FLOOD HYDROLOGY OF THE MOTU RIVER

D. C. Riddell

Power Division, M.W.D., P.O. Box 12-041, Wellington

ABSTRACT

The flood hydrology of the Motu River catchment is reviewed and design floods and the probable maximum flood are estimated for two sites on the river. By comparison with other New Zealand rivers that have been developed for hydroelectric power, the proportion of storm runoff is high and the resulting floods rise rapidly with large peak flows. Diversion works for dam construction will be larger than normal and the spillway for the lower dam site must be larger than any existing spillway in New Zealand.

INTRODUCTION

As part of the investigations into the hydroelectric potential of the Motu river (Fig. 1), the hydrological information available for this catchment has been reviewed and design floods recommended. This paper presents a summary of this review.

A cascade of three dams at distances of 56 km, 30 km and 5 km from the mouth of the river has been proposed. These are respectively termed the M56 (Mangaotane), M30, and M5 (Houpoto) dam sites.

In many parts of the world major hydraulic structures are being designed to safely withstand the maximum anticipated flood. One method in general use is based on the concept of the probable maximum flood (PMF), which is defined as "the flood that may be expected from the most severe combination of critical meteorological and hydrologic conditions that are reasonably possible in the region" (US Corps of Engineers, 1975). In determining the PMF, the most important element is the probable maximum precipitation (PMP), which has been defined as "the theoretical greatest depth of precipitation for a given duration that is physically possible over a particular drainage area at a certain time of the year" (American Meteorological Society, 1959). Wiesner (1970) points out that PMP is merely an estimate, and that its value will depend upon the quality of data, technical knowledge, and thoroughness of analysis.

HYDROLOGY

Most of the precipitation in the Motu region occurs as rain. Snow falls on only a few days a year at higher altitudes, and is insignificant hydrologically, Areal rainfall for the Motu catchment was estimated by fitting isohyets to rainfall data from more than 100 rain-gauges covering the East Cape region. Mean annual rainfall ranges from about 4000 mm along the Raukumara Range in the northeast to less than 2000 mm in the north and south of the catchment.

Water-level recorders were installed on the Motu river at Houpoto in 1957, at a site downstream of Waitangirua station in 1960, and at Mangaotane for a short period (September 1961 to June 1963). In late

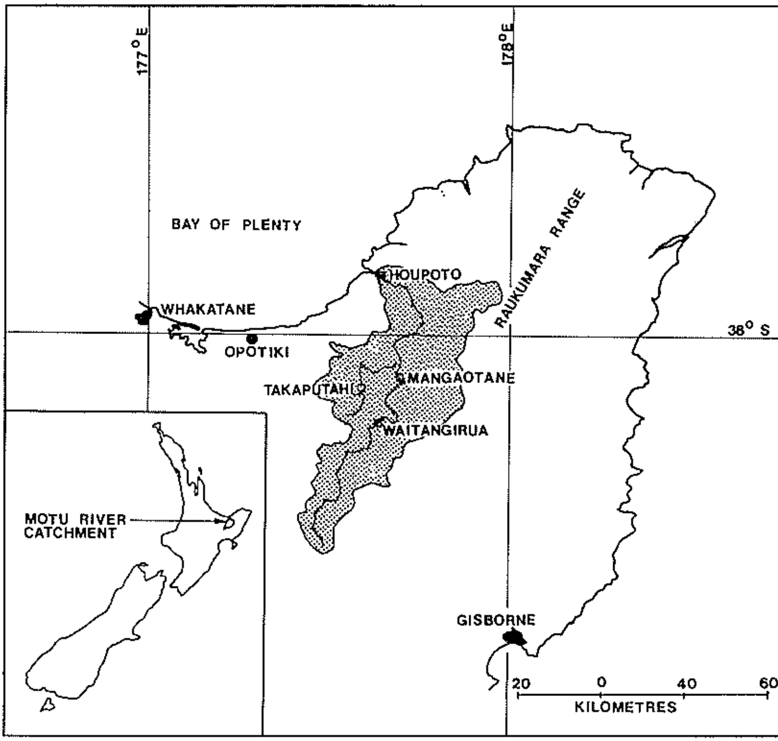

FIG. 1—Motu River catchment and location of water level recorder stations.

