9 SURFACE WATER RESOURCE ASSESSMENT

The assessment of water resources for water supply, irrigation, or hydroelectric power is one of the main engineering applications of hydrological studies. The water resource development may be based on direct abstraction or may require reservoir provision and storage. The assessment may be limited to a single site or may involve the comparison of a number of sites, which will depend in the first instance on estimates of the mean annual river flow. The following examples of such assessments are designed to illustrate some of the variations encountered.

The importance of using as long a period as possible to estimate the mean river flow leads to the practice of extending flow records by correlation with longer flow records, or by comparison with rainfall records. Regression may be based on actual records, or may be preceded by logarithmic or other transformation. Examples of record extension are drawn from various climates. The analysis of yield from river sites can vary from simple run-of-river analysis to the assessment of yield from a storage reservoir. Reservoir analysis can vary from historical trial of the storage required to maintain a given yield, to statistical derivation of the relation between reservoir volume and yield with a given frequency of success. Examples of various approaches used in Botswana are described.

ASSESSMENT OF MEAN RUNOFF

The average river flow is the most commonly used measure of comparison between sites, and is a key element in the studies of water balance which take account of all the hydrological processes within a basin. It is possible to use flow measurements alone to estimate this quantity, but the reliability of the estimate is improved if it is tested by the assessment of a complete water balance. Although the mean annual river flow is a simple basis of comparison, its estimation should include both seasonal variation and long-term variability. It is essential to ensure an average which is consistent between stations, and this implies an average over as long a period as possible covering a common series of years.

The period of flows should sample the variety of droughts to which the region is liable; in Africa in particular the average flow has been shown to vary significantly from one period to another. The Sahel drought which started in the 1970s has demonstrated that river flows, even when based on periods of record of up to 30 years, can be seriously misleading as criteria for design. Hydroelectric schemes in Côte d'Ivoire, for example, could be designed in the 1960s on the basis of records which should have been adequate to sample the runoff regime but have in practice overestimated the potential yield in subsequent periods. In some cases, river flows for the period 1971–1985 were only 50% of the average for the preceding 40 years.

Similar changes have occurred in both directions in the Nile basin. The behaviour of the White and Blue Niles has provided contrasting features which illustrate the importance of basing estimates on long-term records. The White Nile flows were relatively steady from 1896, when Lake Victoria level records and deduced outflows began, until 1961. However, between 1961 and 1964, the lake rose much higher than in the previous period and the outflows doubled. Since that event, the lake levels have remained relatively high, though the trend appears to be downwards. Subsequent study of early accounts of the lake level has revealed that high levels and outflows also occurred in the last quarter of the 19th century. The Blue Nile, by contrast, has suffered droughts in recent years which have been similar to those of the West African rivers affected by the Sahel drought. At the lower limit of the Nile, where flow volumes are dominated by the Blue Nile, the flow records at Aswan and other sites reveal periods of high flows from 1870 to 1900, of moderate flows from 1900 to 1970, and of low flows since 1970. The flows measured during the season when White Nile flows are dominant, however, confirm the high lake levels and outflows in 1878–1895 and after 1964. It is clear that longer periods of record are essential in these climates than had been thought necessary in Europe where 30-year periods of rainfall record were used to illustrate long-term regimes.

In the light of recent awareness of climate change it is even more essential that the longest flow record is used in order to reduce the errors of estimation of the mean and variability. One method of maximising the effective period of record is to extend the river flow record by correlation.

EXTENSION OF RIVER FLOW RECORDS

It is inevitable that in the establishment of hydrological networks, some types of record and some stations will be established before others. In general precipitation records cover a longer period than river level or flow records, as a raingauge is simpler to install and maintain than a flow record. There are exceptions, as some river level records were used for navigation and could later be adapted for hydrological purposes; there are examples on the River Karun in Iran and on the River Senegal.

It is also usual that river gauges are established on major rivers and near major cities, before they are installed on smaller streams. There is therefore usually scope for extending flow records by correlation with longer established stations in the same basin, where flows should be reasonably closely linked. There are also opportunities for extending flow records by correlation with precipitation records, which often cover a reasonable period of time.

Correlation techniques are described in many textbooks; for example applications in hydrology are discussed in Holder (1985). One characteristic of hydrological data is that they are commonly skewed, with a few large values contrasting with many small values. It is often desirable to transform the data, for instance to logarithms of the actual data, before undertaking regression analysis.

Extension of river flows in the Senegal basin

In a study of the control of the River Senegal by the OMVS (Organisation pour la Mise en Valeur du Fleuve Senegal), following the construction of a dam at Manantali in the headwaters, it was necessary to compile a set of records at key stations on the river network (Figs 3.1 and 9.1) providing a consistent series covering the longest possible period. After visits to the key hydrological offices at Dakar and Saint Louis in Senegal, at Bamako in Mali, and at Nouagchott in Mauritania, and to the ORSTOM offices in Paris and Dakar, the key records at three stations in Senegal and 11 in Mali were available for analysis. The flows at the key station of the Senegal at Bakel were corrected by ORSTOM to take account of hysteresis in the rating curve; because the water level gradient is steeper on a rising than a falling river, the rating curve is looped.

There were two main objectives in the analysis (Sutcliffe & Lazenby, 1989). The first was to extend the inflow record for the site above the reservoir at Manantali in order to simulate the operation of the reservoir over a representative period. The other was to derive a consistent set of flows of the various tributaries in order to study the contributions of each to the downstream flow. To meet the first objective, it was necessary to fill gaps in the flow record at Soukoutali, just below the reservoir site, and to extend the flows back to 1904 using the records at Kayes and Bakel downstream. For the second, the objective was met by completing a set of records spanning the period 1952–1984, as a number of stations covered this period. For the first exercise there was a choice of only two stations for extension, but the second exercise could draw on a wider selection.

It is common practice to introduce a stochastic element into the regression, as in the case of the Blue Nile tributaries discussed below, in order to preserve the variance of the measured flow record. In this case, as the stations to be completed were upstream of Bakel, the long-term station, the introduction of random errors would introduce a lack of correspondence between the upstream and downstream stations, and so it was preferred to use a single regression equation. A linear equation for each calendar month was used to extend or complete each station. This was necessary because the proportion of river flow coming from each tributary varied between the months of both high and low flow seasons. The station to be used for extension was selected by correlating each set of monthly flows for each pair of stations to give correlation coefficient (r) values, adding together the 12 r values for each pair of stations, and using the pair of stations with the highest sum. In general the station selected in this way for extension proved to be the nearest station downstream or upstream, but there were exceptions, including a case where the choice for the independent station was the difference of flows between two stations.

