valley	327611	1962–76	2024	—	15.4	24.8	35.7	49.4	65.6	81.4	88.8	—
St Albans	—	1967–81	2036	9.9	15.6	25.6	36.6	49.1	61.1	72.9	82.5	—

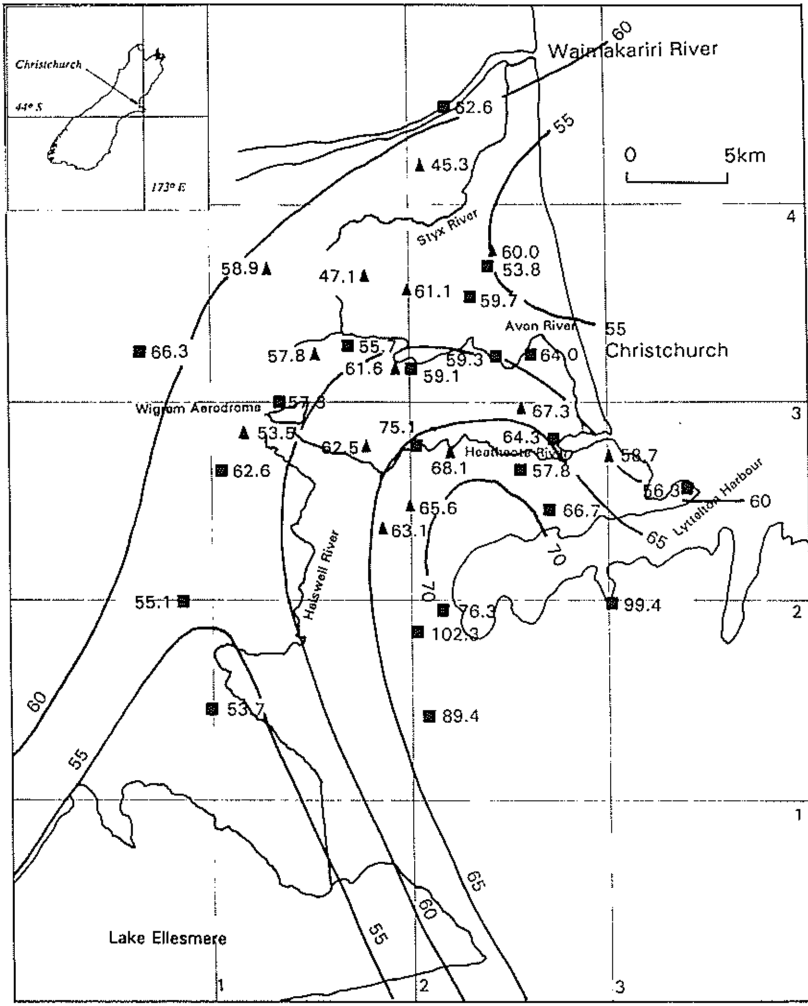

FIG. 3—Christchurch metropolitan area showing raingauge locations and isolines of mean annual maximum 24-hour duration rainfall depth (mm). (Christchurch City Council automatic raingauges shown as triangles; New Zealand Meteorological Service daily raingauges as squares.)

ANALYSIS

Christchurch Storm Rainfalls

Heavy rainfalls in Christchurch result from depressions, with centres south and south-east of South Island producing south-westerly frontal rain with preceding thunderstorms, and with centres north to east of South Island producing north-easterly to south-easterly rain. Falls of more than 100mm of rain in 24

TABLE 2—Daily rainfall stations, mean annual maximum 24-hr rainfall and mean annual rainfall

Station (New Zealand Meterological Service)	Years of Record	Location (Figure 3)	Mean annual maximum 24-hr rainfall (mm)	Mean annual rainfall (mm)
Waimakariri Bridge	1967–87	2245	62.6	654
Windsor	1978–86	2437	53.8	584
Paparua	1967–87	0633	66.3	587
Wigram	1938–68	1330	57.3	638
Prebbleton	1970–86	1026	62.6	648
Clyde Road	1979–87	1733	55.7	690
Christchurch	1873–1987	2032	59.1	653
Cashmere Hills	1941–75	2028	75.1	730
Shirley	1967–87	2335	59.7	613
Pages Road	1968–76	2432	59.3	538
Bromley	1961–86	2632	64.0	608
Mt Pleasant	1964–86	2728	64.3	702
Horotane	1968–85	2526	57.8	614
Godley Head	1967–87	3425	56.3	565
Lincoln	1881–1987	0920	55.1	656
Allandale	1941–73	2219	76.3	863
Living Springs	1979–86	2018	102.3	894
Lyttelton	1967–80	2724	66.7	590
Purau	1967–85	3020	99.4	878
Greenpark	1967–86	1015	53.7	648
Gebbies Pass	1967–77	2114	89.4	841