1978, a recorder was re-established at Mangaotane, and another was installed at a new site on the Takaputahi river, a major tributary of the Motu (Fig. 1).

The long term mean flows (1957-79) recorded at three sites on the Motu river were:

Houpoto	89.3 m^3/s
Mangaotane	36.3 m^3/s
Waitangirua	13.6 m^3/s

(The means of the shorter records at Mangaotane and Waitangirua were adjusted by ratio with the mean at Houpoto.)

Mean annual evaporation calculated from the water balance continuity equation $E = P - Q$, where E = evaporation (mm/yr), P = rainfall (mm/yr) and Q = runoff (mm/yr), ranges from 525 mm/yr for the southern 295 km^2 Waitangirua catchment, to 650 mm/yr for the 1381 km^2 Houpoto catchment (Table 1).

Evaporation increases with increasing forest area and average catchment rainfall (as more water is available for evaporation). The range of evaporation estimates compares favourably with the variation of Finkelstein's (1973) higher open-water values. Although rainfall was accurately determined for the smaller Waitangirua catchment the scarcity

TABLE 1—Catchment water balance.

Motu catchment above	Area km^2	Mean annual — Rainfall mm/yr	Runoff mm/yr	Evaporation mm/yr
Waitangirua	295	1960	1435	525
Mangaotane	646	2360	1770	590
Houpoto	1381	2690	2040	650

of rain-gauges over much of the remaining Motu catchment meant that the estimates of average rainfall over the larger Mangaotane and Houpoto catchments were more subjective. Nevertheless the evaporation values imply that the mean annual rainfall estimates are reliable.

Three weather sequences commonly cause heavy rain in the Bay of Plenty region (Kerr, 1961). Typical meteorological situations associated with these sequences are illustrated in Figure 2. In all cases air-flow is from a north or northeasterly direction and is associated with the southeasterly movement of depressions originating in the Tasman Sea northwest of New Zealand. The duration of heavy rainfall depends primarily upon the speed with which a depression moves across the country.

In summarising the characteristic storm sequences which occur in the Bay of Plenty, Kerr (1961) states: "the rate of rainfall may be high and the duration 6 to 24 hours or the rate may be moderate and the duration as much as 48 hours. The period during which the rainfall rate is high may be preceded by lighter rain and followed by showers or further, shorter periods of rather heavy rain."

In 30 of 49 storms which occurred in the Motu from 1958 to 1978, most of the rain fell within 48 hours or less, and in 25 of the 30 storms all the rain fell within a 36 hr period The storms producing the highest recorded flood peaks at Houpoto had durations of about 2 days or less.

Storm hydrographs were separated into components of baseflow and direct runoff. Baseflow was separated by fitting a straight line from the start of hydrograph rise to the baseflow separation point on the recession limb determined by the intersection of two straight recession lines on plots of logarithmic flow versus time.

Direct runoff was plotted against rainfall for 43 storms for Waitangirua (Fig. 3) and for 49 storms for Houpoto (Fig. 4). The rainfall/runoff relationships at the two sites were similar. Losses to direct runoff (e.g. by interception, infiltration and storage) were greater in the larger Houpoto catchment than in the smaller Waitangirua catchment. Initial losses were marginally higher for Houpoto than Waitangirua but for both catchments the ratio of runoff to rainfall tended to unity after the initial losses.

The ratio of runoff to rainfall varies with storm duration (Figs. 3 and 4). In general storms of 24 to 48 hr duration yield the greatest runoff. No significant relationship was found between rainfall/runoff and antecedent precipitation, antecedent discharge or storm intensity. The lack of relationship with antecedent precipitation and discharge indicate

