7 RIVER FLOW

River flow is the only component of the hydrological cycle which can be measured rather than sampled. Therefore the river flow station is particularly important in the hydrological investigation of a basin or an area. It is essential to ensure that flow records are as precise and consistent as possible. In this chapter some of the techniques of quality control are described and examples given to illustrate likely problems.

USE OF RIVER FLOW RECORDS

The records from flow stations provide the variation over time of the water available at the outfall of a basin. These flows may be used to derive average flows and describe the variability at different periods of the year. Low flows may be compared directly with water demands for run-of-river schemes, while cumulative totals give the volume available for storage where natural flows are inadequate to supply demand throughout the year. The measured flows may be extended to cover a longer period by comparison with adjacent flow records or with rainfall records. Although the accuracy of records is desirable, it is for this purpose that the consistency of records is equally important.

Apart from comparing supply and demand, river flows provide important information about the regime of a basin. Comparison with rainfall provides information on the water balance; a diagram of the seasonal flow gives a simple picture of the regime of the river basin; a typical recession curve, which can be derived from the seasonal flow diagram, gives information about the groundwater regime of the basin; the shape of the flood hydrograph, together with information on the storm magnitude and time distribution of the corresponding rainfall, allows the flood potential of the basin to be estimated.

BASIS OF RIVER FLOW MEASUREMENT

River flows are measured in terms of water level at a site where the level can be directly related to the rate of flow. This site may be at a structure which can give a precise relation between upstream level and flow over a weir; the structure may be designed for this purpose, or may be a structure designed to control the river level which can be adapted to measure flow. The upstream level is converted to flow using a theoretical equation for the structure or a relation derived from measurements. This approach is common in Britain where the river channels are usually small enough for this approach to be economic.

In other cases the river levels are measured at a site on a natural river channel where the relation between level and flow is likely to be regular and stable, for instance above a natural control such as a rock outcrop. In this case the relation between river level and flow is built up by a series of discharge measurements over the range of river level variations. Each discharge measurement consists of a number of velocity observations across the channel, using a current meter at a fixed fraction of the depth, or more rarely sampling the depth profile. The product of velocity and channel depth is integrated to give a discharge linked to the water level at the time of observation. The relation between level and flow is built up into a rating curve from the series of discharge measurements, either by plotting on natural or logarithmic graph paper, or by statistical correlation between level and flow. Account is taken of changes in this relation because of channel changes, so that each rating is linked to a specific period and range of level.

Types of river flow stations

A number of rivers in Britain are small enough to be measured using calibrated structures and automatic recorders, reducing the amount of fieldwork needed to maintain a gauging station; however, in many developing countries the rivers are larger and it is necessary to carry out discharge measurements and to calibrate the station using a rating curve derived from these measurements.

In semiarid countries the periods of river flow are so intermittent that it is difficult to carry out sufficient gaugings to build up a rating curve; in these conditions there are advantages in using a structure, if one can be designed to cope with the sediment and bed loads which are associated with the extreme variability of flow. For example, in the case of recharge to the Abu Dhabi aquifer from the Jebel Akhdar in Oman, discussed in Chapter 6, simple weirs were proposed to measure the flows of the *wadis* because of the remoteness of the potential measurement sites.

Because of the need for long-term flow series to sample the variations in climate which persist over relatively long periods, especially in more arid regions like much of Africa, consistency of flow records over the years is extremely important. Although methods of measurement, calculation and analysis are more complex for flow records than for some other variables like rainfall, homogeneous records are equally important and perhaps more difficult to achieve. The maintenance of complete long-term records at the same site and with consistent methods of discharge measurement, derivation of rating curves, and subsequent analytical methods, should be given a high priority.

Areal sampling

The question of areal sampling was discussed in Chapter 2, but it is useful to recapitulate some points here. In most countries it is not possible to measure the flows of all rivers, but it is necessary to design a network which could be used to estimate flows at ungauged sites, by sampling a wide range of climate, topography, geology and basin size. It should be possible to sample areal variability of runoff as effectively as time variations. Although annual runoff is largely related to basin area and the depth and seasonal variation of rainfall, the distribution of runoff through the year is influenced by the size, the soils and geology of the basin as well as the seasonal distribution of rainfall; all these factors should be sampled by a gauging network.