hours are not unusual, and up to 170mm in 18 hours has been recorded. A very local, intensive, short duration, thunderstorm near Wigram Aerodrome (Fig. 3) in 1975 yielded 30mm in 30 minutes (Tomlinson, 1978). Further details on spatial patterns of daily rainfall are given in Trewinnard and Tomlinson (1986). Detailed records of severe storms from 1963 are reviewed by Pearson (1992).

Rainfall Data

Hourly records were available from 14 automatic raingauges operated by the Christchurch City Council (Fig. 3) (Table 1). Annual maximum rainfalls with durations between 1 and 72 hours were extracted from this set: 0.5 hr values were provided separately by the Council. A secondary data set comprised daily rainfall data from stations operated by the New Zealand Meteorological Service (Fig. 3) (Table 2).

Records from two long-term stations (Christchurch, Lincoln) (Table 2) were used to check for stationarity and serial correlation. For both records serial correlation, trend, independence and split-sample tests confirmed that the 24-hour annual maximum time series were stationary and serially independent. The tests used were those employed by McKerchar and Pearson (1989, pp 14–

15) for New Zealand flood series. This finding is supported by Withers and Pearson (1991) who found no significant trends in Christchurch rainfall in the interval 1880–1990.

Rainfall Depth-Duration Relations

Annual maximum rainfalls for durations of 0.5, 1, 3, 6, 12, 24, 48, and 72 hours, together with annual totals, were extracted from the data. To convert from fixed-time maxima, 0.5 hr and 1 hr maxima were multiplied respectively by 1.05 and 1.14 (Tomlinson, 1980, p7).

Correlations between stations with automatic gauges were calculated for 1-hr and 24-hr annual maximum rainfalls. Pearson correlation coefficients were generally large and positive for the 1-hr data and all coefficients exceeded 0.5 for the 24-hr data (Pearson, 1992).

The spatial pattern for mean annual maximum rainfalls of 24-hr (Fig. 3) and longer durations closely resembles the pattern of mean annual rainfall, but for shorter durations this resemblance diminishes. In earlier studies of Christchurch rainfall, Carver and Greenland (1977) and Carver and Gordon (1982) have shown spatial variation using ratios of rainfalls at different sites. However, in absolute terms the differences are less than sampling errors. In fact, for durations of 0.5 to about 12 hrs the mean annual maximum rainfall appears to be roughly constant over the Christchurch metropolitan area. This behaviour allows the development of a simple non-linear model of depth-duration relations for durations between 0.5 and 24 hr. As boundary conditions we take a constant value of 10.9mm at 0.5hr, and 24-hr values of 55, 60 and 65mm corresponding to the isolines in Figure 3. For the model we adopt the power law

$$\bar{P} = aD^b \qquad 0.5 \leq D \leq 24\text{hrs} \tag{5}$$

in which D is duration and a, b are constants. Introduction of the boundary conditions implies

$$b = (ln\ \bar{P} - ln\ 10.9) \tag{6}$$

$$a = \bar{P}_{24}/24^b \tag{7}$$

where $\bar{P}_{24}$ is the mean annual maximum 24-hr rainfall (Fig. 3). Pearson (1992) provides maps which can be used to interpolate rainfall depths for durations between 24 and 72 hrs.

Rainfall Depth-Return Period Relations

EV1 distributions were fitted by the method of probability-weighted moments (Greenwood et al, 1979) to the annual maxima data for 8 durations (Fig. 4). The fits for each site were found to be acceptable using the hypothesis tests of Hosking et al. (1985). EV1 lines steepen with increasing duration because of increasing rainfall depths for a given return period with longer durations (Fig. 4). Between Christchurch stations EV1 lines steepen as mean annual rainfall increases.