The mean annual flows for the different tributaries were combined in a diagrammatic representation of the basin behaviour (Fig. 9.1) and the long-term mean flows of the tributaries were compared with mean basin rainfall in Fig. 9.2 to illustrate the water balance regime of the area. The scale of the variations of annual flows at Bakel is shown in Fig. 9.3, where the effect of the drought of recent years is evident. It was interesting to note that the variations in river flows from year to year were, as expected, greater on the tributaries draining drier areas (see Fig. 3.1). Thus the proportion of the main river flow passing through the reservoir at Manantali on the Bafing, which was the wettest basin, is higher in dry years. Conversely, the proportion of flow on this tributary is lower in years of high floods. This implies that the reservoir is well placed to store water in years of low flow, but is not so capable of controlling floods in years of high flows.

In a later study (Lazenby & Sutcliffe, 1994), these flows were used to investigate how the Manantali reservoir could be operated to control the total flows of the River

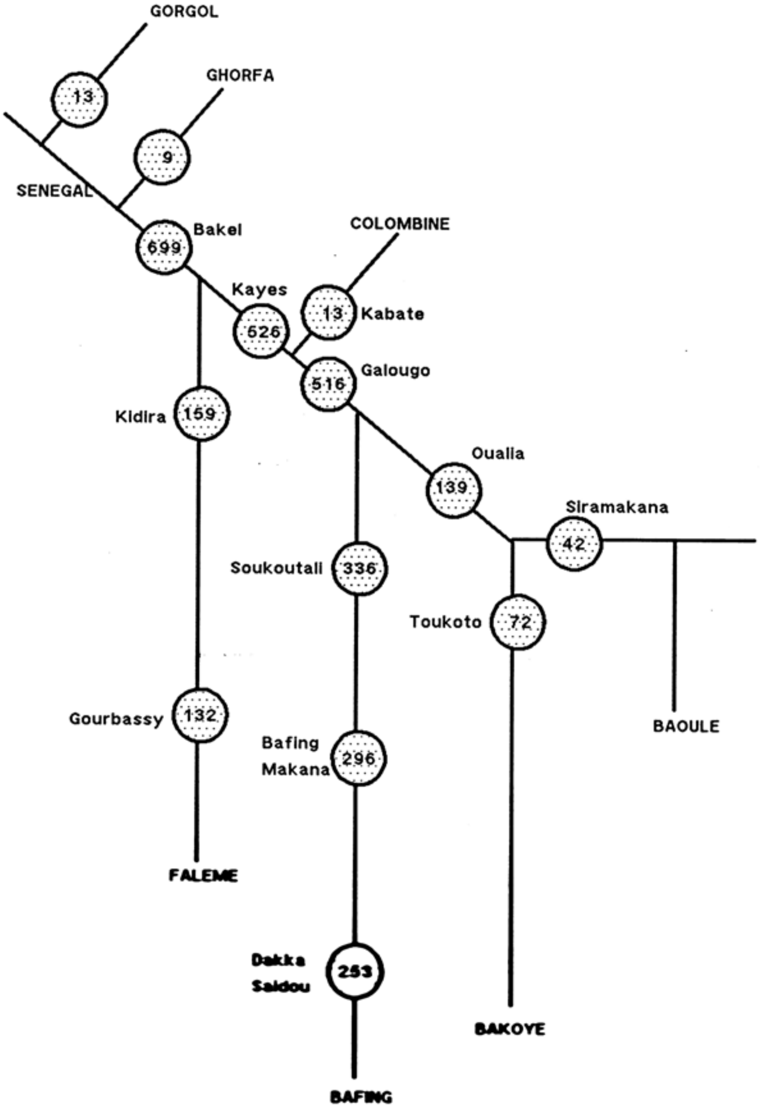

Fig. 9.1 *Senegal basin: representation of mean annual flow 1952–1984* ($m^3\ s^{-1}$).

Senegal. As an interim measure it was proposed to release water from the reservoir to simulate the natural inundation of the flood plain in the lower Senegal. This was used for grazing and natural irrigation or recession culture, exploiting the soil moisture recharged by the flood. The design of this artificial flood, in terms of its shape and duration, took account of traditional practice, and its combination with the hydro-electric, irrigation and navigation components of the project was studied using an operational model of the reservoir.

It would clearly be necessary to monitor flows on the other tributaries in order to calculate the releases from Manantali which would give the desired combined flow hydrograph downstream. Preliminary tests of the reservoir control were based on

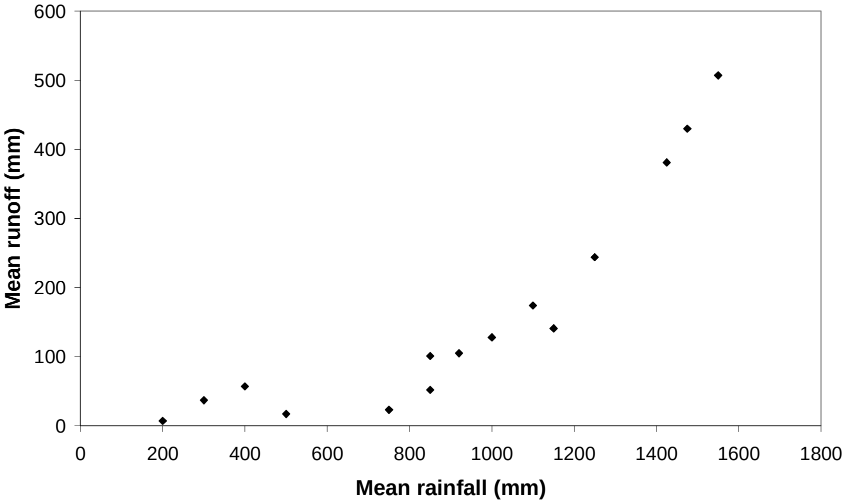

Fig. 9.2 *Senegal basin: mean rainfall and runoff depth (after Sutcliffe & Knott, 1987).*

