3 RAINFALL

Rainfall is the major contribution to the water balance and thus the water resources of an area. Strictly precipitation is the more inclusive and correct term, as it includes snowfall and other forms of contribution; however, nearly all the examples discussed here are taken from countries where rainfall is most common. Rainfall is the simplest term of the hydrological cycle to measure, at least in terms of daily values, and records therefore in general cover a longer period than other hydrological components. Indeed, one of the first actions of settlers in many countries seems to have been the installation of raingauges. In Sri Lanka, for example, the central mountain range was developed with tea plantations, and most sites possessed a raingauge, so that many records are continuous from the 19th century. For the same reason, and because of the lower costs of installation and operation, the raingauge network is usually denser than observations of evaporation or river flow, so that variations in water input as a function of time or over an area can most easily be studied in terms of rainfall.

In this chapter the topic of rainfall is treated in terms of its measurement and the analysis of records to derive mean values and variability according to season and from year to year; the analysis includes the assessment of maximum values. Whereas it was at one time considered sufficient to estimate the averages over standard periods, usually covering 30 years, it has recently become clear that there are significant differences in values in different periods, and changes and trends are now studied more carefully.

The spatial distribution of rainfall can be analysed by the construction of isohyetal maps, illustrating the variation of average rainfall depth with topography, which includes both position and elevation. The main hydrological objective of the isohyetal map, which can be derived subjectively by someone familiar with the effect of topography, or objectively by computer-based techniques, is to deduce the rainfall over a basin to compare with runoff depth. It can be particularly helpful where rainfall records are distributed unevenly through the basin and the influence of elevation could be underestimated. Mountainous areas tend to be under-represented by raingauges because of the difficulty of measurement and access, as in the mountains of Iran discussed later, but these areas are often particularly important for water resources inputs.

Time variations of basin rainfall can be described by the use of station or basin indices, which are related to variations from the long-term average. The number of stations required to estimate basin rainfall to a given precision will depend not only on the climate but also on the duration of the time interval, the basin area and topography, which all affect the variability of rainfall. Examples are given to illustrate the problems involved.

RAINFALL MEASUREMENT

There are many different types of rainfall gauge, but the main distinction concerns the time period over which rainfall is recorded. The standard gauge, of which for example there are some 4000 in Britain, is the daily gauge in which the rainfall caught in a funnel of a given area is extracted at the same time each day and measured in a container which gives the equivalent rainfall depth. The standard elevation above the ground varies according to country, largely according to the incidence of snow storage; the diameter of the gauge funnel also varies.

In remote areas where observers are not available, it may be necessary to supplement daily gauges with storage gauges or automatic gauges. In an investigation undertaken in 1958–1960 of the runoff potential of a mountainous area in the North Island of New Zealand, the four existing raingauges were concentrated in lower areas where reasonably long records had been collected. To investigate the effect of elevation and aspect on rainfall distribution, an additional 12 temporary gauges were installed. Half of these were located where observers could be persuaded to accept them, and the remainder were storage gauges installed and visited weekly (Plate 3.1) at key sites where there were no inhabitants. One gauge was located at an elevation of 1750 m at the top of a ski-lift on Mount Ruapehu, and supplemented by a gauge to measure snow in winter. Use was also made of one existing gauge which had been installed at a remote site; it required a two-day expedition to read this storage gauge. Automatic weather stations or storage gauges which provide regular frequent observations and daily totals would now be used in these circumstances.

Recording gauges have been used for many years to measure rainfall intensity over shorter periods than daily values. Early examples (Strangeways, 2003) used mechanical methods like tipping-bucket devices which recorded the frequency of unit rainfall volumes on charts, but more recently solid-state loggers have been developed for the same purpose. These recording gauges can be combined with daily or storage

Plate 3.1 *Storage raingauge in the Tongariro basin, New Zealand.*

gauges, or even radar observations, to derive the time distribution of storm rainfall over a basin for comparison with flow records in order to investigate the flood response of a basin to heavy storms.

Mean and variations

The simple analysis of a rainfall record provides the monthly and annual average over the period of records, and can provide a measure of variability in the form of maximum and minimum, range or standard deviation. It has been standard practice to cite averages for standard periods of 30 years, e.g. 1961–1990, which was assumed to provide a sufficient period to give a stable average, not only for the annual total but also for the monthly means. However, it has been found in some areas that variations can persist over long periods; for example, it seems that the rainfall regime over and around Lake Victoria has changed after 1961, with somewhat higher rainfall in the second, November–December, rainfall season. This has had significant effects on the outflow from the lake basin, because the mean rainfall over the lake is nearly equal to lake evaporation. Another example of long-term change in rainfall has occurred over the Sahel region of West Africa in the years since 1974, to the extent that water resources projects based on early records have fallen significantly short of their design yields. Weak links have been found between annual flows in some but not all major basins in sub-Saharan Africa, and El Niño Southern Oscillation (ENSO) effects (Farquharson & Sutcliffe, 1998). It is important to quote the period from which averages have been derived, and to treat with caution those averages which are based on limited periods of records. This is likely to become more significant in the light of predicted climate change.

Nevertheless, annual average rainfall estimates, when these have been adjusted to a common period, provide the most useful information on the distribution of available water over an area. When plotted on a topographic map which indicates elevation, these estimates provide evidence of the way in which the topography, in particular relief and aspect, influences rainfall depth. The monthly averages, especially when plotted on a map or diagram in their relative station positions, provide an instant picture of the seasonal rainfall pattern of the whole area, and will reveal any trends in seasonal distribution over the region. An example is shown in Fig. 3.1, where the rainfall over the Senegal basin (which includes parts of Mali and Guinea) is illustrated by isohyets and in Fig. 3.2 by monthly histograms. It is evident that the annual average rainfall decreases rapidly from north to south over the basin, but also that the rainfall is highly concentrated into a limited season, and further that this season decreases in duration from south to north. A time series of basin rainfall or at individual stations would show that rainfall has decreased over the years, but in fact this is demonstrated more dramatically in Chapter 9 by the river flow series.

