# 10  FLOOD ESTIMATION

The estimation of flood potential at a project site differs from the study of other aspects of the hydrological cycle. Most hydrological studies are based on the analysis of measurements within a basin and the deduction of typical values of different processes like basin rainfall, evaporation or runoff, leading to a water balance tying these elements together (Chapter 8). The study of floods involves the extrapolation from flows experienced at a site or at comparable sites, to floods which can be expected to occur with a given risk or frequency of occurrence, or even to a flood magnitude which is not expected to be exceeded. Thus most other studies can be based on what has been observed over a basin, but flood estimation involves an attempt to deduce what might occur outside the limits of what has occurred in the past. It might seem, in relation to the title of this book, that we are dealing with a question of imbalance, but floods are in fact closely related to a balance between rainfall and soil moisture deficit. Several possible approaches to flood estimation are described, with examples drawn from different environments around the world.

## REQUIREMENTS FOR FLOOD ESTIMATION

Flood estimates are required for a wide variety of civil engineering projects, and almost all projects situated near a river need a flood estimate of some form. At its simplest any structure will need an estimate of the risk that the river level will exceed a certain elevation in order to design protection works. Any structure designed to pass the flow of a river—a culvert, a bridge or a channel reach with flood protection levees—will be based on a flood-frequency relation and an appropriate frequency of the design flow being exceeded. Major structures, like a dam and its discharge spillway, may be designed to pass the flow of a lower frequency or longer return period; the return period is the average interval between exceedances of a given flood, or the reciprocal of the frequency. It may, however, be designed to pass an estimated maximum flood to ensure protection of the structure itself or downstream property against dam failure.

Thus flood estimates may range from flows of low return periods to much rarer events or even to the likely maximum flood. It may be necessary for some purposes to express the flood in terms of river level instead of flow. Because rare floods, by definition, are unlikely to have occurred within a short period of record at a single site, it is essential to enlarge the record on which the estimate is based. This may be done in several ways: information may be sought on historical floods which occurred before formal records were begun; records may be included from other sites within an area which could be considered to have a similar flood regime; rare floods may be assessed by combining physical or statistical estimates of rare storms with a means of converting storm magnitude and distribution in time and space over the basin to a flood hydrograph at the project site.

Thus there are a number of ways in which the flood estimate may be made, and the choice may depend on the information available and the design return period. The choice of methods is discussed first, and then the different methods are summarised with examples from different regions.

## CHOICE OF ESTIMATION METHODS

Various methods are available for estimating flood magnitudes, and they have different data requirements. For example, the *Flood Studies Report* (NERC, 1975) presented a number of techniques which were considered appropriate for estimation in the British Isles. At the time, hydrological data in Britain were largely collected to estimate water resources, and there was no central archive of flood flows. Before existing techniques could be tested and developed, the hydrological team involved in the study, based at the Institute of Hydrology, Wallingford, spent a year visiting all the gauging authorities and some 1200 gauging stations; station reports were prepared and flood rating curves discussed with the local authorities and their reliability graded. Some stations were found to lack accurate high flows and others were at the time too short to be useful. Collection and microfilming of about half a million river level charts were followed by extraction of peak flow records at some 500 gauging stations for statistical analysis, and the extraction of flow hydrographs from 140 sites for unit hydrograph studies. Daily rainfall data, recording raingauge charts, and soil moisture statistics were also collected for comparison with flood hydrographs. Basin characteristics were derived from maps for all the sites suitable for analysis. Thus recommendations were based on a very large body of data on storm rainfall and measured river flows, and on the analysis carried out on these data to obtain relations between observed rainfall and subsequent runoff, and also between observed flows and basin characteristics. Although the empirical relations, for example between mean annual flood and basin characteristics, apply to the area for which they were derived and have been revised by subsequent analysis, there is no reason to believe that the principles involved and the criteria for choice of method are not still valid.

In 1999, Reed *et al.* produced the *Flood Estimation Handbook* which brought up to date the earlier *Flood Studies Report*. Application of the recommended methods is based on analogue records rather than geographical grouping and requires a CD-based set of basin descriptors, which limits its direct use to the UK.

The *Flood Studies Report* provided a choice of means (Fig. 10.1) of estimating the flood hydrograph of any return period, or the estimated maximum flood, from an estimate of the storm depth and its time profile and its conversion to river flow. It also provided a means of estimating the flood peak of any return period by statistical methods, either from flood series measured at the site or, if these were not available, from basin characteristics derived from maps. The choice between these two main approaches, based either on analysis of rainfall and runoff, or on statistical analysis of flood series, and the selection of methods of flood estimation suitable for different circumstances, have been discussed by Sutcliffe (1975, 1978). One method may have advantages over another in certain circumstances, but it may also be desirable to compare and combine more than one method of estimation. The first choice between unit hydrograph analysis of the flood corresponding to a design storm, and direct statistical analysis of peak flows, depends largely on two questions:

Is maximum flood required? — Yes

No

Is hydrograph shape required? — Yes

No

*Statistical* approach          *Unit hydrograph* approach

What period of records is available?          Do records exist? — No

>25 years | 10-25 years | 3-10 years | 1-3 years | None | Yes

Fit general extreme value distribution to annual maxima

Estimate $\bar{Q}$ from annual maximum series

Estimate $\bar{Q}$ from peaks over a threshold (POT) series

Derive monthly maxima. Extend record. Estimate $\bar{Q}$

Estimate $\bar{Q}$ from catchment characteristics

Derive unit hydrograph from rainfall and runoff records

Does area exceed 500 km²? If so, derive tributary unit hydrograph and route flood

Estimate synthetic unit hydrograph

Compare estimates of $\bar{Q}$ and combine

Install gauge

Estimate $Q(T)$

Derive $Q(T)$ from $\bar{Q}$ by region curve

If $T > 500$, use countrywide curve and compare with unit hydrograph estimate

Compare estimates of $Q(T)$

If flood volume of given duration required, deduce $\bar{Q}$ from flows of this duration, or fit reduction curve to $\bar{Q}$ of various durations. Alternatively, apply reduction ratio to calendar day flood, estimated if necessary from catchment characteristics. Use region curve to derive $Q(T)$ from $\bar{Q}$.

Deduce duration of design storm. Deduce point rainfall of appropriate return period. Apply areal reduction factor and storm profile. Deduce losses from catchment characteristics, catchment wetness index and rainfall total. Adjust losses from records if these exist. Multiply net storm by unit hydrograph ordinates and area. Add base flow. Route hydrograph if necessary

**Fig. 10.1** *Choice of flood estimation methods (after NERC, 1975).*

– Is the design flood hydrograph required in addition to the peak flow?
– Is an estimate of the maximum flood required rather than the flood of a given return period?

If the answer to either of these two questions is yes, then the rainfall–runoff approach becomes necessary, of which the unit hydrograph method is an example; if not, then either the statistical approach or the rainfall–runoff approach is suitable, and either or both may be used. The choice also depends on whether there are long, short or no records at or near the site where an estimate is required.