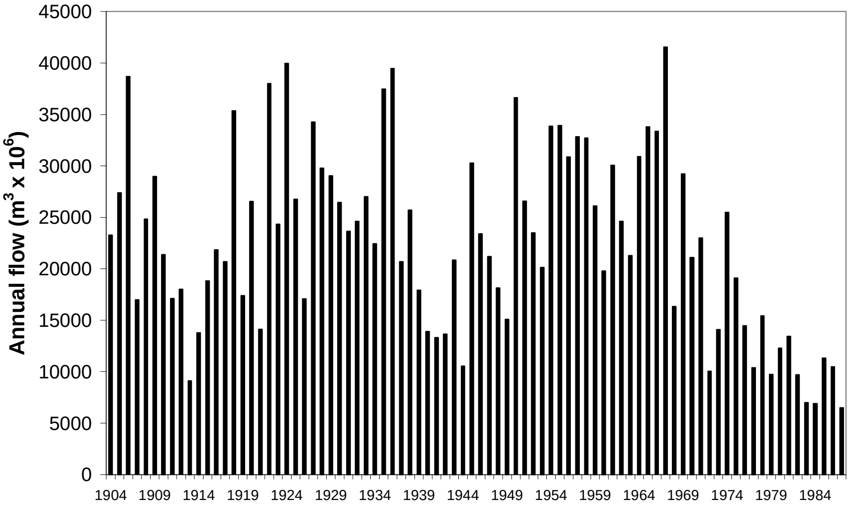

Fig. 9.3 *Senegal at Bakel: annual flows, 1904–1987.*

simultaneous daily flows at Gourbassy on the Falémé and Oualia on the Bakoyé, compared with flows at Bakel, as travel times from these stations and the reservoir were about three days. Later tests of reservoir operating rules were based on the complete record of daily flows, and the potential benefits of flow forecasting have also been studied (Bader, 1992). The actual effect of reservoir releases is illustrated in Fig. 11.12.

Extension of flows on Blue Nile tributaries

A different approach was used to extend the flow series for the Dinder and Rahad, which are relatively minor tributaries of the Blue Nile (Fig. 7.1). The three rivers drain basins in western Ethiopia, but the Blue Nile basin extends to an area of higher ground around Lake Tana where the rainfall is higher. The Blue Nile where it enters the Sudan has a small but important dry season component of flow, due to a longer rainfall season in its southern tributaries and also lake and basin storage, whereas the Dinder and Rahad are dry from January to May at the sites where they enter the Blue Nile between Sennar and Khartoum.

At the time of a water resources study (Institute of Hydrology, 1978), flows for the Dinder and Rahad were required to supplement the records of the Blue Nile, which had been measured at Roseires from 1912 and at El Deim upstream from 1962. The Dinder had been measured near its mouth from 1907 to 1951, and at an upstream site from 1972; the Rahad record was similar, with measurements near its mouth from 1908 to 1951, and upstream from 1972. The gaps in the record between 1951 and 1972 were filled by means of a statistical model, using the earlier concurrent flows measured on the Blue Nile at Roseires and the Dinder and Rahad at their mouths. To avoid including zero values, the months of low flow were grouped into seasons, and an inspection of the corresponding series led to the adoption of a logarithmic transformation before analysis. Cross-correlations between the three flow series, and lag-one serial correlations within each series, were derived from the concurrent flow records. Flow series were generated for the Dinder from the Blue Nile records, and flows for the Rahad were generated from the Blue Nile and Dinder series, preserving both the cross-correlations and the serial correlations. Because the flows were required for an analysis of joint use, and because the three rivers were independent rather than linked like the Senegal examples, a random element was included to preserve the natural variance, and a typical sequence was selected for subsequent analysis. Normally a variety of sequences might be used, but in this case the tributaries provided a minor contribution to the resource.

EXTENSION OF RIVER FLOWS USING RAINFALL RECORDS

It is common for rainfall records to predate measurements of river flows, which require a more formal organisation to maintain and calibrate river level records. As with water balance studies, the type of climate affects the ease with which rainfall data can be used. In a humid climate, the relation between rainfall and river flow is relatively simple as actual evaporation will be close to potential transpiration and will not vary much from year to year. In an arid or semiarid climate, this is no longer true, and basin evaporation is highly dependent on the incidence of rainfall; a more complex or even empirical relation between rainfall and runoff is required, and the uncertainty of the extended series is greater. Although the monsoon type climate, where there is a seasonal switch between humid and arid conditions, would appear to be complex, it is possible to simplify the situation by considering the monsoon season as a single storm. Examples of these situations are introduced to illustrate these differences.

Kenya and New Zealand

In two early investigations (Sutcliffe & Rangeley, 1960a), estimates of water resources potential for irrigation and hydroelectric power were required at sites where river flow records were comparatively short. However, rainfall records over the basins above these sites were available to extend the flow records backwards in order to estimate the mean and variability of flows over a longer time scale.

In the case of the Tana basin in central Kenya, discussed in Chapter 3, the long-term average basin rainfall was estimated as 1170 mm, but the average varied over the basin from 650 mm over the plain at the lower end of the basin to 2000 mm on the mountainous headwaters (Fig. 3.7). Some 22 local rainfall stations provided records which were divided by their individual averages to give annual indices for each station; these were combined to give basin average indices which were multiplied by the basin average rainfall to give an estimate of the annual basin rainfall for a series of 50 years. This series was compared with annual basin runoff over a common period of 11 years (1947–1957), and the annual flow series was extended to a period of 50 years by comparison. It showed (Fig. 9.4(a)) that the runoff coefficient and also the basin evaporation both increased in years of higher rainfall. It is likely that the period during which water was available for transpiration was longer during wet years; the situation is made more complex in this example because there are two separate and marked rainfall seasons. The extension made it possible to place the 11 years of flow record in a wider context; in fact it emerged that the highest and lowest years in the shorter period were also the two extremes of the longer period. During a later review of a reservoir project on the Tana, carried out in 1982, it was interesting to note that the dry year 1949 was still the critical period in the flow record; the high flows had been superseded by the higher flows after 1961.