Adjustment of short-term averages

When some of the stations have records for a consistent long-term period, for example over a 30-year period, and other stations cover shorter periods, it is necessary to deduce compatible estimates by deriving averages over a common, long-term period. This is most easily done by comparing each short-term station with one or more nearby long-term stations, either using correlation analysis or simply by adjusting the average at the

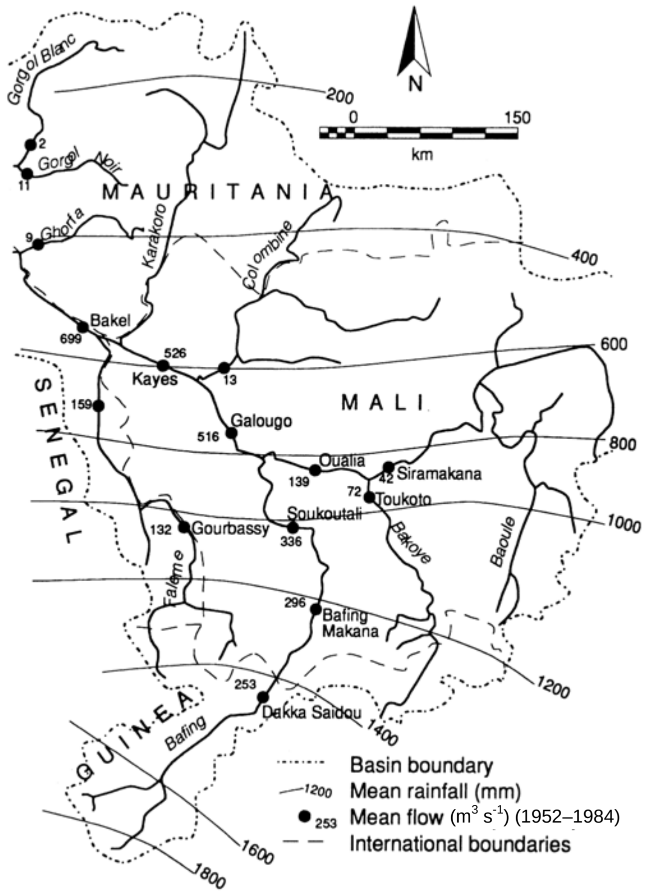

Fig. 3.1 *Annual average rainfall (1951–1980) over the Senegal basin.*

long-term station by the ratio of the short-term to the long-term station during the common period.

CASE STUDIES OF SPATIAL VARIATION

Once the rainfall data have been reduced to consistent long-term averages, the isohyetal map is the simplest means of assessing the variation of average rainfall over an area. In areas of moderate relief, the distribution will be controlled largely by position, and the drawing of the isohyets can be based largely on interpolation between station values.

Botswana

An example of this was an early study of water resources in Botswana, at a time when flow records were so sparse that rainfall data gave almost all the information on the likely volumes of runoff available at different sites. It was possible to make use of rainfall data from adjacent countries, namely South Africa and what was then Southern Rhodesia, now Zimbabwe. The combination of a limited number of records in eastern