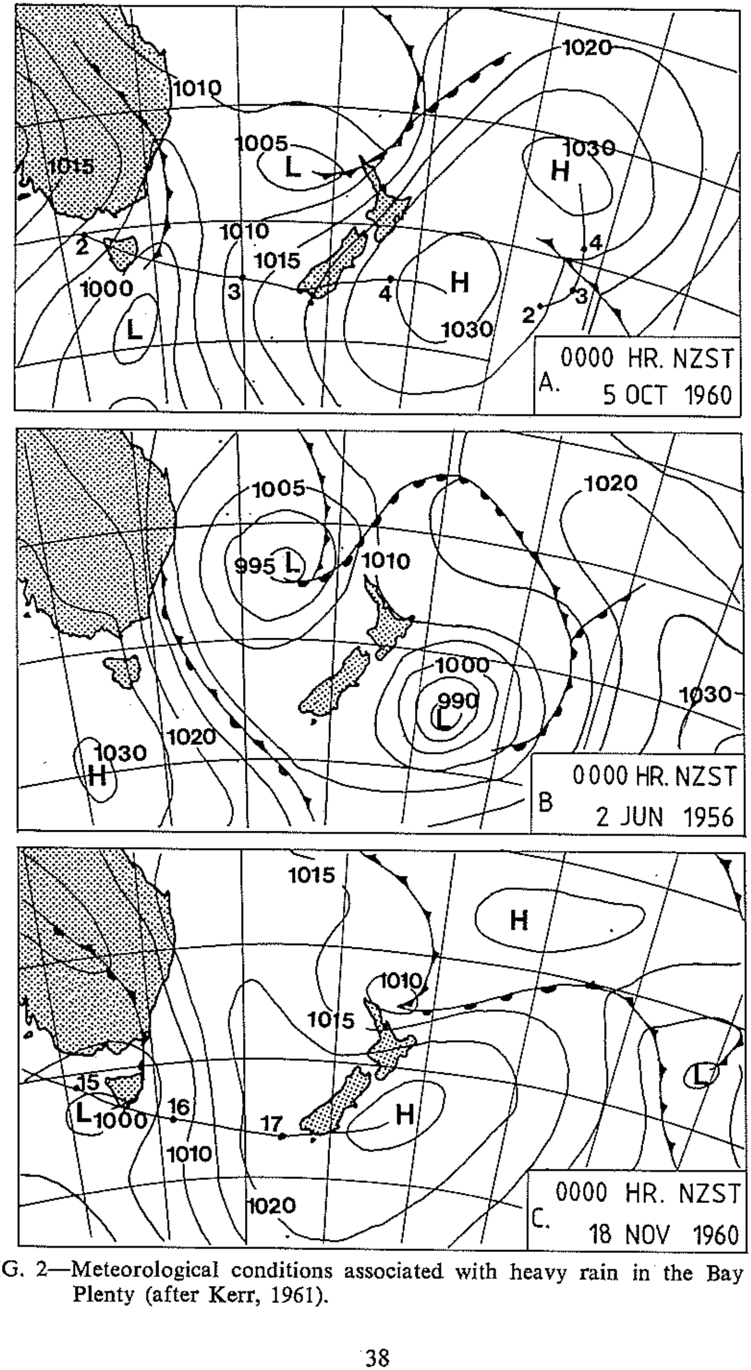

FIG. 2—Meteorological conditions associated with heavy rain in the Bay of Plenty (after Kerr, 1961).

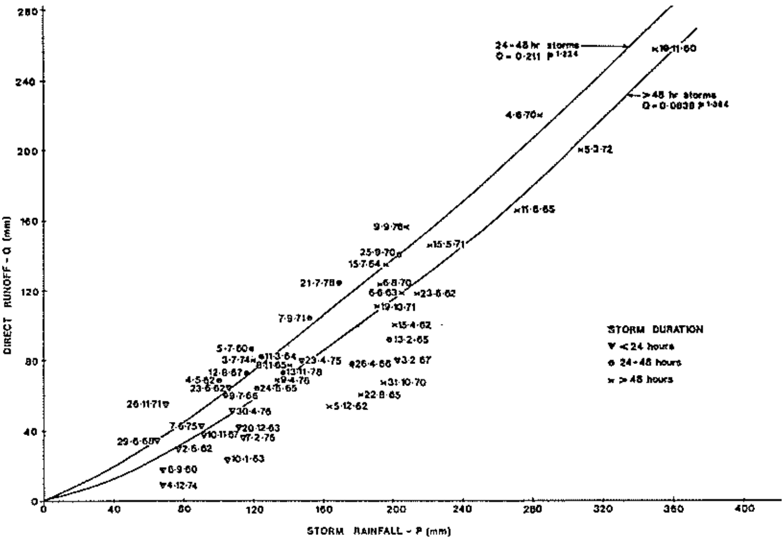

FIG. 3—Waitangirua storm rainfall-runoff-duration relationships.