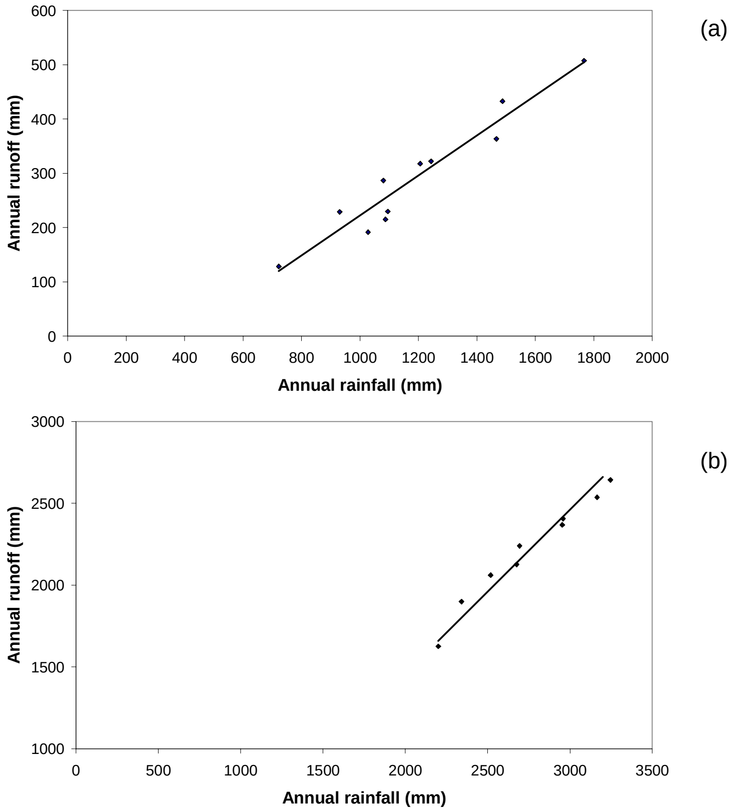

Fig. 9.4 *Annual rainfall and runoff: (a) Tana, and (b) Tongariro (note the different scales of all the axes) (after Sutcliffe & Rangeley, 1960a).*

The Tongariro basin, in the centre of the North Island of New Zealand, drains an area of some 780 km^2 including the volcanic massif of Mount Ruapehu (2800 m), with heavy precipitation throughout the year and falls of snow at higher elevations. The records of five stations in or near the basin showed that mean precipitation was closely linked to elevation, and ranged from about 1270 mm near Lake Taupo to 5000 mm at 1800 m; the average basin precipitation (Fig. 3.3) was estimated at about 2700 mm. Although the number of long-term stations was small, they were reasonably homogeneous, so that it was possible to derive a basin rainfall series covering 30 years, with which the flow record could be compared. The annual basin evaporation loss appeared to be fairly constant at 540 mm from year to year and the rainfall–runoff relation (Fig. 9.4(b)) was drawn on this basis. The runoff record was extended from nine years to 30 years. Because the evaporation was small by comparison with the average rainfall, the variability of the runoff was similar to that of the rainfall and was comparatively small.

Extension of West African river flows

The simple modelling of rainfall and runoff in a monsoon climate has been described in Chapter 5 with the example of the Betwa basin in central India. It was shown that the simple surplus of rainfall over potential transpiration first fills the soil moisture store and is then transformed into runoff or to a lesser extent into groundwater recharge. Thus the seasonal total net rainfall, or the sum of rainfall less potential transpiration, can be correlated with runoff; the slope should be at 45° while the intercept on the net rainfall axis should be equivalent to the soil moisture deficit at the end of the dry season. Following this study, the seasonal total net rainfall during the monsoon season was related to the annual river flows in a regional investigation (Sutcliffe & Piper, 1986) of the hydroelectric potential of Guinea, where the seasonal climate was similar. It was found that the annual series at individual stations (Fig. 5.6, for example) followed the predicted pattern, so that short river flow series could be extended by plotting the two series, and using the line of equality to estimate the runoff in periods when rainfall alone was available.

Similarly the regional relation between rainfall and runoff (Fig. 8.23) could be simply deduced by using the average value of net rainfall over gauged basins. After calculating the average net rainfall at sites with long rainfall records, a net isohyetal map was drawn from the station values and the net rainfall values for basins derived. The average river flow at ungauged sites could be estimated after subtracting the soil moisture deficit, and the annual runoff series could be deduced from basin rainfall series. As the objective of the study was to assess the potential of a number of sites with reservoir storage, the seasonal flow distribution was not critical, and the average monthly distribution at gauged sites could be applied to the annual flows.

PROBLEM OF VARIABILITY OF AFRICAN RIVER FLOWS

Another example of water resources assessment in West Africa was a study in 1986–1987 of the Bandama basin in Côte d'Ivoire. After visits to the key gauging stations to review the record quality, and collation of flows, the water balance was assessed of tributaries flowing from the north towards the south of the country. In order to derive consistent series, the river flows were extended to a common period by correlation with