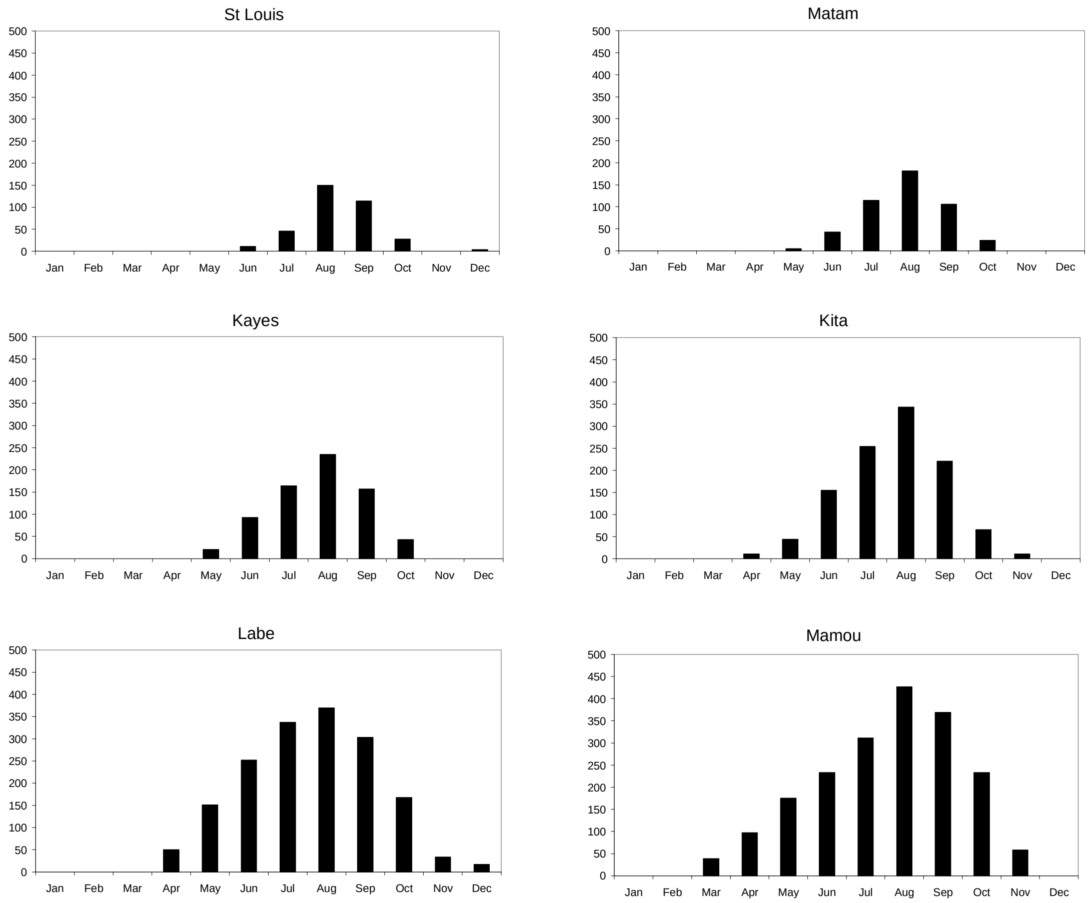

Fig. 3.2 *Monthly average rainfall (mm) over the Senegal basin.*

Botswana, and the adjacent isohyets, suggested the rainfall distribution illustrated for northeast Botswana in Fig. 8.7. The study indicated relatively high rainfall in the south of the country and in the hills near Francistown in the northeast. There was an indication of lower rainfall in the centre, over an area bordering the lower ground of the Limpopo, and this was supported to some extent by the vegetation distribution. In the context of the study, which was to plan the siting of a major reservoir to support the mining potential of the newly independent country, this rather slender evidence was the major factor in recommending that the reservoir should be located near Francistown, where a short record of river flows was available, rather than nearer the location of the mining development itself.

New Zealand: storm direction

In the study of hydroelectric potential in the North Island of New Zealand, referred to earlier, it was necessary to study the rainfall in some detail; the estimated average runoff, based on a short period of nine years' flow records on the main river, the Tongariro, suggested that the runoff depth exceeded the average annual basin rainfall deduced from the official countrywide isohyetal map. In this case it was necessary to

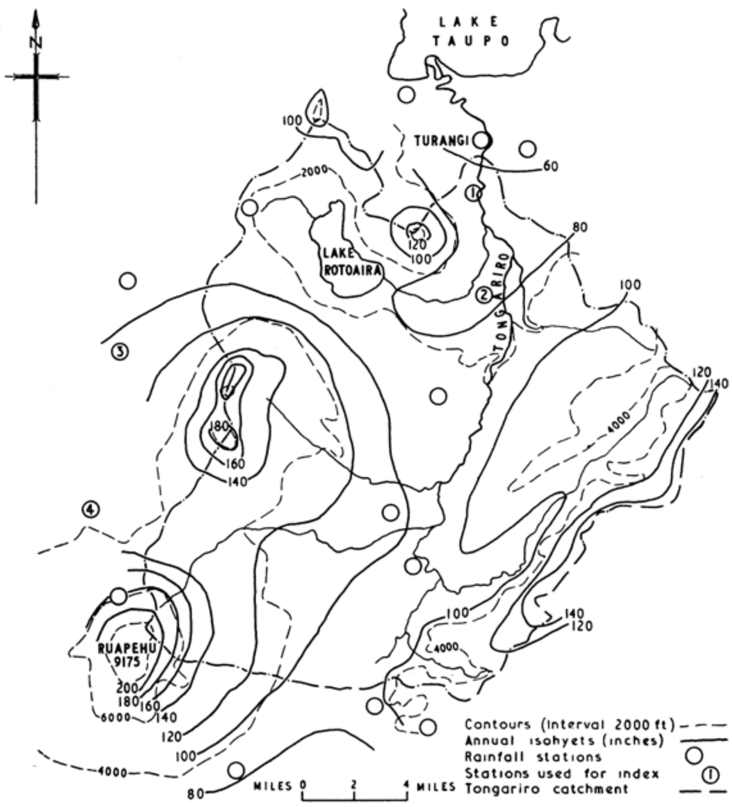

Fig. 3.3 *Tongariro above Turangi: isohyetal map (1929–1958) (after Sutcliffe & Rangeley, 1960a). Note: 1000 ft = 305 m; 100 inches = 2540 mm; 1 mile = 1.61 km.*

relate rainfall to elevation, as the topography around Mount Ruapehu (2800 m) varied considerably in elevation (Fig. 3.3) (Sutcliffe & Rangeley, 1960a). After a number of short-term stations had been established and data recorded for only about a year, it was clear that the precipitation was highly dependent on topography. Correlation of precipitation with elevation showed a steady linear increase from 1500 mm at the general elevation of 800 m up to an estimated 5000 mm at a combined raingauge and snowgauge established at the top of a ski-lift on Mount Ruapehu at 1750 m. In this particular case snow storage was considered as the area included the major ski resort of the North Island; however, a simple estimate was made of the proportion of precipitation stored as snow. This was based on monthly temperatures recorded at higher stations, adjusted at an appropriate lapse rate, to give the elevation at which the monthly mean temperature was less than 0°C. On the assumption that precipitation above this elevation would be stored as snow, this showed that only a small proportion of the basin precipitation was affected.

The records showed that the average to the north of the mountain complex was greater than to the south, although the prevailing winds were westerly. This anomaly was explained after a discussion with a local teacher, who was a keen fisherman and had observed that the heavy falls occurred during northerly storms bringing rain south over Lake Taupo. This observation was checked and confirmed by the New Zealand Meteorological Department, who kindly examined the synoptic charts during the dates of historic heavy storms. This information enabled a local isohyetal map to be drawn, with the rainfall shadow repositioned to take account of the revised storm direction. The anomaly of the apparent excess of runoff disappeared once the basin averages were revised on the basis of this map. This information was also used to correct the national isohyetal map.