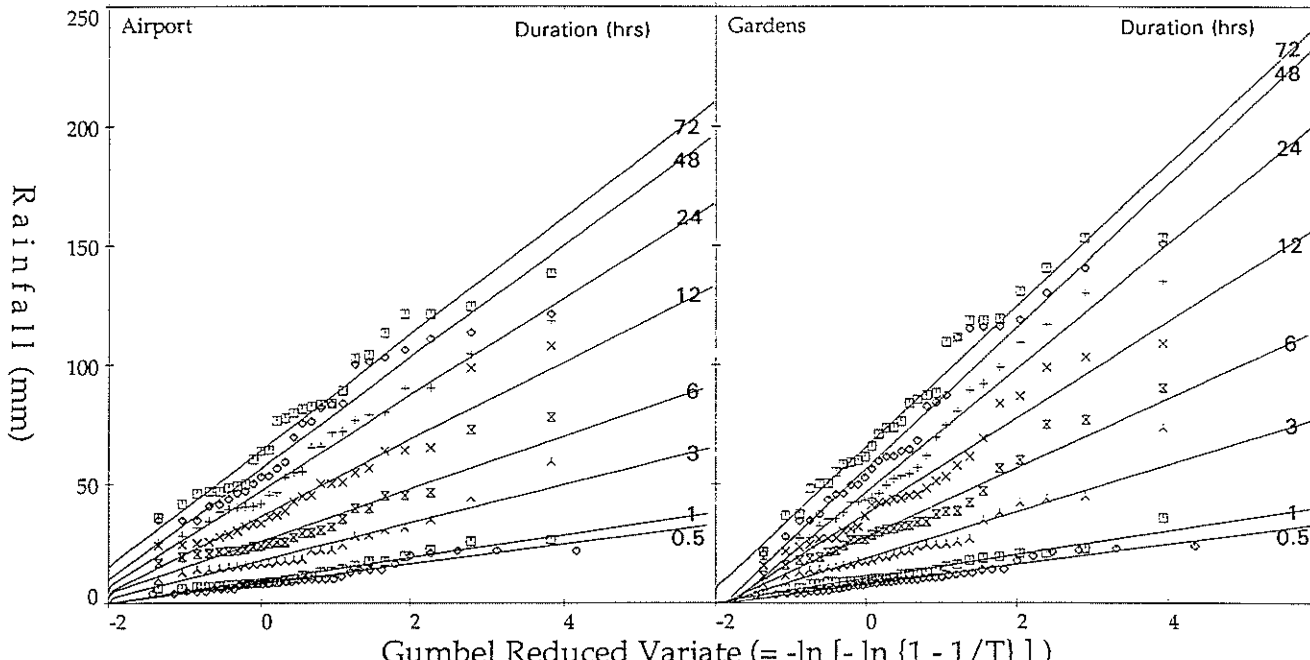

FIG. 4—Examples of EV1 frequency plots for annual maximum rainfall series of various durations. Stations are Airport and Gardens (Table 1). Data plotted using Gringorten (1963) plotting position.