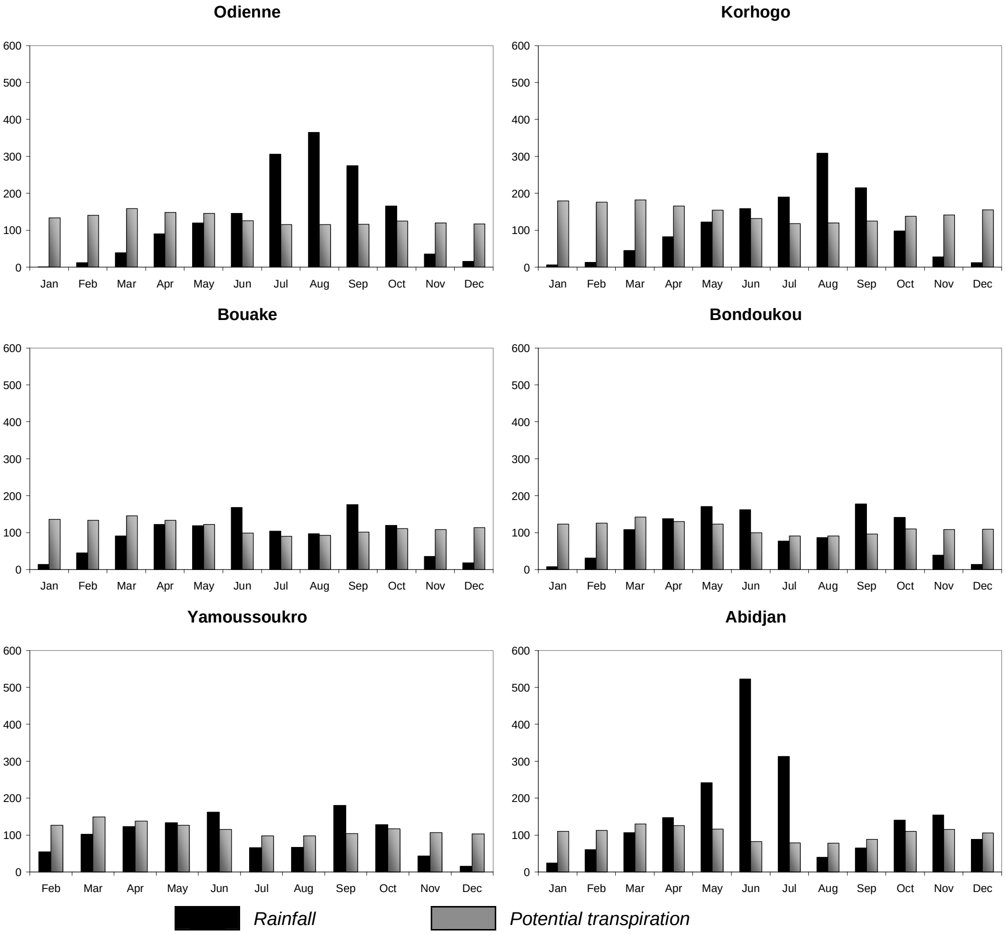

Fig. 9.5 *Côte d'Ivoire: mean rainfall and potential transpiration, mm.*

net rainfall and the records were naturalised by adjusting the flows to restore the effects of reservoir storage and evaporation. This involved the collection of long-term rainfall records and the estimation of basin rainfall series, and the estimation of open water evaporation and potential transpiration for a number of sites. This revealed a transition over the country from a single rainfall series in the north to a bimodal distribution in the south. It was evident that the water balance was affected by seasonal rainfall distribution. Examples are given in Fig. 9.5 of rainfall and potential transpiration to illustrate the distribution over the basin.

A major finding of the hydrological study was that the water resources of the basin had reduced substantially since a previous study in 1966. This decline was compared with flows of the Senegal and Niger during the same period, which showed similar declines. This led to a review of the history of water resources in different parts of Africa over the same period (Sutcliffe & Knott, 1987). It was evident that African river flows are extremely sensitive to variations in rainfall, and that runoff is disproportionately derived from areas with rainfall above 1500 or 2000 mm where runoff exceeds 400 or 1000 mm. These areas are largely confined to the coastal belt of West Africa

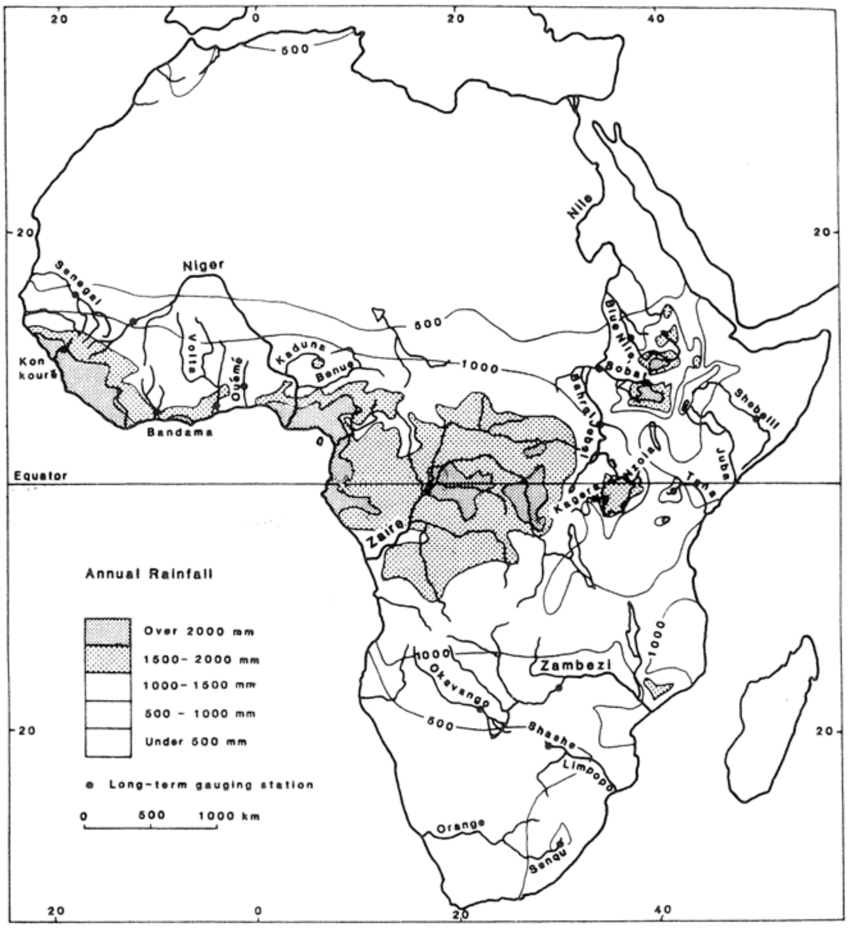

Fig. 9.6 *Mean annual rainfall and drainage basins in Africa (from Sutcliffe & Knott, 1987).*

and the Congo basin, and to limited mountainous areas in Ethiopia and around Lake Victoria (Fig. 9.6). A number of major rivers in West and East Africa have their sources in these limited areas of high rainfall, and their flows are therefore related. Analysis of the flow records of 16 rivers showed that the decline in river flows over West Africa during the 1970s also spread as far east as the Blue Nile basin. In East Africa, by contrast, the flows of various rivers like the Tana in Kenya, the Shebelli in Somalia, and the outflows from Lake Victoria, had all increased after heavy rains in 1961–1964. There had been variations over long periods in basins further south in Africa, as illustrated by the flows of the Zambezi and other rivers, but the periods of relatively high and low flows did not appear to coincide in the same way as in West and East Africa.

OTHER EXAMPLES OF CLIMATE VARIABILITY

Examples of the effects of variability of climate are not confined to Africa. During a visit to north China in 1989, it was clear that the problems presented by prolonged

Plate 9.1 *Cultivation in a reservoir on the Shantung Peninsula, China.*

drought coinciding with industrial development were serious. It might even have been necessary to consider moving the capital if the problem could not be solved. This situation was illustrated vividly by a visit to a reservoir in the Shantung Peninsula (Plate 9.1) where a farmhouse just upstream of the embankment, in the lowest part of the reservoir, was a base for cultivation, and there was the sight of a large boat grounded in the empty reservoir.

In the Jordan valley, long-term records of rainfall at Jerusalem are available to illustrate climate variations since 1846; periods of drought in the 1920s contrast with other periods. The records correspond reasonably with fluctuations in Dead Sea levels, though recent abstractions have superimposed a falling trend. This area is discussed more fully in Chapter 11.