Western Iran

In a study of the water resources of the rivers draining the Zagros mountains in western Iran (Sutcliffe & Carpenter, 1967), it was found that the available rainfall records, analysed after discussion with the Iranian Meteorological Service, revealed a more complex situation. The prevailing winds brought moisture from the plains of Iraq towards a series of ridges rising up to the Zagros and running from NNW to SSE. The rainfall increased up to the top of each ridge, decreased on the leeward side of the ridge, and increased again at the next ridge. A section through the mountains (Fig. 3.4) illustrates the effect of the topography on rainfall depth. Thus rainfall is related to both elevation and position. However, the complexity of the topography and the resulting rainfall distribution made it difficult to compile an isohyetal map in the usual way. After trial and error, the rainfall averages were reduced to a standard elevation of 1000 m, in the same way as atmospheric pressures are reduced to sea level, using a linear gradient of 300 mm/1000 m elevation for this purpose. Once a standardised value of rainfall at an elevation of 1000 m had been derived, it was simple to draw an isohyetal map (Fig. 3.5) of these values, which showed standardised rainfall decreasing over the project area in the direction of the prevailing winds. The rainfall at higher elevations could be deduced from the standardised rainfall using the same linear gradient; basin mean rainfall could also be estimated from basin elevation. This interpretation of the rainfall distribution was supported by the natural vegetation of the

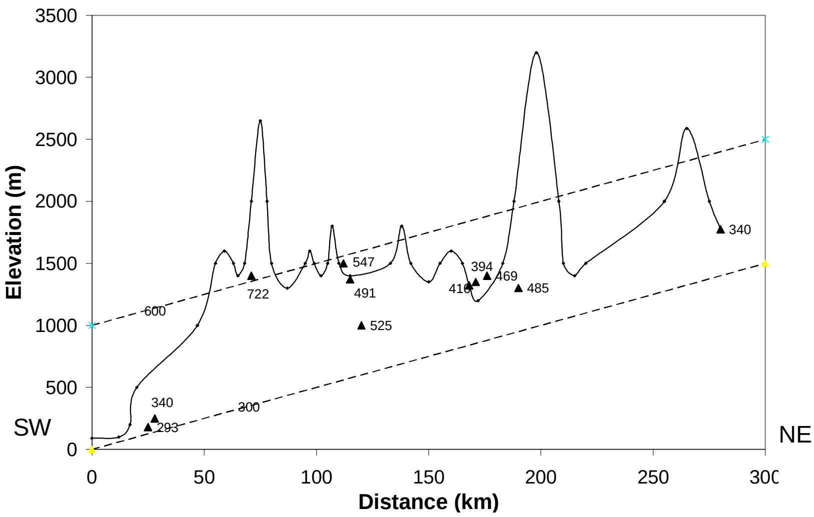

Fig. 3.4 *Zagros Mountains, Iran: cross-section southwest–northeast showing annual average rainfall (mm).*

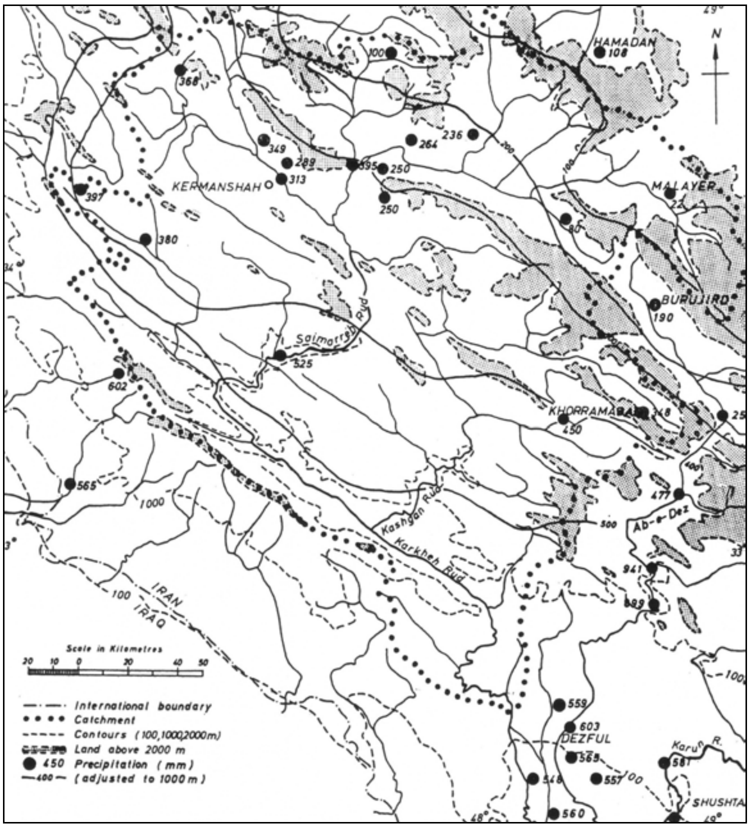

Fig. 3.5 *Zagros mountains, Iran: isohyetal map of annual average reduced rainfall, mm (1945–1964) (from Sutcliffe & Carpenter, 1967).*

Plate 3.2 *Oak scrub on the southwestern foothills of the Zagros mountains, Iran.*

mountains (Plate 3.2); oak woodland and scrub were observed to be thicker on the west-facing slopes above a given elevation, but became less dominant towards the east after the first or second ridges. It was also noted that the woodland was thicker on north-facing slopes, where the insolation and evaporation would be lower. In order to deduce the average rainfall over a given basin, the linear gradient had the advantage that the average standardised rainfall could be deduced from the isohyetal map, and then simply adjusted to the mean elevation of the basin.