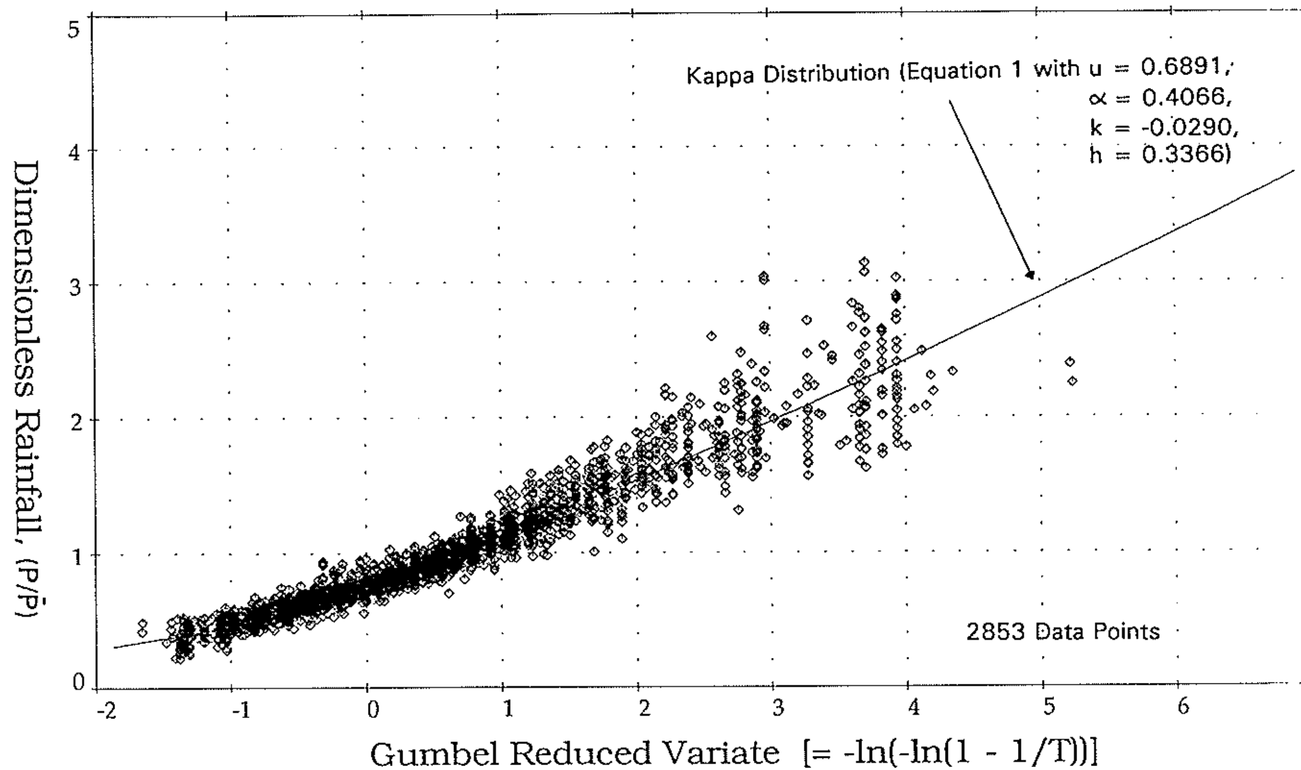

FIG.5—Dimensionless rainfall depth-return-period relation for metropolitan Christchurch. Data plotted using Gringorten (1963) plotting position.

TABLE 3—Dimensionless rainfall depth-return period relation for discrete return periods and durations 0.5 to 72 hrs

Dimensionless rainfall depth $P/\bar{P}$	1.64	1.95	2.37	2.69	3.02	3.46	3.80	4.15	4.62	4.98
Gumbel reduced variate $\ln\{-\ln[1-(1/T)]\}$	2.25	2.97	3.90	4.60	5.30	6.21	6.91	7.60	8.52	9.21
Return period T (yrs)	10	20	50	100	200	500	1000	2000	5000	10000

For regional analysis, L-moment ratios were computed for the above durations. Plots of L-coefficient of variation against L-skewness (L_2/L_1 v L_3/L_2) and L-skewness against L-kurtosis (L_3/L_2 v L_4/L_2), indicate that an EV1 distribution lacks the skewness required to model Christchurch rainfalls, so large rainfall depths for longer periods would be underestimated by this function (Pearson, 1992). This conclusion is supported by the findings of Carver and Greenland (1977) and Carver and Gordon (1982). Three hypothesis tests of Hosking and Wallis (1993) were also applied to the L-moment data. The first identifies grossly discordant rainfall stations, the second estimates the degree of heterogeneity in a group of stations and the third is a goodness-of-fit test for 3-parameter distributions. The principal findings were that the Christchurch metropolitan area can be treated as one homogeneous region, and that the 3-parameter lognormal distribution is the most appropriate 3-parameter function for modelling regional data implying a fixed L_4. A better fit to the sample was achieved using the 4-parameter Kappa distribution (Fig. 5) (Table 3).