A summary of the recommendation is included in Fig. 10.1. If the flood $Q(T)$ of a given return period $T$ is required and a flood hydrograph is not needed, the statistical approach provides the simpler technique. The statistical approach depends on an estimate of the typical annual flood at the site, based on the mean annual flood or the median flood, which may be estimated from the series of flows at the site. The index flood may be derived from the series of maximum peak flows in each year of record. Where no records exist at a site the mean annual flood can be estimated from basin characteristics; useful characteristics in the British Isles included area, stream frequency, channel slope, net short-term rainfall and indices of soil and lake-affected

fraction. These can be deduced from standard topographic maps or from thematic maps illustrating soils or rainfall for the study area. The relation between basin charact-eristics and the index flood can be deduced by analysis of the floods and basin characteristics of stations within a region or group of sites with similar characteristics. However, the standard error of estimate of such an estimate is likely to be high, and it is preferable to base an estimate on flows measured at the site; for this reason, it is essential to install a gauging station at a site where an important project is foreseen.

If the period of record available is short, the index flood estimate may be improved by extending the record using adjacent long-term records. A "peaks over threshold" analysis may also prove useful; this approach extracts all independent peaks above a given threshold, using a simple rule for independence. The mean annual flood may be simply estimated from the average number of exceedances per year and the average magnitude of the peaks over the threshold.

Where a longer period of records exists, say over 10 years, the mean annual flood may be estimated directly from the maximum flows in each year of record. The flood of return period $T$ may be estimated from the mean annual flood using a dimensionless growth curve, in which the flood of a given frequency or return period is expressed as a multiple of the mean annual flood. This approach is useful when the records from a number of stations are combined to derive a group growth curve. In the 1975 *Flood Studies Report* these group curves were derived from the stations within a region, but they may also be derived from a set of stations with similar area, rainfall and soil characteristics. For moderate return periods, for a site with reasonably long records, it is possible to fit a statistical distribution to the annual maximum flows, but a group curve gives added stability to the result.

Where there is a need to specify the flood hydrograph, or to estimate the maximum flood, the unit hydrograph approach (e.g. Shaw, 1983) is appropriate. The unit hydrograph is the response of a basin to a net storm of a given magnitude, originally an inch but later 1 cm, in a given time period normally taken as 1 hour; this response is assumed to be constant for a given basin. The unit hydrograph for the project site should preferably be derived from rainfall and runoff records, but may also be estimated from basin characteristics where no records exist. The appropriate duration of the design storm is derived from the unit hydrograph dimensions, and the return period of the design storm is deduced from the required return period of the design flood. The rainfall depth corresponding to this duration and return period may be derived, either at a point or over a basin, from the meteorological study, together with a time profile of this storm. The mean point rainfall of the given duration and 5-year return period can be deduced from a map; a growth factor is applied to give the mean point rainfall of the appropriate return period, and an areal reduction factor is applied to give the basin rainfall, which is distributed in time by a standard profile.

The proportion of the storm giving rise to immediate runoff is estimated from the basin soil and urban fraction, taking account of appropriate antecedent conditions and rainfall depth. The net storm profile should be multiplied by the unit hydrograph and base flow added, to give the design flood. This procedure may also be used to estimate the maximum flood, using an estimate of the maximum storm rainfall and also more conservative assumptions about antecedent conditions, storm profile and unit hydrograph; the unit hydrograph can be adjusted by reducing its time to peak and increasing its peak. An allowance for snowmelt runoff is added where appropriate.

Thus there is a wide variety of methods available for estimating floods, and the choice depends on data availability and to some extent on the circumstances of the estimate. It is also desirable to use alternative methods and compare the results.

## STATISTICAL DISTRIBUTIONS

The fitting of statistical distributions to annual maximum flood values at a single site was the subject of considerable research, following the adaptation of extreme value theory by Gumbel (1941) to the flood problem. He apparently met an engineer on a skiing holiday and described his research in theoretical statistics, based on work by Fisher & Tippett, and was encouraged to apply this work to flood problems. He noted that the distribution of the largest values in sets of numbers drawn from different parent distributions converged to one of three distributions, which became known as Gumbel Types I, II and III. He proposed the double exponential or Gumbel Type I distribution for annual maximum floods. Bernier (1956) drew attention to flood records which conformed to the Fréchet distribution, which was equivalent to Gumbel Type II. When plotted on specific graph paper, which made use of a "reduced variate" linked with frequency, these three curves emerged as straight lines, concave upwards and concave downwards respectively. Gumbel suggested that the first two distributions were appropriate to floods, while the third was more appropriate to the distribution of low flows or droughts.

In 1955, Jenkinson showed that the three distributions were special cases of a General Extreme Value (GEV) distribution, and this has been widely used after its adoption by the *Flood Studies Report* (1975) on the grounds that it had some theoretical basis and was flexible in application. The GEV distribution is defined by:

$$F(x) = \exp \{- [1 - k(x - u)/\alpha]^{-1/k}\}$$

and is equivalent to Gumbel Types I, II and III as $k = 0$, $k < 0$ and $k > 0$.

However, the fitting of any distribution to a single station record is subject to a high degree of uncertainty, particularly as the typical return period for which a flood estimate is required will usually greatly exceed the length of record available. Although the choice of distribution will affect the extrapolation of the flood record markedly, as the choice between the three Gumbel types would illustrate, the stability of the curve can be improved by increasing the volume of records on which the fitting depends. There are various ways of extending the flood record at a site. In some cases it may be possible to make use of historic records, which are often available in the form of levels from flood marks or local histories. However, a more general way of increasing the effective length of flood records is to include the records of similar stations, and by making the records dimensionless to analyse the whole set as though they were from a single site.

In the investigations leading to the *Flood Studies Report*, the grouping of stations was based on geographical regions. This was partly chosen for simplicity, but it was also based on the belief that the main factor governing the shape of the dimensionless flood frequency curve was the rainfall of the basin, and that this had a geographical basis. The statistical studies showed that the variability of floods was linked to climate indices more closely than to size or soil factors. In order to derive a rainfall factor more directly related to the flood-producing role, it seemed clearly preferable to use a short-term rainfall index than the annual average rainfall used in earlier studies. Further, the

effect of climate in determining the proportion of rainfall which leads to direct runoff was believed to be based on soil moisture state, and the concept of one-day rainfall less mean effective soil moisture deficit was developed for this purpose (see Chapter 5).

The growth curves for the average rainfall for each of the flood regions used, when adjusted for the mean soil moisture deficit to give net rainfall, were very similar to the flood growth curves for the same regions. During the research leading to the 1975 report, the mean climate characteristics for all gauging stations within each region were compiled; these were *RSMD* or net 1-day rainfall of 5-year return period, *SMDBAR* or mean effective soil moisture deficit, and the rainfall growth factor (*MT/M5*) as a function of 5-year daily rainfall. These regional characteristics were used to obtain growth curves of the *RSMD* or net rainfall of different return periods. These values are illustrated in Fig. 10.2; the strong similarity between the two sets of growth curves is evident.