The number of gauges required will depend on the variability of these factors over a region. One way of establishing the adequacy of a network is by developing statistical relations between, for example, mean annual runoff or the mean annual maximum flood, and basin characteristics like size, rainfall and other factors. The more characteristics needed to give a reasonable estimate of flow factors, the more extensive a network is desirable. In practice, the size of a hydrometric network is likely to be affected by the importance of water resources to the national economy, and thus by the number of stations which can be maintained by the allocated budget. Within these restraints, a combination of long-term stations to sample time variations in combination with rainfall stations, and a well distributed network to sample areal variations, will give the optimal basis for water resources assessment for a given budget.

Quality of individual records

Once the network has been designed to sample flow variations in time and space, it is important to maintain the reliability and perhaps even more the consistency of records. As far as possible the whole series of flow records should be of a uniform standard of reliability. Where this is not possible, for instance because of changes of technique or difficulties of measurements in certain periods, it is important that this should be recorded so that this is taken into account when analysing records.

The measurement of river levels is likely to vary according to circumstances, but its frequency should be related to basin size and water level variability. The conversion of water level series to river flow series largely determines the reliability of flow records, and this conversion depends on the rating curve used at the individual site. The precision of flows depends largely on the stability and reliability of individual rating curves, and these depend not only on the methods used for discharge measurements and for deriving curves from them, but also on the physical characteristics of the site itself.

Methods of discharge measurement are reasonably standard and well described (e.g. ISO, 1997b). Velocities are measured at a number of verticals across the river (Plate 7.1) at standard fractions of the depth, using current meters which should be recalibrated regularly. In general measurements are made at 0.6 depth, 60% of the depth below the surface where the mean velocity is assumed to occur, or at 0.2 and 0.8 depth, where the average of the two observations is assumed to correspond to the mean velocity. In Nile basin practice, on the other hand, measurements have been made at half depth and the velocities multiplied by 0.96. Where possible, flows are measured using structures, either designed for the purpose or adapted from other structures. These may be calibrated from theory or from measurements. In general measuring weirs and flumes are limited to smaller rivers, but releases from reservoirs are usually monitored in this way.

At sites where gauging by current meters is not practicable, especially at high flows, velocities may be deduced from surface floats or by hydraulic formulae using cross-section surveys and gradient measurements. However, this is not as simple as it sounds; during flood events in New Zealand, it was extremely difficult to reach gauging sites during peak conditions, let alone attempting to record the flood profile with survey pegs. However, the debris left by the flood provided a consistent set of levels which could be used to estimate the flood discharge using Manning coefficients derived from moderate flows.

DERIVATION OF RATING CURVES

Rating curves, linking water levels to river flow at a given site, are derived from discharge measurements and thereafter used to estimate the river flow at that site from measured levels. The rating curve is thus the key to precise river flow estimation, but

Plate 7.1 *Gauging station, including staff gauges and a cableway, on the River Indravati at Jagdalpur, central India.*

the derivation of rating curves from discharge measurements has not received the attention it deserves. Several questions arise. Should the fitting of a curve be carried out by a hydrologist familiar with the site, or should it be based on an automatic statistical procedure? Should the rating curve be based on the gaugings of a single year, which is common practice in many countries, or on those of a number of years? The answer to the second question may depend on the purpose of the study or the characteristics of the site. For example, most of the records used in the investigations leading to the *Flood Studies Report* (NERC, 1975) were based on high flow measurements over a number of years, as these measurements were rare and the channel control was assumed to be more stable than at low flows. In a study of the outflow from Lake Kyoga in East Africa, a similar approach was taken, with the use of several years of gaugings as the range of lake-fed water levels was insufficient in most single years to determine the rating curve.

Traditional methods of fitting curves to points representing individual gaugings have been graphical, with curves drawn on either linear or logarithmic graph paper taking account of the geometry of the site. More recently, with the advent of computer-based techniques (Institute of Hydrology, 1993), equations of the form $Q = a(h - h_0)^n$ have been fitted over the whole or part of the range of levels. The level h_0 corresponding to zero flow and the exponent n are chosen to minimize the scatter, while bearing in mind that h_0 and n are both related to site geometry; h_0 may correspond with the level of rock control while n should generally be between 1.5 and 2.5. With modern programs, curves may be displayed on screen as linear or semi-logarithmic curves, with successive gaugings grouped and labelled. This enables the hydrologist to consider first whether all records are homogeneous by producing one rating curve to cover the whole period; next all the evidence is available to test whether the rating changes with time and to experiment with different groups of gaugings corresponding with time-varying rating curves; each curve may be divided into several sections where a single equation is not appropriate for the geometry of the whole channel cross-section; finally the need for separate treatment of rising and falling river levels may be examined.