ANALYSIS OF YIELD

Once a reasonable length of flow record at the project site is available for analysis, it is possible to estimate the yield of the site, with or without reservoir storage. Examples of yield without storage are given, in which water is abstracted on the basis of a run-of-river scheme. The yield can be expressed as a firm yield, or one which would have been met throughout the period of record; alternatively the risk of shortage could be expressed in statistical terms, in terms of the frequency of shortage or of its reciprocal, the return period or the average interval between shortages.

Run-of-river project

The simplest form of yield analysis is for a run-of-river abstraction or hydroelectric power project where additional storage is not intended. In such cases low flow frequency analysis is a common tool to estimate the yield of a run-of-river scheme. For example, without the use of storage within the lake, the firm outflow from Lake

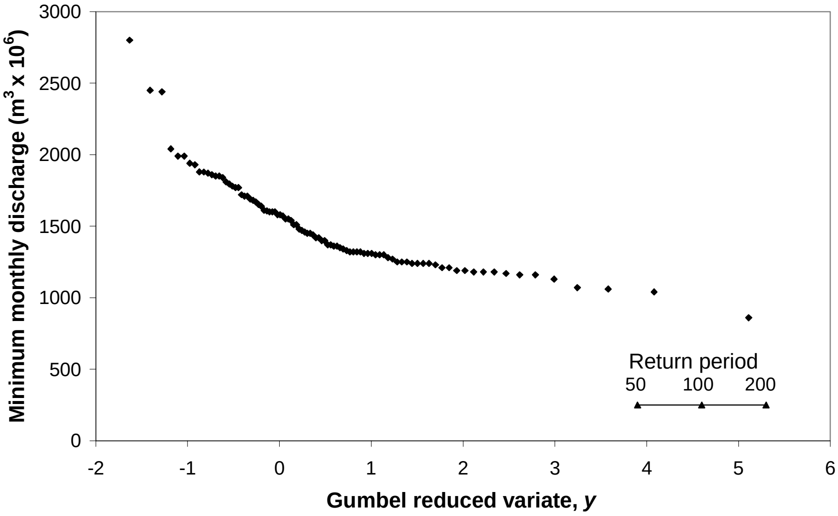

Fig. 9.8 *White Nile at Malakal: annual minimum flows, 1905–1997.*

Victoria at the Owen Falls dam can be taken as the minimum flow over the period of record, which started before 1900. The minimum lake level and outflow occurred in January 1923, when the monthly outflow was 924 $m^3 \times 10^6$, or 345 $m^3\ s^{-1}$. More information could be derived from a statistical analysis of the minimum outflow in each year, in order to deduce the frequency of occurrence of a given flow. However, the Jinja flows are not easy to analyse in this way, as the outflows in successive years are linked by lake storage.

An example of low flow frequency analysis on the Nile system was at Malakal, where the White Nile flows combine the outflows from the Sudd, which are linked with the outflows from Lake Victoria but modified by the effects of downstream lakes and the wetlands of the Bahr el Jebel, and the Sobat River which drains a wide area of southwest Ethiopia. The annual minimum series of monthly flows were plotted against Gumbel *y* according to the Gringorten plotting position. This suggests that there is a limit below which the flow does not go. The flow series is shown in Fig. 9.8, where the significant firm flow derived from the Sudd is evident.

RESERVOIR YIELD

In practice the firm flow of a river is often insufficient to meet the demand, and it is necessary to introduce the concept of reservoir storage to increase the water available. The analysis of yield at a site with a reservoir requires not only a series of river flows but also the dimensions of the reservoir which may be generalised as a relation between reservoir area and volume. There are many ways in which a reservoir scheme may be analysed; in general terms the analysis may be based on historical trials, stochastic generation of synthetic flow series, or statistical analysis of successive years. The following discussion is limited to methods used in successive studies in Botswana, where examples of most types of analysis were used over the years (Parks & Sutcliffe, 1987). As the available data increased, new techniques of analysis made it possible to use more direct methods of assessing the yield of potential dam sites. The methods progressed from the trial of a single critical period, through an analysis based on a generalised study of reservoir geometry and drought frequency, to a selection of techniques of direct reservoir analysis. These included a simple historical trial, an analysis of deficient volumes, and the transition matrix approach, all based on extended flow series.

Rainfall–runoff modelling in Botswana

The extension of flow series in Botswana was discussed in Chapter 8. The water balance of northeast Botswana presents an extreme example of periods of water deficit. In early studies an empirical relation between basin mean rainfall and runoff was used to estimate mean flows at a number of potential reservoir sites. In a later study, sufficient runoff records were available concurrently with rainfall records for the Pitman rainfall–runoff model to be calibrated and used for extension.

With about 15 years of measured flows at the Shashe dam, and rainfall records available back to 1922, the model was used to generate flows which covered 60 years in total. The calibration of the model was based on comparisons of the mean annual flow and its variability, together with the seasonal distribution of runoff. There was considerable variability in the annual runoff (Fig. 8.11).

The simplest method of estimating the yield of a reservoir is the historical trial, in which the reservoir is modelled over the period of flow records. The inflows are added to an initial storage, allowance is made for net evaporation over the reservoir area, and a yield is abstracted from the stored volume. When the reservoir is full, excess water is spilled. When the reservoir is empty the trial fails; the yield is gradually increased until this occurs and this determines the yield of the reservoir over a given period of years. This could be repeated for larger sizes of reservoir to derive a relation between reservoir size and yield. Alternatively, river inflows could be plotted in cumulative form (Fig. 9.9) and lines drawn across the "shoulders" of the graph, using the classical Rippl method to deduce the yield for a given storage volume. The gradient of the line represents the yield and the maximum vertical distance between the line and the graph of cumulative inflow represents the volume of storage required. However, it is not easy