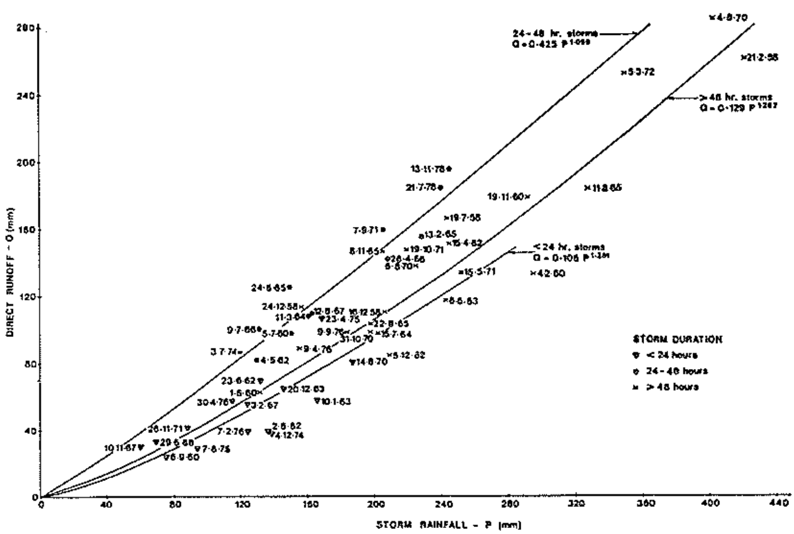

FIG. 4—Houpoto storm rainfall-runoff-duration relationships.

that storage within the catchment is too small to markedly affect storm runoff. While storm intensities influence the magnitude of peak flows, runoff amounts depend more upon total volumes of rainfall.

FLOOD ESTIMATES

Two methods were used to estimate flood frequency—frequency analysis of recorded annual maximum flows, and analysis of unit hydrographs. Whereas the first method uses only the recorded floods, the unit hydrograph method uses both the recorded floods, and the records of maximum rainfalls from many stations, some with up to 60 years of record.

Frequency Analyses

Annual maximum instantaneous, 2 hr, 6 hr, 12 hr and 24 hr flows (by moving mean) recorded at the Waitangirua and Houpoto sites were fitted by least squares (plotting positions determined by the Weibull formula) to a Gumbel distribution. Instantaneous maxima, together with the fitted lines and their 68.3% control curves, are plotted in Figure 5. Control curves were derived using the method proposed by Gumbel and outlined by Chow (1964). Floods calculated for recurrence intervals of 2, 15, 500 and 1000 yr are compared with other estimates in Table 3.

Unit Hydrograph Method

One hundred millimetre direct runoff unit hydrographs for various durations were derived by averaging several flood hydrographs for appropriate storm durations. S-curves were constructed from the average 4 hr-100 mm unit hydrographs. and from these, 100 mm direct runoff unit hydrographs were derived for effective rainfalls of durations up to 36 hr.

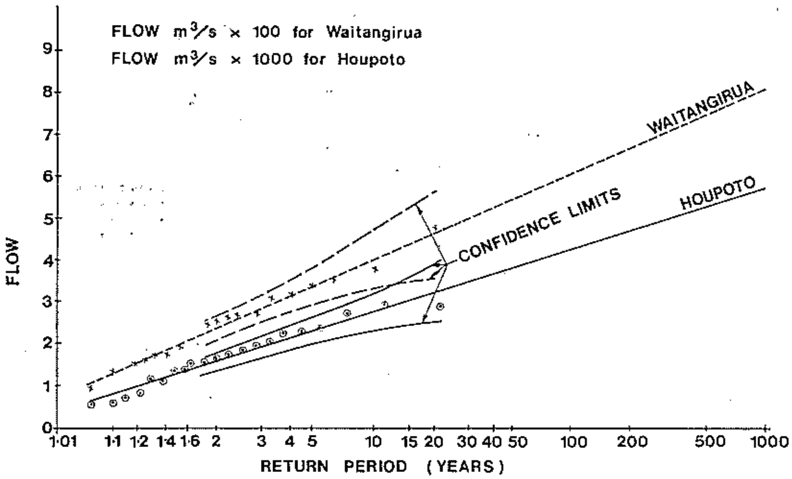

FIG. 5—Gumbel frequency analyses of annual series data.