Examples of rating curves from the Nile basin

During an assessment of hydrological records in several countries in eastern Africa, attention focused on the quality of discharge measurements and particularly on rating curves. Gauging techniques were studied and the ways in which gaugings were combined into rating curves. The resulting flow records were tested by double-mass analysis with other stations, and by water balance comparisons with basin net rainfall estimates. Thus a number of stations in the Nile basin were examined in the course of the study; an outline map of the basin (Fig. 7.1) illustrates the relative positions of these stations.

These examples from the Nile conveniently illustrate the various types of rating curve, as most variants are available. Some ratings are reasonably precise and stable, others are precise over periods of a year or so but vary over time; yet others have looped relations, where the relation on a rising curve differs from that on a falling curve. In other cases it is preferable to derive ratings from a number of years, as the range is inadequate in a single year.

The outflow from Lake Victoria was historically controlled by the geometry of the Ripon Falls, where the relation between upstream lake level and lake outflow depended on rock outcrops which formed sills and islands which were stable during historic times. In order to establish a rating curve for the lake outflow, discharge measurements were made from 1923 at Namasagali, a site some 80 km downstream of the lake, and were related to water levels at Jinja, near the outfall from the lake. This relation was well defined by the gaugings. After 1951 the construction of the Owen Falls dam, some 3 km downstream of the Ripon Falls, was begun with the construction of a coffer dam. Thereafter the flow was controlled by agreement between Uganda and Egypt, to accord with the natural flow based on the lake level and the rating curve, at least over periods of about 10 days to a month. This “agreed curve” is illustrated in Fig. 7.2, together with gaugings made between 1923 and 1950. After 1961–1964, when the lake level rose dramatically and remained above the limits of previous gaugings, the curve was extended from the earlier curve by hydraulic modelling. The gauging site was moved some 20 km upstream from Namasagali to Mbulamuti, to avoid the disturbance from the rise of Lake Kyoga downstream. The gaugings were supported by measurements of turbine flows and sluice releases past the dam. It will be seen later that the rating curve is confirmed by comparison with downstream flows.

Another station with a stable site supported with discharge measurements is the Blue Nile at el Deim, about 85 km upstream of Roseires near the border between Sudan and Ethiopia. This station was established in 1962 during the construction of the Roseires dam, and discharge measurements have been carried out regularly since that date. Figure 7.3 illustrates the rating curve and the gaugings on which it has been based; it is clear that the rating is precise and has not changed over the period of some 30 years.