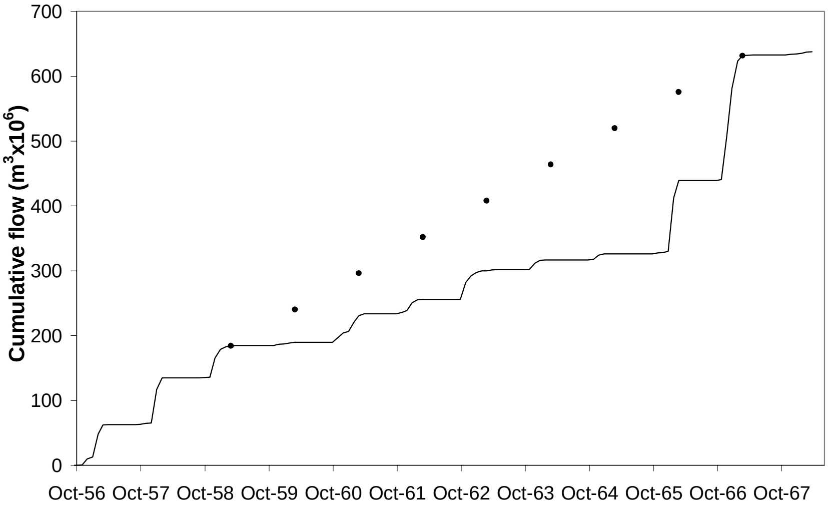

Fig. 9.9 *Rippl diagram: Shashe flows, Botswana.*

to allow for reservoir evaporation, as this varies with the current area of the reservoir; evaporation is a major component of reservoir water balance in arid countries like Botswana. Moreover, this approach makes no estimate of frequency of failure and depends entirely on the characteristics of the flow series, including the order of the sequence.

OTHER METHODS OF RESERVOIR ANALYSIS

Other methods of reservoir analysis provide estimates of frequency of failure to achieve a given yield. A series of analyses in Botswana (Parks & Sutcliffe, 1987) illustrate the different techniques available as the length of flow record increased and analyses progressed from reconnaissance to detailed design. In 1968, when only six years of flow records were available above a reservoir site on the River Shashe, rainfall records indicated that the recent drought of 1963–1965 was the most severe since 1911–1914; in order to test a three-year critical period, a third year of drought was added to the flows recorded in 1963–1965. A simple correlation between Francistown rainfall and river inflow was used to estimate the probable reservoir storage at the beginning of the critical period for various reservoir volumes. These values were compared with the reservoir volumes required to provide a given supply during the critical period to deduce the yield for several reservoir volumes. This provided an estimate of the yield that would have been available from a specific site during a historic drought. Because the drought was within the memory of local people the benefits of the reservoir were easy to convey; however, the uncertainty of the return period of the drought makes an economic analysis rather subjective.

When reservoir yield estimates were required in 1976 at a large number of sites for a preliminary regional feasibility analysis, reservoir yield methods developed by Midgley & Pitman (1969) were used. The method, which was based on the analysis of many flow records in neighbouring South Africa, depends on dimensionless tables of cumulative deficient flows, expressed as percentage of mean annual runoff, for different return periods. They present curves for different climate zones in South Africa, and for example the curve for the zone adjacent to the Botswana border gives for a frequency of once in 50 years a total 8-year cumulative flow of 2.02 times the mean annual runoff. These curves are then combined with generalised reservoir geometry to derive dimensionless relations between net yield and reservoir capacity with both expressed in terms of mean annual runoff. Because the dead storage greatly affects the relation between gross and net yield, which takes account of reservoir evaporation, and because dead storage could not be estimated without site survey, a simple relation was derived to estimate net yield of 1 in 50 year frequency against storage as a percentage of mean annual runoff. This curve was used to estimate the net yield at each site, and 13 out of 75 sites were selected for detailed reservoir survey in the second phase of the study.

The method of estimating net yield was then applied to each individual reservoir. The curve determines the storage required to maintain a given yield, if reservoir evaporation is neglected. However, reservoir evaporation is important in this area and can be deduced from reservoir geometry, which may be expressed as $A = cV^n$ in terms of area and volume, and the reserve or dead storage. The method assumes that the reserve storage is reached at the end of the design drought, and, working backwards in time, the storage volumes and thus areas during the drought are calculated from the balance between inflow, abstraction and evaporation. The net evaporation rate is estimated as the difference between open water evaporation and dry year rainfall. This calculation determines the storage needed to maintain a given net yield, and a series of calculations provides a curve linking net yield to effective storage at each site. This method provided estimates of yield available for different return periods but assumes that the reservoir is full at the beginning of the drought. It was therefore suitable for the reconnaissance survey of 1976 where the yield potential of many sites was required. However, the approach depended on the considerable previous analysis of a large number of flow records, and such regional information would not usually be available.

For subsequent analyses of specific reservoir sites, more detailed behaviour methods were employed. Once a long sequence of runoff records, measured or synthetic, was available, the water balance of a hypothetical reservoir could be modelled to deduce the yield which would have been obtained from a given storage. In the simplest method the inflows were used in a monthly balance model. The number of years or months in which a failure occurred could be expressed as a percentage of the total number of years or months. This provides an estimate of the return period of failure for a particular yield, and a storage–yield curve may be deduced. However, for the periods available of about 60 years this approach is somewhat imprecise.

A new technique based on deficient volumes was developed to relate yields more precisely to associated failure rates. This is also based on reservoir water balance, but in theory incorporates an infinite reservoir volume. The water balance then provides a series of annual drawdowns, or deficient volumes, for statistical analysis. The series of annual maximum monthly deficient volumes is ranked and plotted using a log-normal plotting scheme (Parks & Gustard, 1982). In the absence of evaporation this method can be used directly to determine a yield–storage relationship, but where evaporation is important, as in Botswana, the method can be adapted to define a series of specific storages and calculate the associated deficient volumes. As the drought severity increases, the deficit increases until the net reservoir capacity is reached and a failure occurs; thereafter the deficit is constant (Fig. 9.10). Interpolation from the series of reservoir volumes leads to identification of the volume which supplies the required yield with the design return period of failure. The exercise is repeated with different yields and the results interpolated. The method combines a probabilistic approach with reservoir simulation. It links the yield with the return period of failure for a given reservoir capacity.

The 59-year record also enabled matrix methods of reservoir yield to be applied to the study of Francistown supply. The Gould method, described in McMahon & Mein (1978), was used. A monthly water balance, including evaporation, produces a transition matrix describing the likelihood of ending the year with a given live storage, conditional on the initial year storage. Each year of the inflow data is routed separately through the reservoir, and a transition matrix is derived from the number of times each end of year state is reached from each initial state. The number of occasions of failure and spill are included in the analysis. The steady state probability of storage contents can be derived from successive combination of the transition matrix and the starting conditions; this method takes no account of the order in which annual flows occur. The results can also be expressed as probabilities of failure and water supplied for a given reservoir capacity.