This illustrates a theme which will recur in this book; it is unsafe to draw conclusions without visiting the study area and discussing the regime with those who know the area well. These examples demonstrate that there is no substitute for first-hand knowledge of the project area when water balance studies are being carried out. Discussions with local observers and meteorologists are also essential to avoid drawing inaccurate conclusions. Isohyets can be derived by statistical methods, in which rainfall is related to position, elevation, aspect and other variables like distance to the sea or a barrier; however, some understanding of the factors affecting the local meteorology and even the natural vegetation should be included in the analysis.

Northern Iran: use of vegetation evidence

The value of the evidence from natural vegetation is illustrated by the water balance of the Alborz mountains between Tehran and the Mazanderan plain near the Caspian Sea. The area was investigated in 1968 (Sutcliffe & Swan, 1970) in the context of transfer of water to the south to meet growing demand. There were striking differences between the two aspects of the Alborz massif in the seasonal distribution of rainfall (see Chapter 8) and the vegetation. To the south the rainfall is low, and confined largely to the months October to May; to the north of the mountains the rainfall is higher and occurs throughout the year, especially in the foothills. The rainfall distribution is illustrated in Fig. 3.6. The difference in vegetation is equally striking, with thick forest and woodland

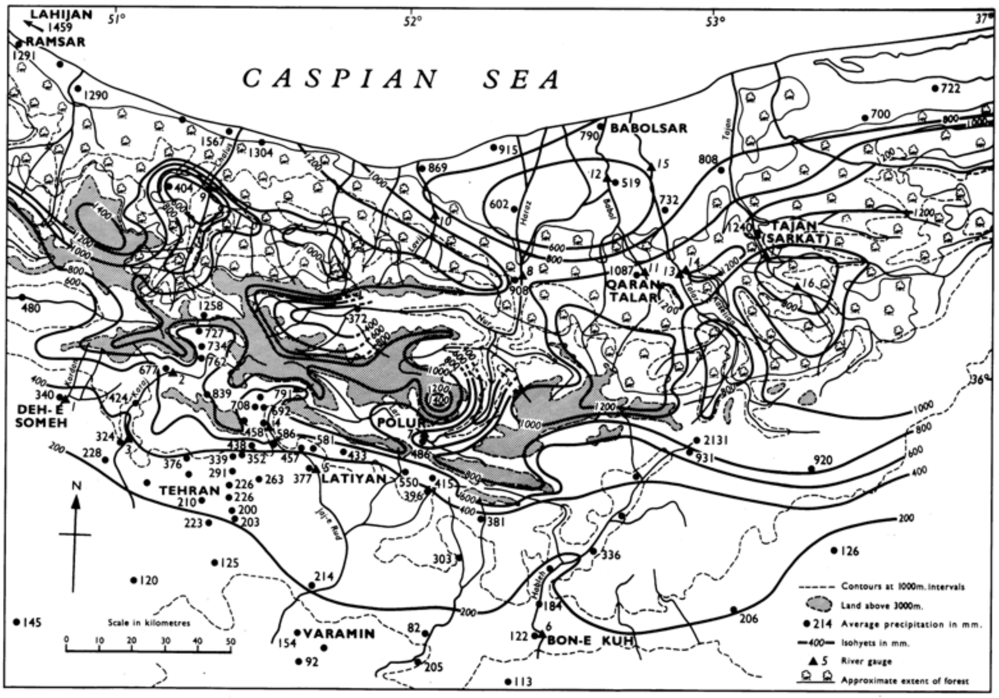

Fig. 3.6 Alborz mountains, Iran: isohyetal map of annual average rainfall, mm (1951–1966) (from Sutcliffe & Swan, 1970).


(a)


(b)

Plate 3.3 *(a) Woodland and rice cultivation on the northern slopes of the Alborz mountains, Iran; (b) the southern slopes of the same mountain range.*

(Plate 3.3(a)) to the north of the mountains and little vegetation (Plate 3.3(b)) to the south, except for a brief period in spring.

Point estimates of mean annual rainfall were compared with the natural vegetation during a tour of the area, supplemented by a map with an outline of the forested area; it was evident that the woodland coincided with the area of perennial rainfall and that the density of the vegetation was related to the depth of annual rainfall. The thickest vegetation was found on the nearest ridge facing the coast, and thinned out to scrub towards the south at a rate which depended on the prominence of the ridges. Towards the watershed, the south-facing slopes become sparse and then bare. Thick woodland extended further south in those valleys, like the Babol, which were open towards the coast.

It was evident that the woodland is limited to those areas near the Caspian Sea with summer rainfall, where the trees are able to survive the summer with its higher transpiration, and that the density depends largely on the total summer rainfall. Within the foothills, where the rainfall is seasonally more uniform, the woodland density indicates the total rainfall which in turn is controlled by the ridges to the south of the coastal plain.

Local meteorologists explained that though heavy frontal rain often passes from west to east over the Caspian side of the mountains when rain is also occurring to the south of the range, the rainfall confined to the northern slopes of the foothills occurs with northerly winds from the Caspian Sea at relatively low levels. This explains the shielding effect of the ridges and the complex relation between topography and rainfall in the northern Alborz. The relation between precipitation and elevation was more direct to the south of the mountains.

Although the number of gauges was small, comparison of rainfall records with observations of the natural vegetation led to the compilation of an isohyetal map (Fig. 3.6) on which the station averages and woodland distribution are included. Once an isohyetal map has been compiled, the long-term mean rainfall over a basin or a number of basins can be deduced. This average basin rainfall is the primary factor in the water balance of an area, together with the monthly distribution of rainfall. This map formed the basis for a water balance of the north- and south-flowing rivers (see Chapter 8), which, because of the differences in actual evaporation, including interception by the woodland canopy, carried similar depths of runoff.