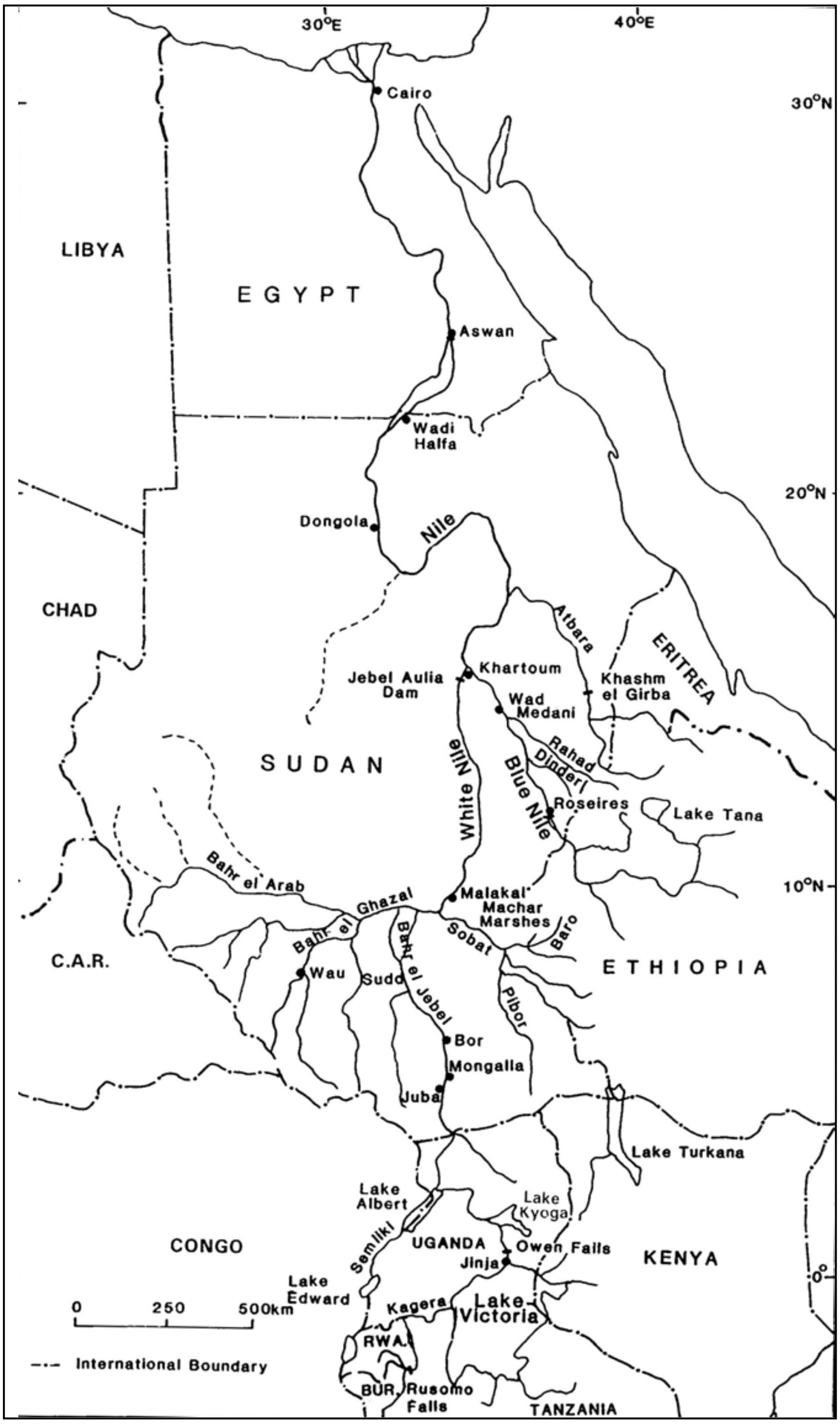

Fig. 7.1 *Map of the Nile basin showing key stations.*

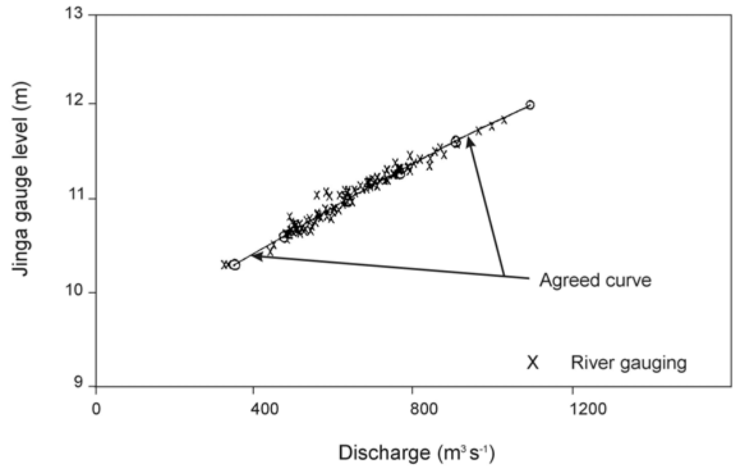

Fig. 7.2 *Outflow from Lake Victoria: "agreed curve" and gaugings at Namasagali (after Sutcliffe & Parks, 1999).*