Flood estimates for return periods of 2, 15, 500 and 1000 years were obtained as follows:

1. Annual maximum 1, 2 and 3 day 9 a.m. point rainfalls from 37 rain-gauges were analysed using the Gumbel frequency method. This method is used by the N.Z. Meteorological Service (Robertson, 1963) for determining rainfall depth-duration-frequency relationships. Areal rainfall was estimated by planimetering the area between isohyets fitted to the point rainfalls. Annual maximum *daily* point rainfalls were not adjusted (upwards) to annual maximum *24 hour* falls as in Robertson (1963), nor were they reduced for area using depth-area-reduction curves (e.g. U.S. Weather Bureau, 1958) because these two operations tend to balance. Tomlinson (1978) is of the opinion that area reduction curves for assessing areal rainfall from point rainfalls cannot be satisfactorily constructed for New Zealand because of the large spatial variation in rainfall.
2. Typical temporal patterns of rainfall distribution were derived from automatic raingauge records from either Matawai, Opotiki or Waipaoa—depending which had the best record during the particular event. Hydrographs were derived for 24, 36 and 48 hour rainfalls.
3. Direct runoff associated with the depth and duration of the extreme rainfall was obtained from rainfall/runoff relationships (Figs. 3 and 4).
4. Total losses to direct runoff (i.e. interception, infiltration, storage and evaporation) were calculated by subtracting direct runoff from storm rainfall. Losses were assumed to be uniform throughout the storm, and the ordinates of the 4 hr-100 mm unit hydrographs were multiplied by the proportion of rainfall excess which occurred in each 4 hr period. The resultant 4 hr hydrographs were then used to produce a composite hydrograph of direct runoff.
5. An estimate of baseflow was added to the direct runoff hydrograph. Baseflow was defined from the median antecedent discharge and median slope of the baseflow separation line of the recorded flood hydrographs.

   The critical storm duration (i.e. that which produces the largest flood peaks) is 36 hr (Table 2).

TABLE 2—Unit Hydrograph flood estimates (m^3/sec).

Site	Return period (yr)	Rainfall duration		
		24 hr	36 hr	48 hr
Waitangirua	2	210	270	250
	15	380	460	420
	500	650	740	660
	1000	700	800	715
Houpoto	2	1830	1980	1730
	15	2960	3280	2860
	500	3980	5070	4410
	1000	4932	5390	4700

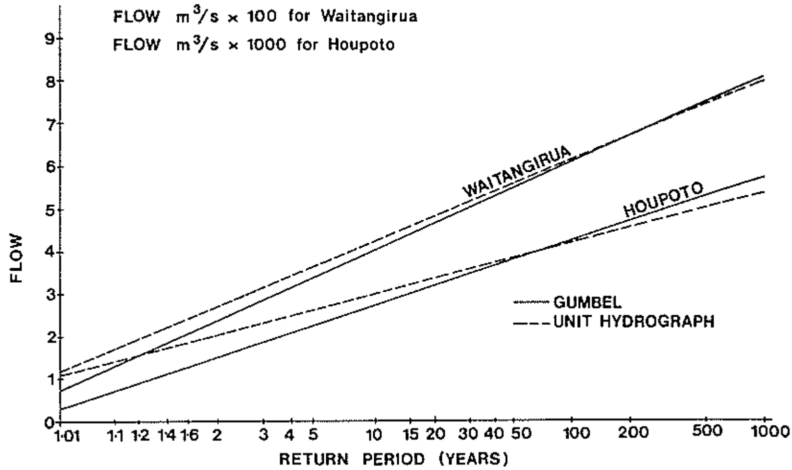

FIG. 6—Comparison of Gumbel and unit hydrograph flood estimates.

COMPARISON OF FLOOD ESTIMATES

Estimates from the frequency analyses of flows and the unit hydrograph method (Fig. 6) differ most at low return periods and least at high return periods.

Further flood estimates were generated by fitting several other frequency distributions to the annual series data (Table 3). Description of these distributions is given by Maguiness *et al.* (in prep.). The estimates varied considerably but there was good agreement between the Extreme Value Type I (EV1) distribution (with data fitted by both the maximum likelihood and least squares methods) and the unit hydrograph and Gumbel estimates.

TABLE 3—Comparison of flood estimates.