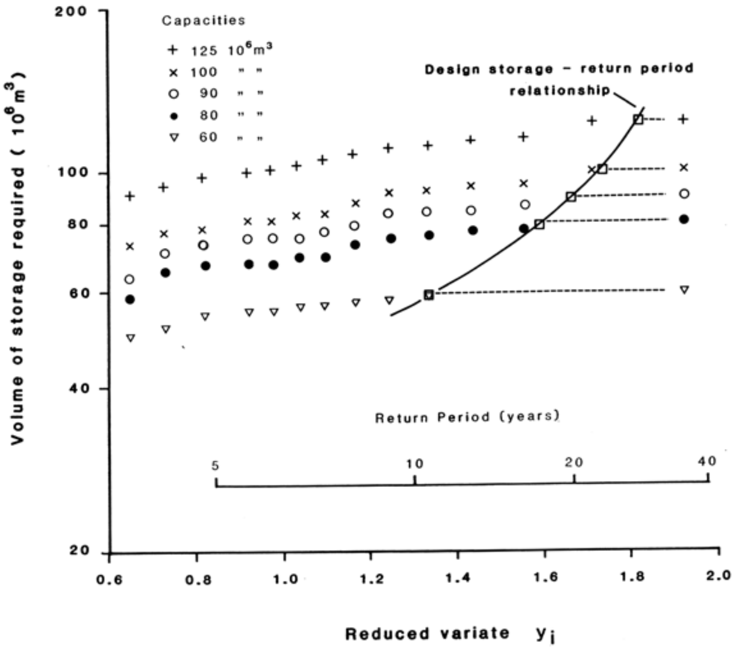

Fig. 9.10 *Botswana: deficient volume analysis (from Parks & Gustard, 1982).*

It is also possible to incorporate the possibility of rationing into reservoir analysis. The return period of failure has historically been used in reservoir design; however it is unrealistic to assume that the reservoir would be operated at full demand until the reservoir fails. Rationing would be used to conserve the available storage when the water level is low. The Gould matrix method can be adjusted to include rationing based on simple design rules within the water balance. Where two or more water uses depend on the same reservoir, it is useful to consider the effect of reducing one form of use. Examples range from garden watering in an arid climate where domestic or industrial water supply is more essential, or irrigation of annual or perennial crops where the area planted with annual crops can be reduced in years when the reservoir storage is low. The combined yield of several reservoirs can be estimated with flow series extended by stochastic generation of flows to provide flow series to test a more complex system.

DOWNSTREAM EFFECT OF RESERVOIRS

Following a number of analyses of individual reservoirs in Botswana, a related problem was studied. A number of small dams, for village supply or livestock watering, were being constructed upstream of major reservoirs. It was not clear how much effect these dams would have on the inflow to the major reservoirs downstream, on which the urban and industrial water supply of the country depended. The problem was studied empirically (Meigh, 1995) by deriving the surface areas of these 320 small dams from aerial photography or maps and surveying a sample in different parts of the country in order to deduce relations of the form $V = aA^b$ between area and volume. The volumes of these dams in each basin were deduced from the measured areas and a typical non-dimensional area–volume curve was derived. The three major catchments draining to the main reservoirs were divided into sub-catchments, and the small dams were divided into categories and amalgamated into composite dams within each subcatchment. Daily flows for the period 1970–1990 were generated for each subcatchment using a rainfall–runoff model and the operation of the small reservoirs was modelled, with abstractions estimated according to use for watering or irrigation. The outflows from groups of reservoirs were deduced and channel losses included to estimate inflows to downstream reservoirs while the number and total capacity of the small dams within the basin were increased in the model. The effect of the number and size of the small dams was examined by this modelling; the total capacity of the small dams was found to be the main factor affecting the runoff. Dams with a total capacity of 10% of the mean annual runoff caused a similar decline in catchment runoff. However, dams in the headwaters were found to have a smaller effect, while a few large dams had less effect than a large number of small dams with the same total capacity. The effects on floods and sedimentation were also studied.

COMBINED RESERVOIR ANALYSIS

It is often possible to link the operation of several reservoirs and this can improve the efficiency of the system, or in other words reduce the frequency of failure. An example where several different functions could be combined was investigated on the upper Vistula above Krakow in southern Poland. Several reservoirs had been constructed to provide water supply for urban and industrial use in this area, with some storage allocated for flood control downstream.

In the assessment of the potential role of a reservoir under construction, the contribution which this reservoir could make to flood control was investigated. The inflow hydrographs for a number of flood events were collated, and the effect of flood control operation on flows through Krakow city was investigated by computer-based reservoir trials. Fixed control rules were applied and the reductions of downstream peak flows were noted. It was found that the reductions were improved by combining the roles of the different reservoirs and transferring the volumes dedicated to flood control from one site to another to take account of the potential of the different tributaries. The improvement in frequency of downstream flooding was significant.

Where complex reservoir systems are to be designed or controlled for a variety of objectives, such as water supply, irrigation and hydroelectric power production, linear or dynamic programming may be used to analyse the system in order to maximise the benefit, which has to be expressed for each function in economic terms.

CONCLUSION

The assessment of the water resource availability at a site or a number of sites depends in the first instance on an estimate of the mean annual flow and its variability, both seasonally and from year to year. Because of the variations which can occur in even the mean annual flow over time, especially where runoff depths are low as in Africa, it is important that estimates should be based on as long a period as possible. This period may be increased by extension of river flows by correlation with longer flow records or rainfall records. Such extension is simpler in humid than in arid climates, as evaporation losses are more predictable. Monsoon climates may be treated as seasonally humid. Flow records may also be extended by stochastic generation of flows with similar properties to the measured record.

Once long flow records have been obtained or estimated, the water resources yield of a site may be based on direct abstraction or on the inclusion of a storage reservoir. The yield of a run-of-river scheme may be assessed by statistical analysis of annual minimum low flows. However, many sites require the provision of a reservoir to maintain an adequate yield, and this will involve reservoir analysis to relate reservoir capacity to the yield which can be maintained with a given frequency of shortage. There are many available forms of analysis, and the choice depends partly on the length of records available; examples from Botswana include historical trials, statistical analysis of deficient volumes and transition matrix methods. Multiple objectives and the effect of rationing control can be included. Whereas such techniques would at one time have required analysis on mainframe computers, they can now be carried out using software available for a PC. The spreadsheet is now a key tool for those designing water resources projects.