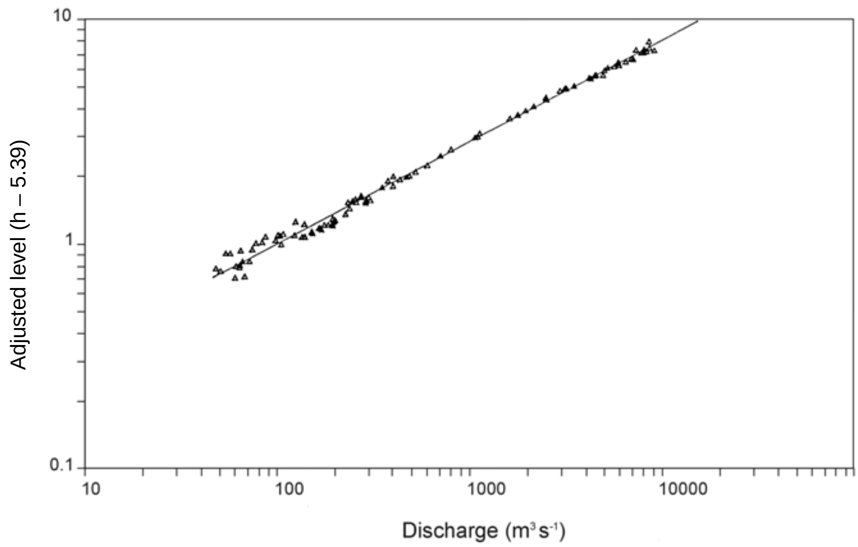

Fig. 7.3 *Blue Nile at El Deim: rating curve and gaugings, 1962–1981.*

Although the outflows from Lake Victoria can be derived from lake levels measured since 1896, and a combination of the rating curve and other measurements, the outflow from Lake Kyoga downstream has been less precisely monitored. Although levels have been measured at Masindi Port below Lake Kyoga at a site which was believed to have a stable rating, subsequent measurements revealed that the rating changed at intervals. During an investigation of flows between Lake Victoria and Lake Albert (Sutcliffe, 1996), rating curves were derived for Kamdini, some 100 km below Lake Kyoga. Levels were available from 1940 to 1980, while gaugings had been carried out at Kamdini itself from 1940 to 1959. However, gaugings were also available downstream at Fajao and Paraa, between Kamdini and Lake Albert, from 1940 to 1979, and there are no significant tributaries between the two sites.

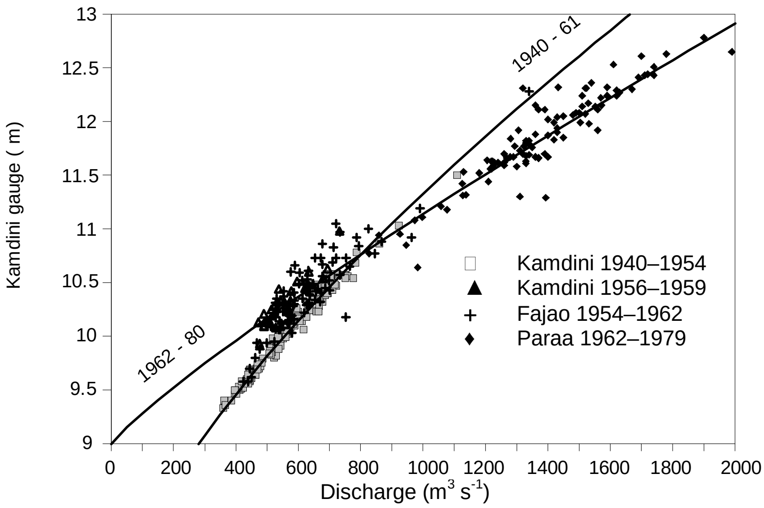

***Fig. 7.4** Kyoga Nile outflow at Kamdini: gaugings at Kamdini, Fajao and Paraa, 1940–1980 (from Sutcliffe & Parks, 1999).*

Because the levels at Kamdini are dependent largely on outflows from Lake Victoria, there is insufficient range of level or flow in a single year to define the rating curve. However, it was possible to derive a family of curves from gaugings at Kamdini itself and at Fajao and Paraa, related to levels measured at Kamdini. These curves, which appeared to be reasonably stable over one or more years, differed only in the level corresponding to zero flow, which was derived from all the gaugings in the period. After 1961, when Lake Victoria rose and the outflow more than doubled, there was also a change (Fig. 7.4) in the slope of the curve. Thus a series of curves could be derived to convert the levels to flows in this reach.