Return period (yrs)	Peak flood discharge (m^3/s) using method:*								
	1	2	3	4	5	6	7	8	9
				Waitangirua					
2	270	240	234	239	239	231	240	232	260
15	460	440	420	415	415	436	398	419	402
500	740	750	706	582	582	709	563	703	619
1000	800	810	762	589	589	723	587	758	661
				Houpoto					
2	1980	1560	1551	1583	1615	1503	1659	1551	1813
15	3280	3040	2926	2938	2830	3198	2687	2978	2778
500	5070	5290	5036	4109	3641	5706	3381	5167	4260
1000	5390	5730	5449	4161	3674	5847	3452	5596	4550

* METHOD

1 Unit hydrograph.

2 Gumbel: fitted by least squares. Plotting positions by Weibull.

3 Gumbel: fitted by least squares. Plotting positions by Gringorten.
4 Log-Pearson Type 3 (LP3): fitted by the method of moments. Plotting positions by compromise formula proposed by Natural Environment Research Council (NERC) (1975).
5 LP3, with an adjusted coefficient of skew: fitted by the method of moments. Plotting positions by compromise formula proposed by NERC (1975).
6 Log-normal: fitted by the maximum likelihood method. Plotting positions by compromise formula proposed by NERC (1975).
7 General extreme value (GEV): fitted by the maximum likelihood method. Plotting positions by Gringorten.
8 Extreme value Type I (EV1): fitted by the maximum likelihood method. Plotting positions by Gringorten.
9 EV1 distribution using the Jenkinson method. Plotting positions by Gringorten.

Most of the variation in the estimates results from the different methods used to plot the data and to fit the curves, but the lower Log-Pearson Type 3 and general extreme value estimates are functions of those particular distributions.

Final flood estimates were chosen after comparing results from all methods but particular weight was assigned to the unit hydrograph and Gumbel (with plotting positions by the Weibull formula) estimates.

PROBABLE MAXIMUM PRECIPITATION

The maximum amount of moisture available to a storm was estimated by multiplying measured rainfalls by the factor P_m/P_s, where P_m is precipitable water at maximum persisting dew point temperature and P_s is precipitable water at the dew point temperature representative of the storm. Precipitable water was obtained from tables relating moisture to dew point temperature and altitude (U.S. Weather Bureau, 1951). Maximum persisting dew point temperatures for each month of the year were selected from maximum dew point temperatures recorded at Gisborne and from mean monthly sea surface temperatures (Reid, 1972) measured at latitude 30° to 32° S and due north of East Cape, where most of the heavy rainstorms occurring in the Motu originate (Table 4). Dew point temperatures representative of the storm (12 hr or 24 hr persisting, depending upon the duration of the storm) were estimated from the Gisborne climatological station records.

Maximum available moisture was calculated for average catchment rainfalls for severe storms in both the Waitangirua catchment and the Houpoto catchment. The highest 24 hr duration maximum rainfalls were 393 mm for the Houpoto catchment, and 347 mm for the Waitangirua catchment. For the latter a 424 mm maximum rainfall was calculated from the 48 hr storm of November 1960.

Rainfall values for storms which have occurred in regions meteorologically similar to the Motu were considered for transposition to the Motu catchment. The most significant storm ever recorded in such a region was that of March 1964 which was centred over the Waioeka catchment immediately adjacent to the Motu. This storm, which was documented by Coulter (1965, 1967), produced the largest recorded flood

TABLE 4—Dew Point Temperatures (°C).

Month	Maximum recorded Dew Point Temperature at Gisborne (1967-78) Hourly	12 hour persisting	24 hour persisting	9 a.m.	Mean monthly sea surface temperature	Max. persisting Dew Point
Jan	23	20	19	20	23	21
Feb	22	20	19	21	23	21
Mar	24	21	20	24	23	21
Apr	21	18	17	19	22	19
May	18	17	15	16	21	18
Jun	17	15	14	16	19	16
Jul	15	13	12	15	18	15
Aug	15	13	12	15	18	15
Sept	17	15	14	16	18	16
Oct	19	16	14	17	19	17
Nov	20	17	15	17	20	18
Dec	20	18	17	19	21	19

in the Waioeka and Whakatane area. The storm from the NNW, lasted about 36 hr.