VARIATION OF RAINFALL OVER TIME

Because rainfall records often cover a longer period than river flows, the rainfall series is likely to provide more information on variations in water resources than runoff series alone. It is often useful to relate river flows with basin rainfall over the common short-term period, and then to extend the flow record using this relation and the longer rainfall record. For this purpose it is necessary to derive a consistent series to represent the rainfall over the basin during both the short-term and long-term period. The evidence which can be used for this purpose is the set of monthly rainfall records at a number of sites within or near the basin. It is unlikely that the records will be complete at all stations over the whole period, and therefore the method of deriving the series must remain reasonably consistent.

Tana basin, Kenya

An example of this problem was presented during a study of the water resources of the upper Tana basin in Kenya (Sutcliffe & Rangeley, 1960a). The basin of 9300 km^2 is bounded by the Aberdare mountains and Mount Kenya, and ranges from moorland at over 3000 m to semiarid plains at about 1000 m. As the basin is near the Equator the rainfall pattern is markedly seasonal with rainfall occurring in April–May and November–December. Average rainfall varied from 650 mm on the plain to 2000 mm at about 2500 m in the mountains, with a rainfall shadow between the two ranges. All of the 166 rainfall records were used to compile an isohyetal map (Fig. 3.7) from which the long-term average basin rainfall was estimated as 1170 mm. This compared with an average runoff of 293 mm, but the runoff estimate was based on only 11 years of record at the time.

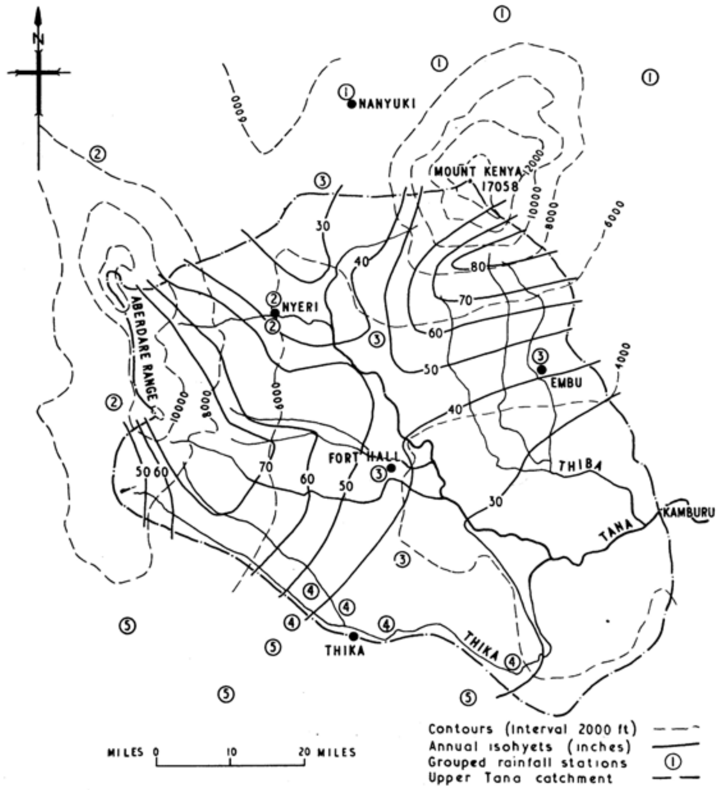

Fig. 3.7 *River Tana, Kenya: isohyetal map of annual average rainfall (1928–1957) (from Sutcliffe & Rangeley, 1960a). Note: 1000 ft = 305 m; 100 inches = 2540 mm; 1 mile = 1.61 km.*

As 22 rainfall stations were available for a common period of 30 years (1928–1957), their averages were computed over this period, and each annual rainfall total was expressed as a percentage of this station mean to give a station index for each year. The stations were divided into five groups according to location, and the mean of the station indices was averaged for each group. The mean of all the station indices was taken as the catchment index, and as a test of homogeneity the group indices were correlated with the catchment index; coefficients varied from 0.88 to 0.97. This suggested that the catchment index was representative of variations of annual basin rainfall. As a reasonable number of records dated back to 1908, reducing from 12 in 1916 to five in 1908, a catchment index was calculated back to this date. It was used to estimate a 50-year record for comparison with measured river flows. This method of deriving a rainfall index is often referred to as an isopercentile approach, as the rainfall can be expressed as a percentage of the long-term mean. It has the advantage that it can be used to compile an index from a raingauge network with missing data, as it assumes that the percentage variation from the mean can be estimated from a varying number of gauges.

Betwa basin, India

A similar approach was used in a research study in the Betwa basin near Bhopal in central India. An analysis of the surface water balance (Sutcliffe *et al.*, 1981) was

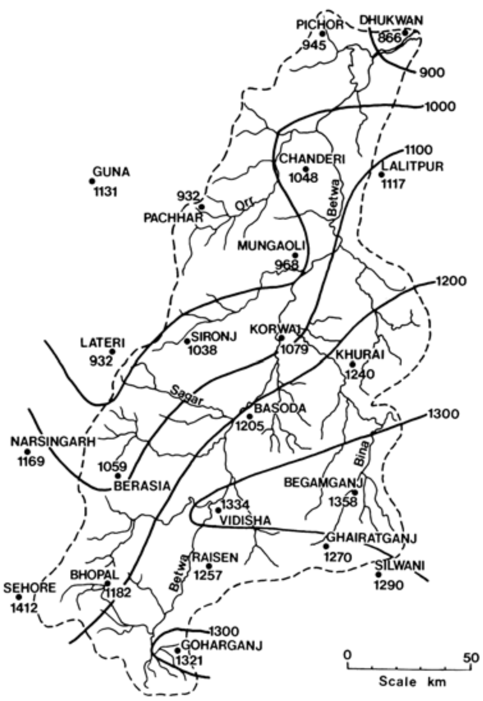

Fig. 3.8 *Betwa basin, India: isohyetal map of annual average rainfall, 1926–1975 (mm) (from Sutcliffe et al., 1981).*