The next long-term station downstream of Kamdini was established in 1905 on the Bahr el Jebel at Mongalla, where the inflow to the Sudd is measured in a single channel. Although gaugings were infrequent between 1905 and 1921, river levels were measured regularly and were converted to flows using a general rating curve based on all measurements during this period. After 1922 measurements were frequent, with an average annual total of 260 between 1922 and 1931. Gaugings continued reasonably frequently until 1978, but were discontinued after 1984. Successive rating curves over the years show that the level corresponding to a given flow rose steadily (Fig. 7.5) from the beginning of the century until 1964, when it fell abruptly. This pattern was confirmed by the rise in the bed level derived from gauging records. The detailed change after 1963–1964 is illustrated in Fig. 7.6, where a fall in effective level of about one metre is shown. These changes were doubtless related to the fall from high Lake Victoria levels at the end of the last century, and a reversal after the sudden lake level rise in 1961–1964.

A different problem is illustrated by rating curves at Khartoum, where there is a marked difference (Fig. 7.7) between the gaugings during periods of rising levels and those of falling levels. There is a clear loop between the ratings for the two periods. Similar hysteresis effects are shown at other sites near junctions, like those of the Sobat and White Nile. At Khartoum the picture is complicated by an apparent change in

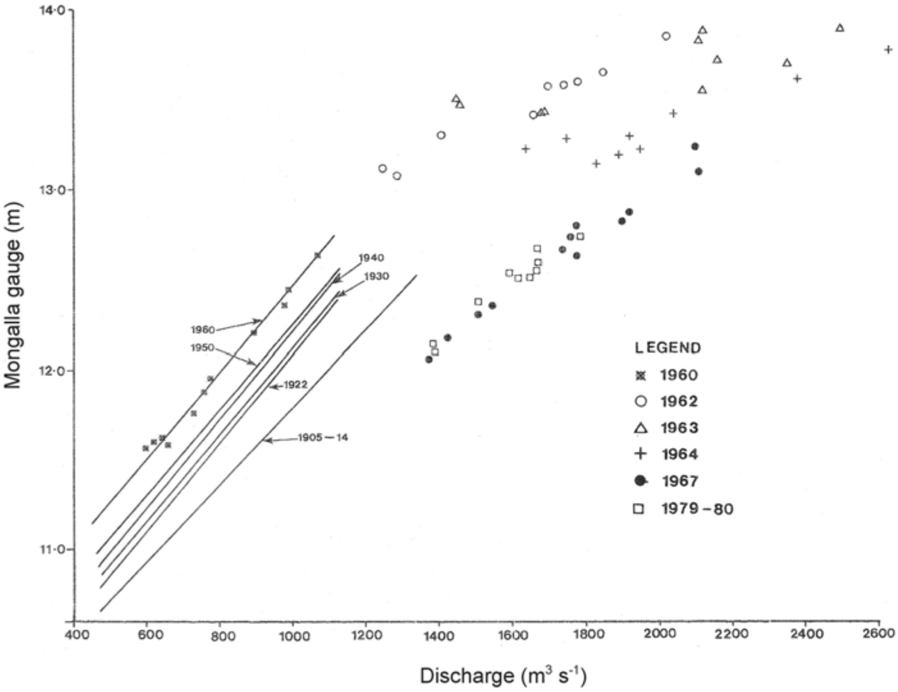

Fig. 7.5 *Bahr el Jebel at Mongalla: gauge discharge relations, 1906–1980 (from Sutcliffe & Parks, 1982).*