Isohyets presented by Coulter (1967) were overlaid on the Motu catchment and the average catchment rainfall obtained was used to estimate maximum storm moisture content using a P_m/P_s factor of 1.42. This gave maximum values of 503 mm for the Houpoto catchment, and 413 mm for the Waitangirua catchment.

Final PMP estimates listed in Table 5 were based primarily on the estimated maximum available moisture of the March 1964 Waioeka storm transposed to the Motu with variation in depth of PMP following the observed rainfall depth-duration pattern.

Statistical Estimates

Statistical estimates of PMP were made using the method developed by Hershfield (1961) and based on the general frequency equation; $X=\bar{x}+K\sigma$, where X is the observed value, $\bar{x}$ is the mean of the observed values, σ is the standard deviation, and K is a frequency factor dependent upon the statistical distribution used, the number of years of record n and the return period T. In an analysis of many world-wide precipitation records, Hershfield (1961) found that K never exceeded the value of 15; and hence suggested that an upper limit of PMP is given by the equation $PMP=\bar{x}+15\sigma$. Using this equation estimates of 24 hr and 48 hr duration PMP were derived for all raingauge records previously analysed by the Gumbel frequency analysis method. Point rainfalls were contoured and the following average catchment PMP estimates were obtained: Motu catchment above Houpoto; 774 mm in 24 hr, and 1065 mm in 48 hr; and above Waitangirua; 566 mm in 24 hr, and 837 mm in 48 hr.

Empirical Estimates

Maximum point rainfalls recorded in New Zealand at altitudes below 900 m are enveloped by the equation $P = 112.1\,T^{0.553}$, where P is the rainfall in millimetres and T is the duration in hours (Tomlinson, 1980).

If it is assumed that these greatest recorded rainfalls approached PMP then this equation yields the following PMP estimates: 650 mm in 24 hr; 813 mm in 36 hr; 954 mm in 48 hr.

Both the statistical and empirical methods give estimates which are considerably higher than those obtained by calculation of maximum available moisture of storms that have occurred both in the Motu catchment and in meteorologically similar regions. The statistical estimates based on the K value are doubtful because K may be related to factors other than rainfall duration and the mean of the annual series; the value of 15 may be too high for areas of generally heavy rainfall and too low for arid areas (World Meteorological Organisation, 1973). Tomlinson's (1980) empirical approach gives point estimates of PMP but because of area reduction (which will increase with recurrence interval) the PMP averaged over the Waitangirua and Houpoto catchments will be much less than given by the formula $P = 112.1\, T^{0.553}$. Because the errors involved in reducing rainfall depth for area are unknown there is inherent uncertainty in the use of both the statistical and empirical methods.

PROBABLE MAXIMUM FLOOD

In calculating the probable maximum flood (PMF) the most extreme circumstances were assumed to apply. To arrive at values for the Waitangirua and Houpoto sites, flood hydrographs were derived for PMPs of 12, 24, 36 and 48 hr duration as follows:

1. Extreme temporal patterns of rainfall distribution were used. The PMP was distributed symmetrically so that the maximum rainfall intensity in every duration was centred on the peak of the storm profile (NERC 1975, Riedel, 1977). The maximum rainfall intensity thus decreased slightly with the increasing rainfall duration. Temporal patterns selected for PMPs are shown (Fig. 7).

   A maximum intensity of about 100 mm/hr occurred in the 12 hr PMP, while the intensity in the 48 hr PMP reduced to about 50 mm/hr, but was sustained for 5 to 6 hours. While these intensities were not exceptionally high, they apply to precipitation distributed over a large area; although point rainfall intensities in excess of 100 mm/hr are likely to occur, corresponding average rainfall over the area will be much less.
2. A storm was assumed to have occurred one to two days prior to the storm which produced the PMF. In the Motu, where there is negligible river storage, antecedent storms deplete the small amount of soil-water and depression storage within the catchment. For this reason the losses in the actual PMP storm were assumed to be zero and the amount of direct runoff was therefore equivalent to the PMP.
3. The PMF direct runoff hydrograph was calculated from PMP using the method described in step (4) of the procedure for deriving flood estimates by unit hydrograph.
4. An estimate of baseflow was added to the direct runoff hydrograph. Values used were based on those measured in the recorded flood