It was possible to interpret the statistical relation in physical terms. Although the relation between mean annual flood, *Qbar*, and basin characteristics appears complex and somewhat arbitrary:

$$Qbar = 0.021\ AREA^{0.94}\ STMFRQ^{0.27}\ S1085^{0.16}\ SOIL^{1.23}\ RSMD^{1.03}\ (1 + LAKE)^{-0.85}$$

it can be argued that the equation shows the mean annual flood as proportional to basin area (*AREA*) and net rainfall (*RSMD*), and that the soil term (*SOIL*) represents percentage immediate runoff, while the terms for channel slope (*S1085*) and stream frequency (*STMFRQ*) reflect the shape of the basin response or unit hydrograph.
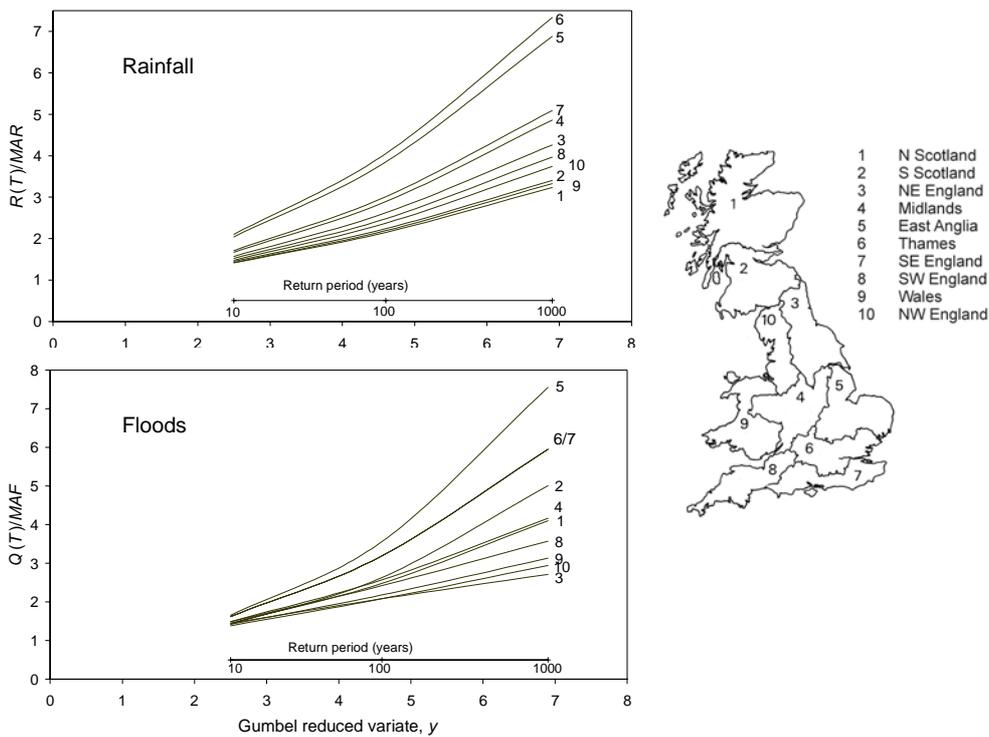


**Fig. 10.2** *Growth curves of net rainfall and floods in Britain: the curve numbers refer to the regions shown on the map.*

Subsequent research (e.g. Wiltshire, 1986; Reed, 1999) has led to the use of sets of gauging sites, which are similar to the project site in terms of basin area, rainfall and soil type. However, in parts of the world where thematic maps are rare the concept of geographical regions is a useful starting point for flood studies.

## FLOOD STUDIES IN DIFFERENT AREAS OF THE WORLD

The completion of the *Flood Studies Report* naturally led to the question of the relevance of the research to other countries. It was felt that the general approach was relevant: the emphasis on appraisal and collation of flood records; the choice between methods of estimation, and the circumstances in which the statistical approach or the deterministic approach is appropriate; the regional approach, in which the mean annual flood is estimated from records and the growth curve used to convert to floods of a given return period; the concept of preserving the return period of the design storm through the conversion to a flood hydrograph.

One immediate application of the techniques developed was the regional growth curve, which was used in a number of overseas applications after the completion of the report. Experience in different areas drew attention to the very wide variety of flood regimes in different climates. Studies of floods in Botswana, where flood runoff approaches most nearly the traditional concept of runoff resulting from heavy rainfall of high intensity exceeding the infiltration rate of the soil surface, showed that flood growth curves were extremely steep and curved upward. Floods in several West African countries, by contrast, showed an opposite tendency, with flood peaks growing very slowly with return period, to an extent that the fitting of GEV distributions to flood records produced curves which were concave downwards and thus implied that an upper bound existed.

During a study of the water resources of Guinea in 1982, preliminary estimates of spillway design floods were required for comparative economic appraisal of potential sites for hydroelectric power. Daily flow series were available for nearly 20 gauging stations, and annual maximum series were extracted to derive regional flood curves for three provincial groups of stations. There appeared to be no differences between the groups, so that a common curve was used to provide growth factors to convert esti-mates of the mean annual flood to floods of given return period. Figure 10.3 illustrates this joint curve, which is extremely flat and even appears to curve downwards; however, a straight line relation was adopted as the concept of an upper bound was not accepted.

In a regional study of dam sites in Botswana in 1986, the number of gauging stations with flood records was low, but a regional flood growth curve was derived to support estimates of the mean annual flood at key sites. The annual maxima from 10 stations with a total of 135 station-years of data were analysed using the GEV distrib-ution to give the regional curve also shown in Fig. 10.3; the contrast with the regional curve from Guinea is great. This curve was supported by analysis of corresponding records from South Africa and Zimbabwe.