The regional frequency approach does not allow systematic calculation of standard errors. Nevertheless, with regional procedures errors are usually proportional to $1/\sqrt{nN}$, where n is the average record length and N is the number of records (National Environment Research Council, 1975). Based on this result we estimate limits of ± 30% to standard errors for rainfall-depths of return period less than 1000 years.

Area Reduction Factors

A limited but random check was conducted on the applicability of area reduction factors derived by Natural Environment Research Council (1975) to the Christchurch metropolitan area. Annual maximum flood runoff data (1981–1985) for the Avon Catchment above Gloucester Street (site 66602; Walter (1990); area = $25km^2$) were used to calculate spatially integrated values of rainfall. Point maxima were obtained from rainfall stations at Gardens and Riccarton (Table 1) and area reduction factors were calculated for 5 durations (Pearson, 1992) (Table 4). All values of these factors are less than the estimates of Natural Environment Research Council (1975), but the differences are probably not statistically significant. They may arise from sampling error and from the necessary

TABLE 4—Comparison of area reduction factors derived for Avon Catchment, Christchurch and for United Kingdom (Natural Environment Research Council (1975))

Duration (hrs)	Area Reduction Factor Avon	United Kingdom
1	0.78	0.87
3	0.83	0.92
6	0.84	0.94
12	0.82	0.95
24	0.74	0.97

assumption of the coincidence of annual maximum flood peaks and annual maximum spatial rainfalls (Pearson, 1992).

Risk and Climate Change

The rainfall distributions derived in this study may be used to predict future storm rainfalls, assuming that climate doesn't change during the design period (up to 100 years). This may be unrealistic, as several lines of empirical evidence suggest climate is changing (Ministry for the Environment, 1990). But there is little agreement about the magnitude of change over the next 50 years or so, let alone the rate. Our results do, however, allow the user to accommodate the effect of climate change on storm rainfall predictions. For example, if the rate of future change is linear, so that an increase of p% in rainfall intensity in a design life of L years implies an annual increment of (p/L)%, then the risk, r, of at least one exceedance in L years defined by (Benjamin and Cornell, 1970)

$$r = 1 - [F]^L = 1 - [1 - (1/T)]^L \qquad (9)$$

becomes, for the future period,

$$r = 1 - \prod_{j=1}^{L} F_j \qquad (10)$$

where the probabilities of exceedance are independent from year to year. Equation 10 may be evaluated using Equation 1 expressed in discrete form as

$$F_j = \left\{1 - h\left\{1 - [k\,[\,(P/\bar{P}) - u_j]\,/\,\alpha_j\,]\right\}^{1/k}\right\}^{1/h} \qquad (11)$$

in which

$$\alpha_j = [1 + (jp/L)]\alpha \qquad (12)$$

and

$$u_j = [1 + (jp/L)]u \qquad 0 \leq j \leq 1 \qquad (13)$$

TABLE 5—Risks of exceedance of 100 and 1000-year rainfalls for discrete increases in rainfall intensity and design life

		Increase in rainfall intensity				
		0%	5%	10%	15%	20%
(a) T = 100 years						
		Risk of exceedance				
	Design life L(yr)					
	20	18	21	24	27	30
	30	26	30	33	37	41
	50	40	44	49	54	59
	100	63	69	74	79	83
(b) T = 1000 years						
	20	2.0	2.4	2.9	3.6	4.3
	30	2.9	3.6	4.3	5.2	6.3
	50	4.8	5.9	7	8.5	10
	100	9.5	11	14	16	19

The results of applying Equations 11, 12 and 13 to a 100-year and a 1000-year event for various design periods and for several linear climate-change scenarios are listed in Table 5. Risk of exceedance for a given design life increases as the change in rainfall intensity gets larger, and the longer the return period the greater the proportional increase (Table 5). Because these changes in risk are significant the prudent user might well make some allowance for climate change.

APPLICATION

To show how the previous analysis can be applied, two examples are given of calculating design or future storm rainfalls in catchments within metropolitan Christchurch. Further examples are set out in Pearson (1992).

Example 1

Problem: Obtain a design rainfall depth, storm hyetograph and spatial distribution at the centroid of the Buxton Terrace sub-catchment of Heathcote River for a 0.5-hr duration, 500-year storm.