required to support a research investigation of groundwater recharge in a typical hard-rock area of Deccan trap basalts, sandstone and granite. Over the basin of 20 600 km^2 the elevation only varies between about 300 and 700 m, but the average rainfall decreases from south to north from over 1300 mm to less than 900 mm. The average rainfall over the whole basin was estimated from an isohyetal map (Fig. 3.8) for the 50-year period 1926–1975 as 1138 mm. The rainfall distribution is highly seasonal, with 92% of the total rainfall occurring in the four months June–September. In order to derive a seasonal balance, the monthly rainfall series at each station was converted to percentages of its long-term mean annual total, and the average of 17 monthly station indices were averaged and multiplied by the basin long-term average to give a monthly series.

It is interesting to note the difference between the variability of station and basin annual rainfall totals. The coefficient of variation (CV, the standard deviation divided by the mean) of rainfall over the basin is 18.5%, compared with the CV at individual long-term stations which ranges from 25.3 to 34.1%. This illustrates that rainfall over an area is much less variable than rainfall at a point.

Short-term rainfall

A similar technique was used to derive short-term rainfall over the basins upstream of gauging stations in Britain during the investigation leading to the *Flood Studies Report* (NERC, 1975). In comparing storm distribution over relatively small basins with the resulting runoff in order to derive unit hydrographs at different sites, the total rainfall over the storm was calculated by the isopercentile method and related to the long-term basin average. The ratio of the storm total at each station to the station annual average was expressed as a percentage and averaged for all the chosen daily gauges; this percentage was then multiplied by the annual average for the basin, assessed from large-scale isohyetal maps. This was distributed through time in accordance with the hourly falls recorded by one or more autographic gauges, weighted where necessary according to the distance from the centre of the basin. This procedure gave a short-term rainfall series for each storm which could be compared with the resulting runoff, to deduce the response of the basin.

PRECISION OF ESTIMATE OF BASIN RAINFALL

When extending river flows by comparison with basin rainfall, it is important to estimate the number of gauges required to estimate the basin rainfall to a given precision. This may be based on statistical analysis of existing networks. Some estimates have been based on the assumption that point measurements are independent measurements of the mean, and thus that the standard error of the basin estimate is the standard deviation of the point estimates, divided by the square root of the number of stations. This neglects the underlying effect of topography on rainfall, and exaggerates the number of gauges required. The true precision can be deduced by separating the variability of rainfall totals into that due to position, which may be termed the "persistence factor", and that due to random distribution; it is the latter which affects the precision of flow extension.

The persistence factor can be estimated by correlating the rainfall at individual stations with position, elevation and aspect, and assuming that the residual variance reflects the random variation. However, it is also possible to estimate the relative importance of areal pattern and random variation, by correlating the network totals between successive periods and deducing how much of the total variance could be explained by position if all the relevant factors were included. The algebra may be found elsewhere (Sutcliffe, 1966), but the standard error is reduced by the "persistence factor", which can be estimated as $\sqrt{(1 - R)}$ from the correlation coefficient R between the two independent series.

This approach is best explained by examples from two contrasting basins, the Ystwyth above Aberystwyth in Wales and the Ray above Grendon Underwood in central England. The Ystwyth basin of 200 km^2, studied by Rodda (1962), varies in elevation from 8 to 450 m with a rainfall range from 1000 to 2000 mm; the Ray basin of 20 km^2, established by the Institute of Hydrology, is relatively flat with a rainfall range from 460 to 540 mm. Two successive years of rainfall records over the two basins were compared (Fig. 3.9) and analysed; the correlation coefficient R was 0.987 for the Ystwyth compared with 0.412 for the Ray. The rainfall over the Ystwyth basin with its sharp relief is much more variable than that of the Ray; although the mean annual rainfall of the Ystwyth is over twice the Ray, the standard deviation of the individual stations is over ten times larger; much of this increased variability is due to the persistence factor because of topography. Once this is taken into account, the standard error of the Ystwyth basin rainfall is less than twice that of the Ray. This suggested that the random variation of rainfall could be much more conservative than total variation, and that consistent estimates of basin rainfall over time should be obtained from a relatively small number of gauges established over the whole period of

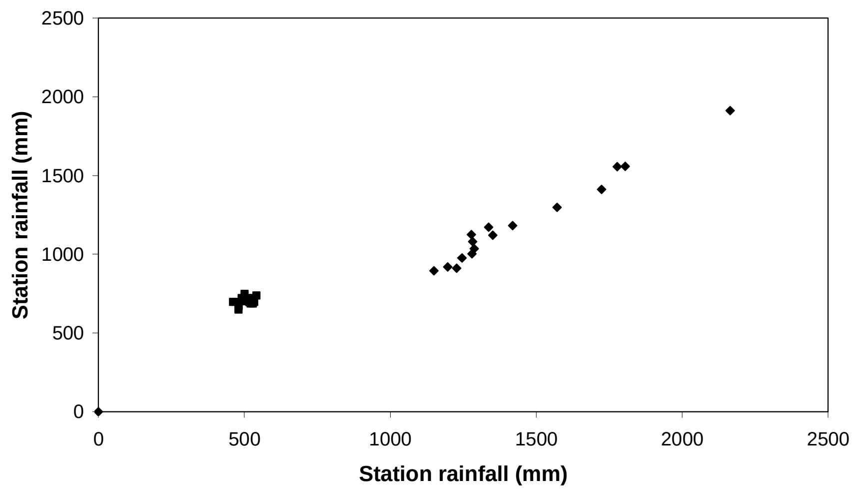

Fig. 3.9 *Correlation of annual rainfall totals: ♦Ystwyth basin, 1959 vs 1958 rainfall; and ■ Ray basin, 1965 vs 1964 rainfall.*

records rather than from a larger but varying number of gauges. This principle is discussed later in Chapter 8 in relation to Lake Victoria.