This experience of contrasting flood curves in different African countries led to a series of investigations in a large number of countries. Although attempts were also made to relate mean annual floods to basin characteristics, these were hampered by the lack of basic data except basin area and annual rainfall; although the results could be useful in a local context, the more generally interesting results involved flood growth curves.
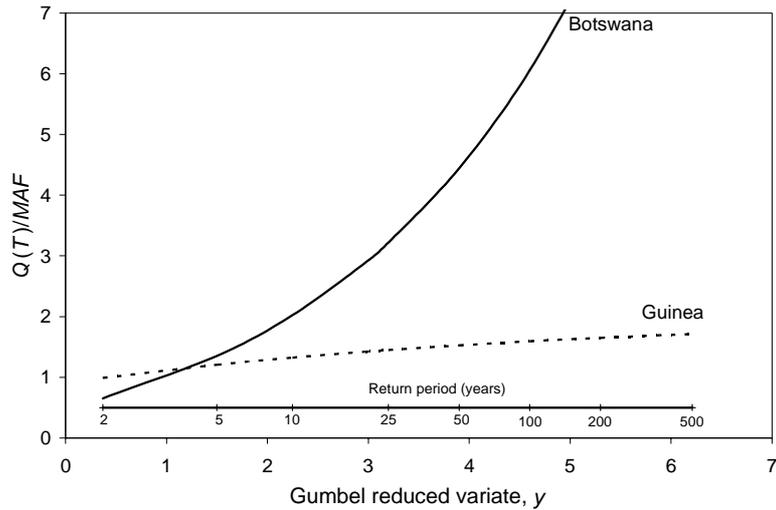
**Fig. 10.3** *Growth curves: Guinea and Botswana.*

## Semiarid areas

A group of areas with similar growth curves was found in warm semiarid regions, defined as those with annual average rainfall below 600 mm. Flood records were collected (Farquharson *et al*., 1992) from Botswana and parts of South Africa, Saudi Arabia and Yemen, southern Queensland, parts of southwest USA, and southwestern parts of the former Soviet Union. The records from these groups of stations were used to obtain flood growth curves by fitting a GEV distribution by the method of probability-weighted moments (PWM), which was shown to be an efficient method of fitting frequency curves (Hosking *et al.*, 1984). The Gringorten plotting position was used. The results showed a close fit (Fig. 10.4) between regions of highly diverse geographical location, which shared in common the characteristic of low rainfall.
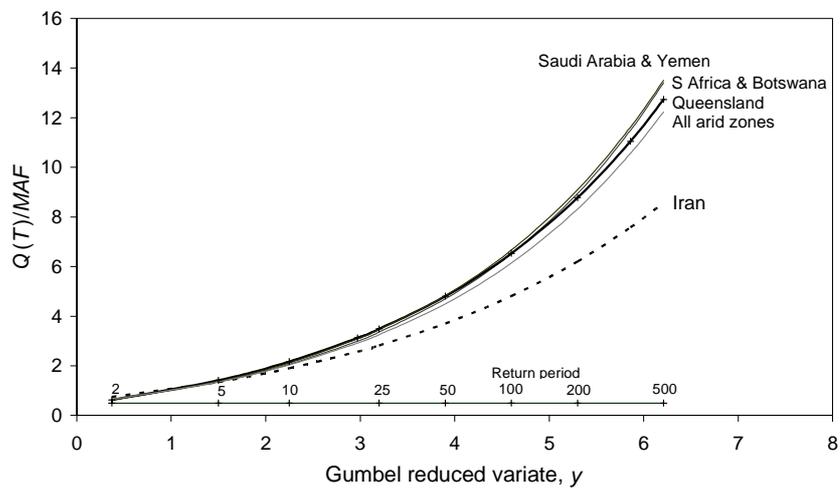


**Fig. 10.4** *Growth curves: semiarid regions (after Farquharson et al., 1992).*
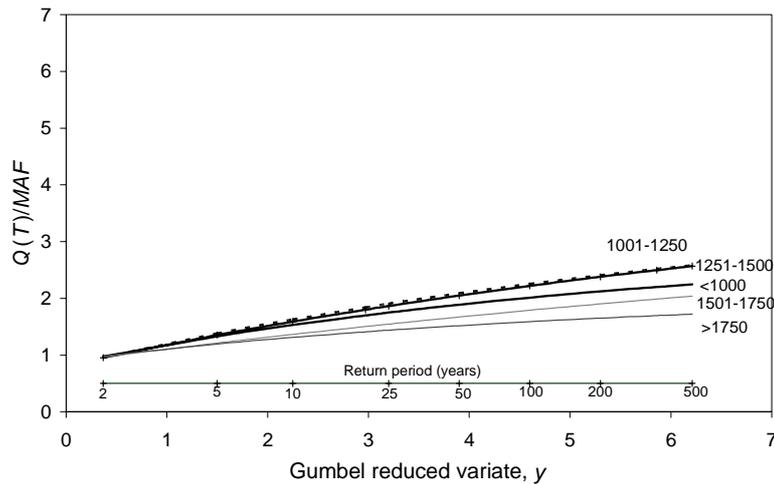
**Fig. 10.5** Growth curves for rainfall zones in West Africa (rainfall ranges in mm) (from Sutcliffe & Farquharson, 1998).

## West Africa

A detailed study of flood records over a wide area of West Africa was made possible by the valuable records published largely in ORSTOM monographs. Flood records from Senegal to Cameroun (Farquharson *et al.*, 1993) were assembled and their mean annual flood values compared with area and mean annual rainfall. Their growth curves were also derived and grouped according to variables which appeared to give similar curves. These variables involved a mixture of geographical regions, defined by latitude and longitude, and also ranges of rainfall (Fig. 10.5) and basin size. However, the growth curves were characterised by their similarities rather than their differences, and they were uniformly of gentle slope and either straight or even curved downwards.

## Other regions

A few exceptions to these flat growth curves were encountered in countries with similar annual rainfall. In Kenya, and even more clearly in Sri Lanka, the growth curves were comparatively steep and curved. One difference between the climate of these countries and those of the West African examples is that there is more than one rainfall season, and as a result the dates of occurrence of the annual maxima range throughout the year, while in West Africa the maximum flood dates are extremely regular. It appears that in the West African case the floods are caused by the accumulation of soil moisture and rainfall over a single monsoon season, and the flood is related more to a seasonal rainfall total than to individual storms.

A similar effect is observed in the case of snowmelt rivers located in the northwest USA, Canada and northern Russia; here the growth curves are extremely flat, and the dates of annual maxima again show little variation from year to year.

A preliminary study of flood regimes over Europe (Sutcliffe & Farquharson, 1998) was based on available records, which varied from abundant in western Europe to sparse in parts of central and eastern Europe. This difference reflected the ready availability of published sources rather than the density of gauging stations. A series of curves (Fig. 10.6) indicated an interesting pattern ranging from flat curves in the
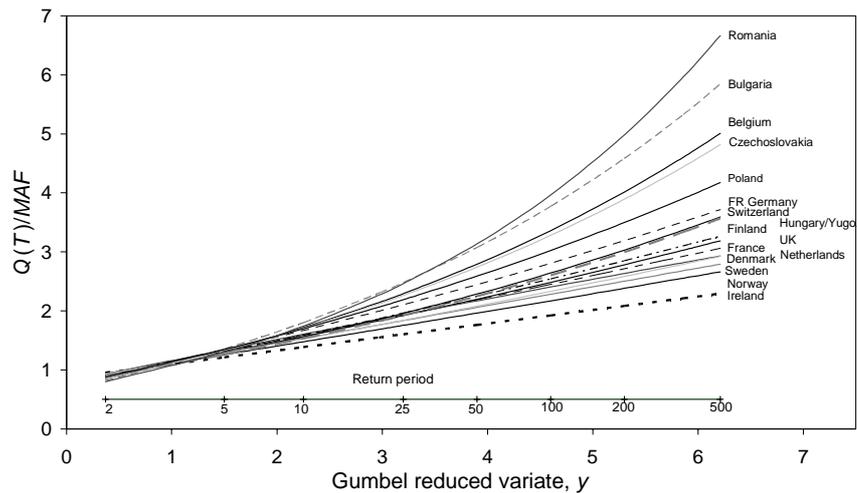
**Fig. 10.6** *Growth curves: Europe (from Sutcliffe & Farquharson, 1998).*

maritime regions of western Europe (e.g. Ireland and Norway) and increasing in gradient and curvature towards the records available in Poland and the Balkans. This study provides material for further research.