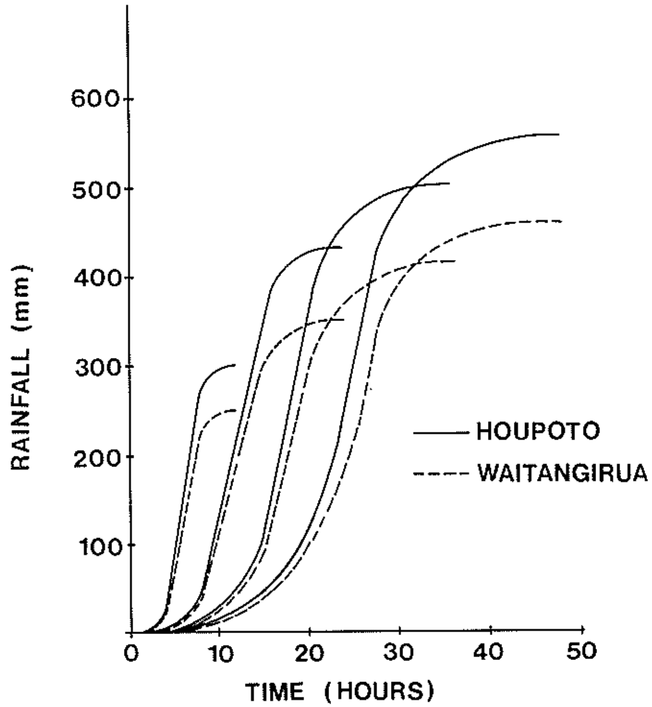

FIG. 7—Temporal patterns of probable maximum precipitation.

hydrographs. Antecedent flow was assumed to be 40 m^3/s and 360 m^3/s at Waitangirua and Houpoto respectively, and the slope of the baseflow separation line was set at 300 $l\,s^{-1}\,hr^{-1}$ at Waitangirua and 2250 $l\,s^{-1}\,hr^{-1}$ at Houpoto. These values are slightly higher than in any of the recorded floods and were based on the assumption that an antecedent storm had occurred.

Selection of PMF

Peak discharges derived for PMPs of duration 12, 24, 36 and 48 hours are listed in Table 5.

As the duration of PMP increases, the difference in peak discharge decreases (Table 5). Thus the peak discharges associated with the 36 hr and 48 hr PMPs are similar. For the Motu catchment, the storm giving rise to the probable maximum flood (PMF) was assumed to be of 36 to 48 hours duration, with average rainfalls of 505 to 555 mm over the Houpoto catchment, and 415 to 460 mm over the Waitangirua catchment. The PMF estimates are summarised with other flood estimates in Table 6.

CONCLUSION

Mean annual precipitation over the Motu catchment varies from less than 2000 mm in the south and north, to about 4000 mm in the eastern

TABLE 5—Peak discharges derived from various duration PMPs.

Duration of PMP (hr)	Waitangirua PMP (mm)	Waitangirua Peak discharge (m^3/s)	Houpoto PMP (mm)	Houpoto Peak discharge (m^3/s)
12	250	987	300	6439
24	350	1246	430	7868
36	415	1355	505	8178
48	460	1353	555	8364

TABLE 6—Recommended design flood estimates.

Return period	Peak discharge (m^3/s) at: Waitangirua	Houpoto
2	250	1800
15	450	3100
500	740	5100
1000	800	5500
Probable maximum flood	1350	8300

ranges. Average mean annual rainfall for the Houpoto catchment is 2690 mm, and the recorded mean flow (1957-78) is 89.3 m^3/s, which is equivalent to a mean annual runoff of 2040 mm. From the water balance equation the mean annual evaporation is thus 650 mm.

The relatively steep gradient and absence of lake storage in the Motu river means that floods resulting from heavy rainfalls occur quickly and have large instantaneous peak flows compared with floods in lake-controlled river systems.

The recommended design floods for the Motu are correspondingly large by comparison with those for New Zealand rivers developed for power to date. The nominal construction flood (15 year return period) for the Houpoto site is 3100 m^3/s which is almost as large, for example, as the 500 yr design flood (3200 m^3/s) for the Clyde dam site on the Clutha river (Jowett and Thompson, 1977). The 500 yr and 1000 yr design floods for the Houpoto site are respectively 5100 and 5500 m^3/s, and the probable maximum flood is 8300 m^3/s. Thus any spillway designed for the Motu river at Houpoto must be larger than any existing spillway in New Zealand.

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