USE OF RAINFALL FOR FLOOD FORECASTING AND PREDICTION

Apart from their use in water balance appraisal, rainfall measurements are needed in flood forecasting and prediction. The distinction is that flood, or more generally flow, forecasting is carried out in real time, while flood prediction is related to probability, without reference to timing. Both activities require additional information on antecedent conditions, especially soil moisture state which is discussed in Chapter 5, but it is convenient to describe here some aspects of rainfall information required for these purposes.

Flow forecasting

Flow forecasts are needed for flood warning, to enable flood defence measures to be operated and to alert the public to the possibility of inundation, and more generally to provide the necessary information for reservoir operation. The advantage of incorporating rainfall information in flow forecasts is the gain of time and precision over forecasts based on upstream flows alone; the benefit of the time gain depends to some extent on the size of the basin, and is especially valuable in smaller basins. The type of information required is no different from that needed for water balance purposes: estimates of the variation over the basin and over time of rainfall depth. This supposes a need for autographic or continuous measurements to estimate short-term amounts, but on large basins like the Nile or Senegal daily falls are likely to be adequate.

To be useful for forecasting purposes, rainfall measurements or estimates are clearly needed in a forecasting centre as the rainfall occurs, and therefore some form of communication or data transmission is needed. The conversion of raingauges to telemetric mode is covered by Strangeways (2003), but transmission can be based on radio, telephone communication or satellite communication as in the Niger basin in West Africa.

Nevertheless, there are advantages in less traditional methods in some situations. The use of weather radar has brought benefits in visual immediacy in communications, and, after calibration of radar imagery, can provide quantitative estimates of rainfall distribution over areas where the collection and assembly of a sufficient number of direct measurements would not be practicable. The introduction of weather radar has been proposed in parts of Africa to facilitate flow forecasting for development projects, but it presupposes access to the basin which is not always possible.

In some areas it is difficult to obtain measurements from the upstream basin. In the hope that satellite imagery could be used to overcome these problems, the derivation of cold cloud duration has been used in some examples of flow forecasting systems. The network of raingauges in the Senegal basin provided historical records to calibrate the conversion of satellite estimates of cold cloud duration, the number of hours indicated by imagery below various temperature thresholds, into estimates of daily rainfall. It was found that rainfall estimates from satellite imagery could be used in simple runoff models to forecast downstream river flows with similar precision to routine rainfall measurements (Hardy *et al.*, 1989). Following this example, this technique was incorporated into a forecasting system for the Blue Nile and Atbara, where the bulk of the runoff derives from the remote part of the basin in western Ethiopia. The imagery had provided useful information during the Khartoum flooding of August 1988, when it showed that current upstream rainfall was unlikely to cause further river flooding to worsen the situation. Subsequently a flow forecasting system was developed using satellite imagery to give rainfall estimates in real time, a conceptual hydrological model to convert rainfall to river flows at key sites, and a hydraulic model to forecast levels and flows down the river system (Grijsen *et al*., 1992).

Flood prediction

Rainfall records can provide an important contribution to flood prediction. The first requirement is a long and consistent series of daily totals from stations over the project basin, which is similar to the information required for a water balance study. However, the analysis of point rainfall data for flood prediction is usually based on the annual maximum series, which is made up of the maximum daily fall in each calendar or hydrological year of record. This series is analysed in accordance with an appropriate statistical distribution, from which the frequency with which the rainfall is likely to be exceeded can be estimated. The frequency may be expressed by its reciprocal: the return period, or the average period between years in which the rainfall is likely to exceed a given amount. Because the frequency distributions used in this analysis are also used for the analysis of flood flow records, their use is described in Chapter 10.

Similar analysis to that applied to daily rainfall series may be used for rainfall of two or more successive days, and can also be applied to series of basin rainfall, deduced in the usual way from a number of records over the basin. Where autographic or other records of shorter duration rainfall are available, annual maximum series of durations of three hours or six hours, for example, may be extracted and analysed in the same way. These analyses can be combined to derive regional relations between daily rainfall amounts and rainfall of different durations, for given frequencies or return periods; these are known as storm duration curves.

The derivation of basin rainfall from estimates of point rainfall is often based on the concept of areal reduction curves, which illustrate the reduction of average storm depth as the basin size increases; these can again be derived from relations between point rainfall and equivalent average rainfall over different areas.

An alternative to statistical analysis of rainfall, which is used for design purposes where a minimum risk of underestimation is acceptable, is a physical approach to estimation of what is known as the “probable maximum storm”. In brief, the factors affecting storm amount, such as atmospheric moisture content and inflow, and the storm efficiency, are maximised from physical evidence; the resulting maximum storm is estimated. The procedure is described from examples in Chapter 10.

Before rainfall data can be used to derive an equivalent river flow, a rainfall:runoff conversion of some type is required. As described in later chapters, this depends largely on antecedent conditions in the basin, and specifically on soil moisture state; therefore further discussion of the use of rainfall estimates or statistics in flood prediction is to be found in Chapter 5 and Chapter 10.

CONCLUSION

The main use of rainfall measurements is as the major input to water balance studies, which provide the key method of checking the quality of river flow measurements and analysis, and assist in understanding the hydrological processes. However, they are also valuable for the extension of short-term flow records and identifying the critical periods for water resources purposes. In the case of regional water resources investigations, rainfall studies provide the simplest guide to variations in water supply over an area. However, the records need careful analysis, linked with an understanding of the effect of topography and aspect on rainfall distribution.