Solution: From Equations 5, 6, and 7, $\bar{P}$ = 10.9mm (the lower boundary condition defined above) and substitution of this value in Equation 1 (with T = 500) or using Table 3 yields a 0.5-hr, 500-yr point estimate of 37.7mm. For a catchment area of 63.4km^2 the areal reduction factor (Fig. 1) is 0.76, so the required rainfall depth is 28.7mm. Bounds to temporal cumulative profiles are prescribed by Equations 2 and 4 which yield for this example

$$P/28.7 = 2t^{1.37} \quad \text{(Upper)}$$

$$\text{and } P/28.7 = 1-(1-2t)^{1.37} \quad \text{(Lower)}$$

$$0 \leq t < 0.5\text{hr}$$

A uniform storm hyetograph could be a reasonable choice for such a short duration event. The spatial pattern should be uniform, in line with observations of the distribution of other 0.5-hr rainfalls.

Example 2

Problem: Obtain a design rainfall depth, storm hyetograph and spatial distribution at the centroid of the Gloucester Street subcatchment of Avon River for a 12-hr duration, 50-year storm.

Solution: From Figure 3 the mean annual maximum 24-hr rainfall at the sub-catchment centroid is 58mm. Substitution of this value into Equations 5, 6, and 7 gives b = 0.432, a = 14.7 and P = 43mm as the mean annual maximum 12-hr rainfall. The frequency multiplier for a 50-yr event from Table 3 is 2.37, which implies a design rainfall depth of 102mm. For a catchment area of 25km^2 the areal reduction factor is 0.955 (Fig. 1) so the required rainfall depth is 97mm. Bounds to temporal cumulative profiles are (Equations 2 and 3)

$$P/97 = (t/12)^{1.54} \quad \text{(Upper)}$$

$$P/97 = 1-(1-(t/12)]^{1.54} \quad \text{(Lower)}$$

$$0 \leq t \leq 12\text{hr}$$

and final choice of profiles lies with the user. The spatial pattern should follow the 24-hr pattern (Fig. 3).

FUTURE WORK

A high density of raingauges, a moderate amount of record and a small metropolitan area have allowed estimation of reasonably precise design rainfalls up to a return period of about 100 years. The main task for the future is to develop methods for extrapolating recorded data to the upper tail of the probability distribution of rainfall depths. The problem is a very difficult one and its solution will most likely involve probabilistic transposition of storm, flood and catchment data from elsewhere along with ergodic transformation, that is, substitution of spatial for temporal variation.

A systematic method is needed for calculating standard errors and further testing of the applicability of area reduction factors derived in the United Kingdom to metropolitan Christchurch is desirable.

The effects of climate change on risks of exceedance of design rainfalls may be accommodated if the magnitude and rate of future change in rainfall intensity is known. Unfortunately it will be many years before climate trends can be established. In the meantime we should continue to monitor rainfall behaviour, otherwise the investment in recording and analysis to date may be of little value.

CONCLUSIONS

The main conclusions of this study are:

(1) Statistical tests indicate that annual maxima recorded at rainfall stations in the Christchurch metropolitan area are stationary and serially independent.
(2) Metropolitan Christchurch forms a single homogenous hydrological region for the relationship between dimensionless rainfall depth and return period. A 4-parameter Kappa distribution provides an excellent fit to the data which extends up to a return period of about 100 years.
(3) The spatial pattern of 24-hr and longer duration rainfalls is similar to the pattern of mean annual rainfall over Christchurch. This resemblance weakens as durations decrease; below about 12 hr the spatial distribution is approximately constant.
(4) A random check on one catchment in central Christchurch indicates that area reduction factors derived in the United Kingdom may be used to infer areal rainfall of given duration and return period from point rainfall of the same duration and return period.
(5) Variability of recorded storm profiles allows use of a wide range of hyetograph shapes. Theoretical envelopes to the range of shapes can be specified, assuming triangular rainfall patterns for 10-yr storms and a uniform hyetograph for a storm with infinite return period.
(6) The effect of linear change in rainfall intensity arising from climate change on the risk of exceedance of rainfall in a given design life can be readily calculated. It would be prudent to make some provision for this effect when estimating design rainfalls, particularly for large return period storms.

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