## Software

Software is available to analyse flood records in various forms. Software linked to the *Flood Estimation Handbook* is relevant to the estimation of floods in the United Kingdom. On the other hand, the *IH Floods* package (CEH, 2001) has been prepared with funding from the UK Department for International Development (DFID) for use in developing countries and is freely available from Wallingford. This program is designed for the storage and analysis of annual maximum flood data. It includes the ability to fit a variety of frequency distributions to the data at a single site. It also allows the selection of groups of stations by a number of different approaches, and the fitting of regional flood frequency distributions to the grouped data. It can thus be used to develop regional flood frequency curves which can be used to make flood estimates at both gauged and ungauged sites in a region.

## Polish floods

An example of the use of regional analysis in an apparently homogeneous region of moderate size is given by the investigation of floods in the Krakow region referred to in the previous chapter. The flood regime of the Vistula through Krakow depends on several southern tributaries, which drain the steep Carpathian mountains with average annual rainfall ranging from 700 mm to over 1200 mm. The rainfall distribution is highly seasonal, concentrated between May and September; in addition to snowmelt floods, the flood problem is compounded by summer storms which often track from west to east, so that tributary contributions have a tendency to build up along the main river above Krakow. In a study of the role which a group of dams on the upper Vistula could play in flood control, a regional analysis of flow records above Krakow was
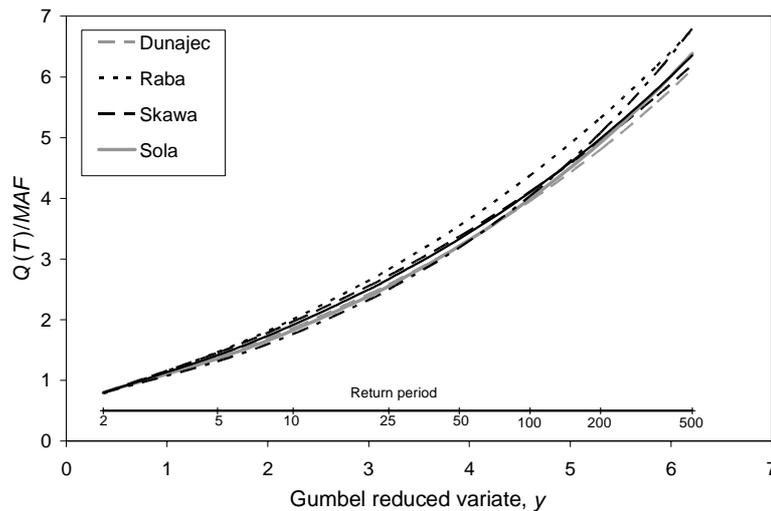
**Fig. 10.7** Growth curves of southern Vistula tributaries near Krakow, Poland.

carried out. The contributions of the various tributaries to the flood potential were examined statistically. The flood records from the right bank tributaries were assembled and provided 925 years of record from 21 stations. These were analysed in the usual way, and revealed a set of growth curves which were highly consistent but also highly curved (Fig. 10.7). This seemed appropriate as the paper by Fréchet (1927) which led to the proposed use of the Gumbel Type II distribution (Bernier, 1956) was originally published in Krakow.

The effect of this regime is illustrated by flood marks in the city near the river (Plate 10.1), which mark the levels reached in February 1876 and August 1903, together with the earlier higher flood of 1813. The same building is shown in a view (Plate 10.2) of the subsequent flood embankments. After the flood contributions of the individual tributaries of the upper Vistula had been analysed, the potential effect of joint flood control using a combined group of reservoirs was studied by trials involving specific flood events, and it was found that a distribution of the flood control role between the reservoirs would be advantageous. By this means a significant potential reduction in flooding risk could be established.

### Hydrological flood forecasting

This Polish example illustrates the benefit of flood forecasting. If a system of meteorological observation or forecasting can be linked to a runoff forecasting system, which was under development, providing estimates of flood hydrographs in time for action to be taken, then it may well be possible to reduce the impact of heavy storms and subsequent runoff by operating reservoirs to attenuate the flood peak. A system of flood warning may at the very least make it possible to reduce the damage or loss of life. The establishment of such a forecasting system may involve radar observation of storm movement, the linking of instrumental measurements of precipitation or river levels and flows by telemetering to a central control office, and the modelling of runoff using updated measurements or modelling of antecedent conditions on the basin.

***Plate 10.1*** *Flood marks in Krakow showing 1813 (highest), February 1876 and August 1903 flood levels.*



***Plate 10.2*** *Flood defences in Krakow. The building in Plate 10.1 is the central one in this photograph.*

## USE OF HISTORICAL INFORMATION

The inclusion of historical information in flood frequency analysis has the potential to increase significantly the period over which floods are sampled and thus reduce the extrapolation required. Provided that correct statistical procedures are followed this inclusion can improve the confidence with which rare floods are estimated. The historical information can take a number of forms and examples are discussed from different areas. The basic information is likely to be a peak water level, which can be converted to a flow, and a date, which may or may not be precise.

### Britain

In Britain historic floods are often recorded on marks or plaques, especially in older cities. During the investigations for the *Flood Studies Report* (1975) an attempt was made to collate all historical information available at or near existing gauging stations, which in most cases had already been assembled by the gauging authorities from physical marks, newspapers, books and verbal accounts. This collection of historical information is presently being continued by the Centre for Ecology and Hydrology (Black & Law, 2004). If a series of historic flood marks is reasonably continuous, it should be possible to assume that all floods above some threshold have been recorded, and the series may be treated as the highest, second and so on over the whole period of record. If any recent floods have exceeded this threshold, their rank may be deduced over the historic and recent records. It may be possible also to take account of a given flood having been the highest since an earlier date or within living memory.

For example, annual maximum floods were available for the Trent at Trent Bridge in Nottingham for the period 1884–1968. There were also flow estimates for the peak floods of 1795 and 1875, with the additional information that the flood of 1795 was reported as the most severe of the 18th century and the lower 1875 flood was the most severe of the 19th century. It could therefore be deduced that the 1795 flood was the highest since 1700, with the 1875 flood probably the second highest. Graphical presentation of historical information illustrates the value of the record, which depends on a reasonably stable channel cross-section. Where a continuous record of annual maximum floods is ranked in size order, each flood can be allocated a plotting position according to its rank $i$ in the $N$ years of record. Cunnane (NERC, 1975; Cunnane, 1978) showed that the Gringorten formula for frequency:

$$F_i = (i - 0.44)/(N + 0.12)$$

gives a reasonably unbiased plotting position based on the Gumbel reduced variate $y$ obtained from:

$$y = -\ln (-\ln F_i).$$

Equivalent plotting positions can be deduced for historic floods, by allocating ranks over various periods. The historic floods for the Trent at Nottingham are included in Fig. 10.8, with the 1795 flood assumed to be the highest since 1700.

### China

An even longer example is presented by the Chang Jiang (Yangtze) at Yichang, where annual maximum floods are available for the period 1877–1981, excluding 1979–1980 (Rodier & Roche, 1984). The mean annual flood from this record is 51 700 $m^3$ $s^{-1}$. An
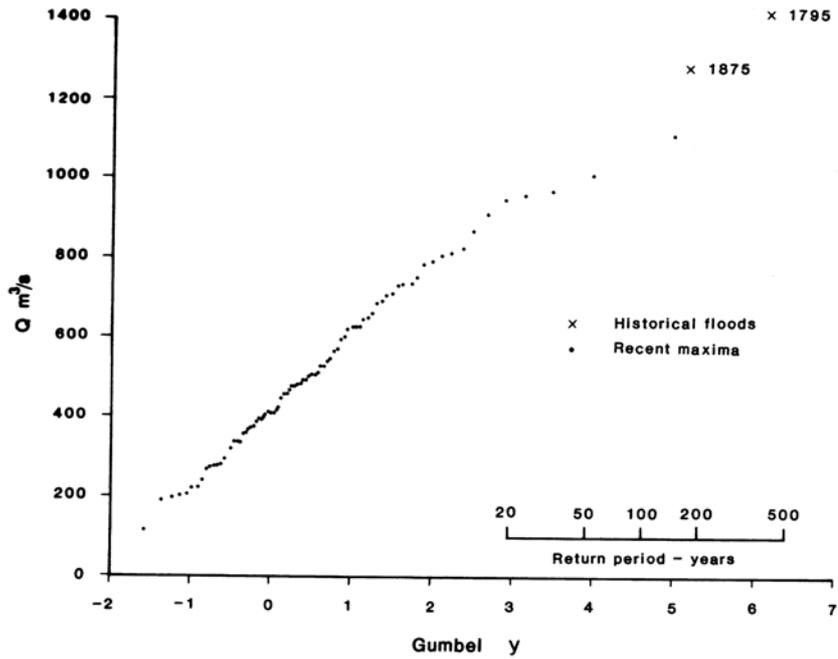
***Fig. 10.8*** *Historic flood frequency: Trent at Nottingham, 1884–1968 (from Sutcliffe, 1987).*

additional eight historical flood marks are available from 1153 to 1870 AD, and because the rating curve on this reach should be stable the flows have been deduced. Because three floods in 1227, 1560 and 1870 are higher than that of 1153, it is reasonable to assume that the four highest floods since 1153 have been recorded; as the 1860 event was little below the 1153 flood, these floods are included in Fig. 10.9 as the five highest since 1153.
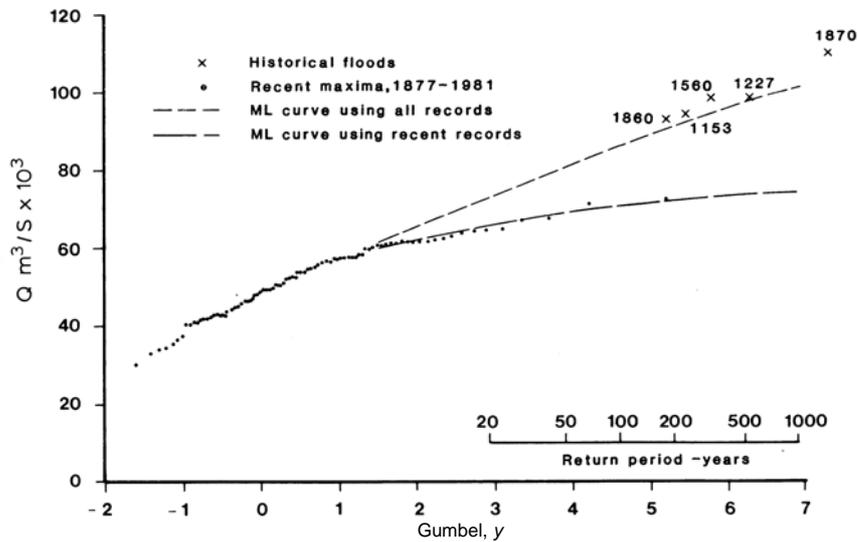


***Fig. 10.9*** *Historic flood frequency: Chang Jiang at Yichang, 1153–1981 (from Sutcliffe, 1987).*

It is possible to analyse annual maximum series including historic floods by treating the whole record as censored below a threshold during the historic period. The method of maximum likelihood can be used with a censored sample. It can therefore be used to estimate the flood frequency distribution from the recent and historic records. A simple program was used to estimate the GEV parameters which maximise the likelihood for the 1877–1981 record and repeated with the historic records included to give the alternative results plotted on Fig. 10.9. Whereas the recent data suggest a distribution with an upper bound of 77 000 m$^3$ s$^{-1}$, the addition of the historic floods, with a number of floods above this upper bound, alters the fitted distribution dramatically. The estimated floods for higher return periods are increased by over 30% to correspond with the historic floods.

### Indus

By contrast, another example illustrates an exceptional event which it is difficult to incorporate into a statistical analysis. There is a long and apparently consistent record on the Indus at Attock in Pakistan where a staff gauge was installed in 1868 to provide telegraphed flood warning downstream. The channel at the site is controlled by a rock bar which provides a stable control, and the level series can be converted to floods using a single rating curve, whose stability was confirmed by a comparison of rainfall and runoff. The 1868–1978 flood record (Rodier & Roche, 1984) provides an apparently consistent flood frequency relation (Fig. 10.10) from which the prediction of rare events appears simple. However, there is evidence that an exceptional flood occurred in 1841, after a landslide from Nanga Parbat blocked the gorge below Gilgit for six months. Unusually low flows had been experienced downstream during the spring so that the main river had been fordable. A lake "35 miles (56 km) in length and
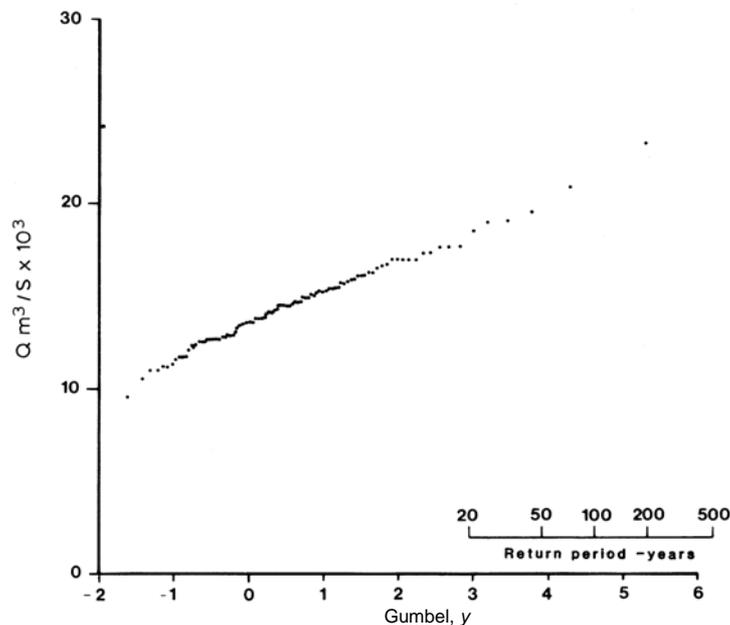


**Fig. 10.10** Historic flood frequency: Indus at Attock, 1868–1978 (from Sutcliffe, 1987).

of great depth" (Knight, 1893) is said to have drained in one day after breaching the dam. Drew (1875) estimates the length at 35 miles, an average width of a mile, and a depth of about 300 feet above the ordinary river level at its lower end. An account of the subsequent flood described how the river "in a few minutes tore and swept away everything in its course, including a whole Sikh army that had encamped on its banks below Attock with its tents, baggage and artillery" (Wadia, 1975). In the words of the Zemindar of Tarbela (*J. Asiatic Society of Bengal* XVII, 1848, p.232): "As a woman with a wet towel sweeps away a legion of ants, so the river blotted away the army of the Raja". Estimates have been made of the volumes of other floods (Hewitt, 1982), and while it should be possible to estimate the volume stored in this event from satellite imagery, it would not be easy to translate this to a peak flow. However, a tentative estimate of its volume from Drew's information (56 km $\times$ 1.6 km $\times$ 91 m $\times$ 0.5) allowing for the attenuation of depth, gives a volume of 4.08 km$^3$, or 47 000 m$^3$ s$^{-1}$ for a day; it is clear that the flood was significantly greater than other floods experienced at this site.

It is also difficult to see how statistical analysis of the flood series can be adjusted to incorporate such an exceptional flood caused by a totally different cause from the other flood events. In fact design estimates for the Tarbela dam above the Attock site were based on maximisation and physical reasoning. A maximum snowmelt flood, derived from statistical analysis, was combined with an extreme storm over the foothills, transformed to flows at the dam site by unit hydrograph methods; the breaching of a natural dam was added to the other flows to provide a design flood.

## ESTIMATION OF DESIGN FLOOD

An example of a combined statistical analysis of rainfall and unit hydrograph assessment of runoff was used to estimate a design flood for Gaborone dam in Botswana, where flow records had to be deduced from reservoir levels which covered a short period. Longer daily rainfall records were available at five sites which were considered reasonably independent. Their combined records were used to estimate daily maxima for return periods from 20 years up to 500 years, and locally derived areal reduction factors were used to give mean daily rainfall for the basin of 4300 km$^2$. Falls of other durations were also deduced from regional studies. In order to derive a unit hydrograph for the site, inflows were deduced from reservoir levels during several storms; the median unit hydrograph from five storms was accepted as the design unit hydrograph. The percentage runoff model of the *Flood Studies Report* (NERC, 1975) was adapted to local observations, with a standard percentage runoff of 10% increasing to 24% for the 20-year event and 39% for the 500-year flood. The 500-year peak was estimated as over three times the 20-year peak before reservoir routing.

## ESTIMATION OF MAXIMUM FLOOD

For major projects where no significant risk of overtopping could be accepted, the estimation of the maximum flood is normally specified. The "probable maximum flood" may be described as the physical upper limit of flood discharge at a site. This was the recommendation of the Institution of Civil Engineers (1978) for major dams in the UK.

There must be an element of judgement in the various stages of estimating a maximum flood. The estimation of the maximum storm and its time profile may be

straightforward if a comprehensive meteorological study has been carried out, but this is the exception in most dam design investigations in developing countries. However, with the increasing acceptance of the concept of the maximum flood, the basic meteorological analysis has often been carried out on a regional basis. For example, the review of flood design for two projects in India in the 1980s involved individual estimates of the storm magnitude, while a similar review in the 1990s could take advantage of a countrywide analysis of maximum storms. The conversion of storm estimate to runoff hydrograph is more clearly linked to local conditions and depends crucially on storm losses; the estimation of these losses often involves extrapolation from conditions already sampled to exceptional conditions. Two examples illustrate some of the problems normally encountered. One of these involved a dam on the Yarmouk, a tributary of the Jordan draining a semiarid basin in Jordan and Syria; the other was the Victoria dam on the Mahaweli Ganga in central Sri Lanka.

### Jordan

In the case of the Jordan site, the maximum rainfall was estimated by transposing a historic storm, which covered the east bank of the Jordan valley, to the basin of the Yarmouk. This storm was then maximised by comparing the available moisture during the historic storm and the maximised moisture content and efficiency derived by the UK Meteorological Office during a regional study of potential floods in the Jordan valley. This led to an estimated 24-hour maximum storm of 245 mm, which exceeded the historic storm by a factor of 4.5. However, during the review of the study the estimate was reduced to take account of seasonal variations in the maximum moisture available. A number of observed storms were examined to derive depth–duration relationships, from which an envelope curve was used to give incremental depths for the design storm. These rainfall increments were arranged in an order which led to a critical flood-producing sequence.

Estimates of the potential basin losses were based on losses appropriate for comparable soil types in the USA, and the rainfall excess was distributed according to a 4-hour unit hydrograph developed for the dam site. The initial peak flow estimate at the site, before reservoir attenuation, was 8800 $m^3$ $s^{-1}$, which compared with an estimated peak flow of 50-year return period of 800 $m^3$ $s^{-1}$, based on statistical analysis of 15 years of flood peaks. The estimate of over ten times the 50-year estimate reflected the contrast between the normal storm in these semiarid conditions, and the potential precipitation in an extreme storm, but also included an element of conservative design which was corrected at the review stage.

### Sri Lanka

The basin of the Mahaweli Ganga at the Victoria dam site below Kandy (Piper *et al.*, 1994) was, by contrast, mountainous and humid (Plate 10.3), with rainfall occurring in each month. The average basin rainfall at Gurudeniya, the nearest river gauge upstream, was 2800 mm. As peak flow records were limited in duration and based on extrapolation of rating curves, the use of flood frequency methods for spillway flood estimation would not be precise. On the other hand, the river basin had been developed for tea plantation and a dense network of rainfall gauges had been in operation since about 1880. The most reliable approach was therefore the estimation of the maximum

*Plate 10.3* Tributary of Mahaweli Ganga between Kandy and Nuwara Eliya, Sri Lanka.

precipitation and its conversion to a flood hydrograph using the unit hydrograph method. An annual isohyetal map (Fig. 8.1) was compiled from the records of over 100 stations maintained by the Meteorological Department. Another map was compiled showing the date and amount of the maximum daily rainfall recorded at each station; this statistic was conveniently listed in yearbooks. Because of the large number of long-term gauges, this gave a useful indication of the likely magnitude of the maximum storm over the basin. It was observed that many of the stations recorded their maximum storm around the same date: 14 August 1947. This simplified the subsequent analysis. A number of recording gauges had been installed more recently, and the data had been used in a rainfall depth–duration–frequency study for the whole of Sri Lanka (Baghirathan & Shaw, 1978).

An earlier unpublished study (Sumanasekere, 1977), based on personal research by a member of the staff of the Meteorological Department, provided much of the material for an analysis of moisture maximisation. He had examined the 30 heaviest storms and isohyetal maps had been drawn for each storm from daily data; this confirmed that the storm of August 1947 was the highest on record. It also showed that all the large storms had a similar shape, orientation and centre, presumably because of the mountainous topography. It was not considered appropriate to transpose the centre or the orientation of historic storms to maximise the design storm. As the August 1947 storm was the highest storm recorded at 21 out of 37 stations, had covered much of the upper basin, and had led to the largest flood on the upper Mahaweli since records began in 1888, it was decided to use a simple method of maximisation of this storm to estimate the maximum flood.

An observed storm may be maximised for orientation, wind speed, moisture content and storm efficiency, but as many of the large historic storms covered the
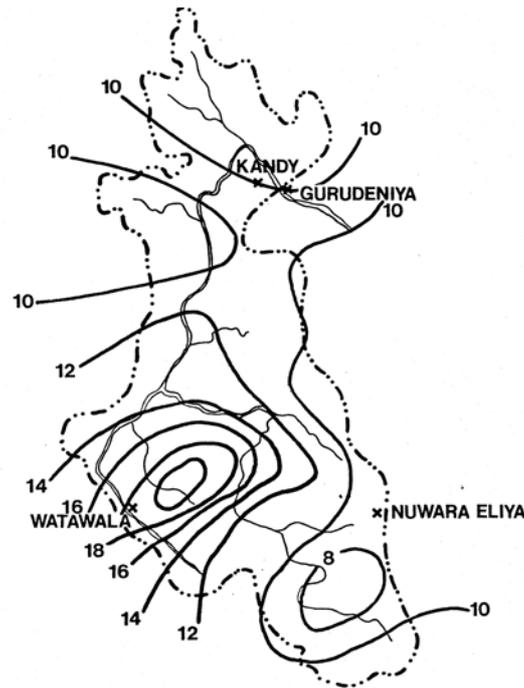
**Fig. 10.11** *Isohyetal map of daily storm of August 1947 above Gurudeniya. Note: the units are inches, 1 inch = 2.54 cm.*

same, extensive area of the upper basin, it was assumed that the storm efficiency had approached the maximum possible. The 1947 storm (Fig. 10.11) was maximized for moisture content alone, using data from the climate stations at Kandy and Nuwara Eliya. Comparisons of the maximum dewpoints ever recorded at these sites with those measured during the 1947 storm were used to estimate the ratio of the maximum precipitable water to that during the actual storm. The design storm over the project basin was estimated by multiplying the isohyetal map by this ratio, which was relatively modest at about 1.25. Statistical analysis suggested that this storm lay between estimates of the 1000-year and maximum storms. The duration and time profile of the design storm were based on the profile recorded in 1947.

The conversion of the storm profile to the corresponding flood hydrograph followed the principles of the *Flood Studies Report* (NERC, 1975), namely the derivation of a unit hydrograph from historic storm and flood records, the conservative estimation of basin losses and the convolution of rainfall excess with unit hydrograph ordinates. Only two events were considered suitable for unit hydrograph derivation, but tests of the derived unit hydrograph were judged satisfactory. The percentage of storm rainfall contributing to flood runoff is critical, but is related to basin characteristics, antecedent basin wetness and storm size. On this basis, the percentage runoff observed in 1947 of 56% was increased to 70% for the design case. The resulting design flood hydrograph is illustrated in Fig. 10.12, with a peak flow of 9500 $m^3 s^{-1}$, and compared with an estimated 1000-year flood, based on a storm derived from statistical analysis, with a peak flow of 6400 $m^3 s^{-1}$. This flow compares with a mean annual flood of 1400 $m^3 s^{-1}$ at Gurudeniya upstream.
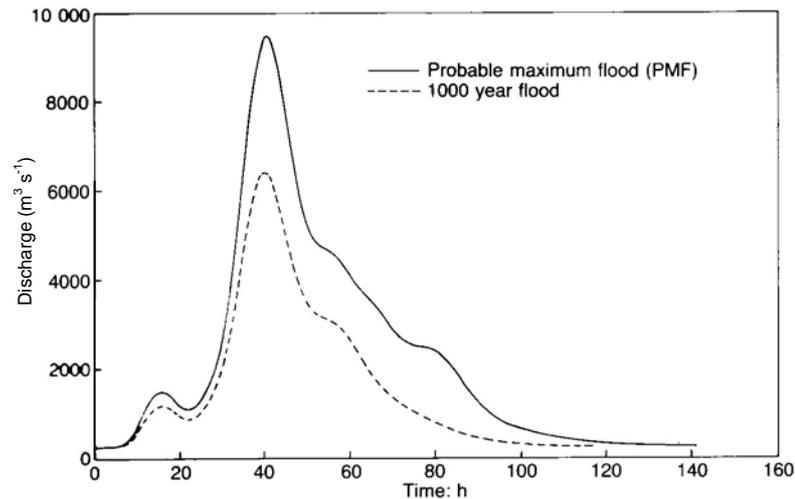
**Fig. 10.12** *Design flood hydrograph: Victoria dam, Sri Lanka (from Piper et al., 1994).*

This result contrasts to the maximum flood in Jordan, where the design flood was a much higher multiple of the mean annual flood. It illustrates the point that the maximum flood is more likely to be approached in a historic record in a humid than an arid climate. Meigh *et al.* (1999) have shown that although mean annual floods are much lower in areas of low rainfall, the growth curves are much steeper than in humid climates where the mean annual flood is much higher. Indeed, in the UK it has been shown (Farquharson *et al.*, 1975) that the maximum floods vary less from west to east in the direction of decreasing precipitation than mean annual floods or floods of moderate return period.

*CONCLUSION*

There are several different methods of estimating design floods, but the choice depends largely on the records which are available, and the return period required for the particular project. Statistical methods of analysis are greatly strengthened by increasing the effective length of record, either by grouping flood records from various sources or by incorporating historical information. The influence of climate on flood frequency relations is very significant. Physical methods may be based on storm analysis and evidence of the conversion of storm to flood events.