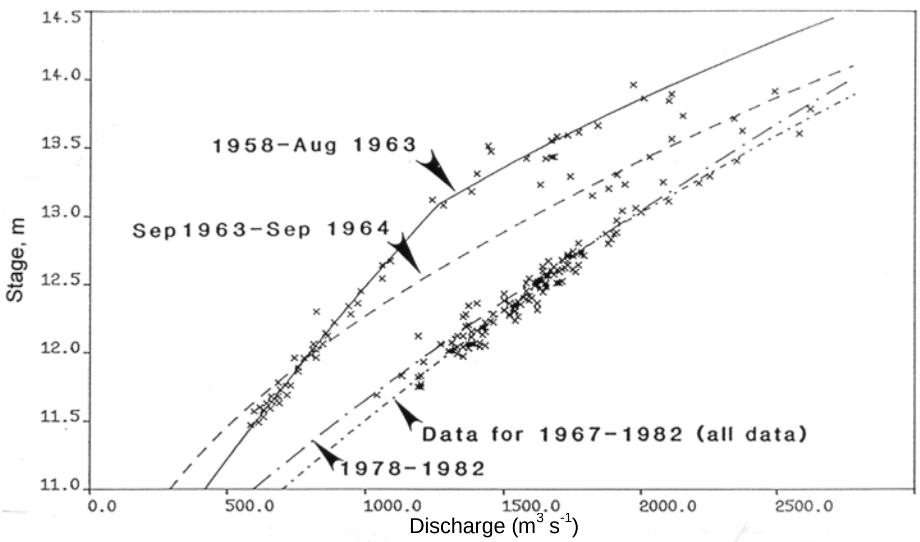

Fig 7.6 *Bahr el Jebel at Mongalla: detailed change after 1963/64 (after Sutcliffe & Parks, 1999).*

ratings at high flows, where a rise of about 0.5 m between 1902 and 1982 (Fig. 7.8) has been deduced from an analysis confined to the highest gauging carried out in each year.

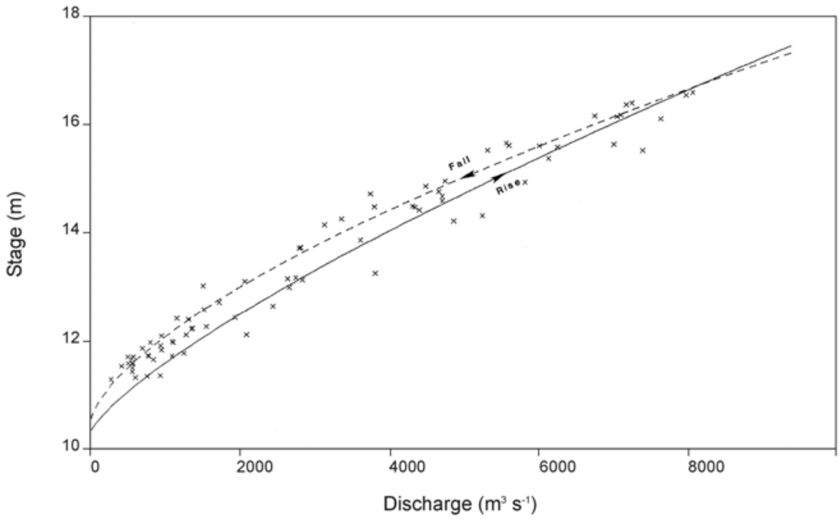

Fig. 7.7 *Blue Nile at Khartoum: rating curves on rising and falling levels generated using data for 1959, 1969 and 1980.*

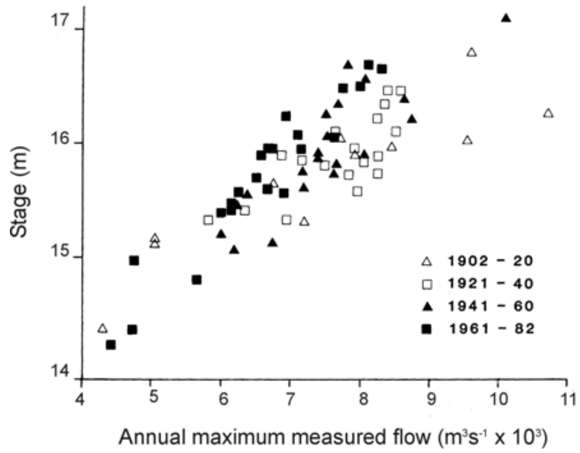

Fig. 7.8 *Blue Nile at Khartoum: ratings at high flows (from Sutcliffe et al., 1989).*

These examples from a single river basin illustrate a number of different types of relation between level and flow. The differences depend on the stability of the river profile and also on upstream and downstream conditions. It is important that the rating curves at specific sites should be reviewed over the years. This has been made easier by modern techniques of analysis which reduce the time necessary for routine computation and thus make it easier to compare gaugings and ratings over the whole period of record.

INDIRECT METHODS OF APPRAISAL

There are a number of indirect ways in which river flow records can be assessed for precision and consistency. These include double-mass curves, which provide a graphical comparison of different records, and statistical methods of comparison.

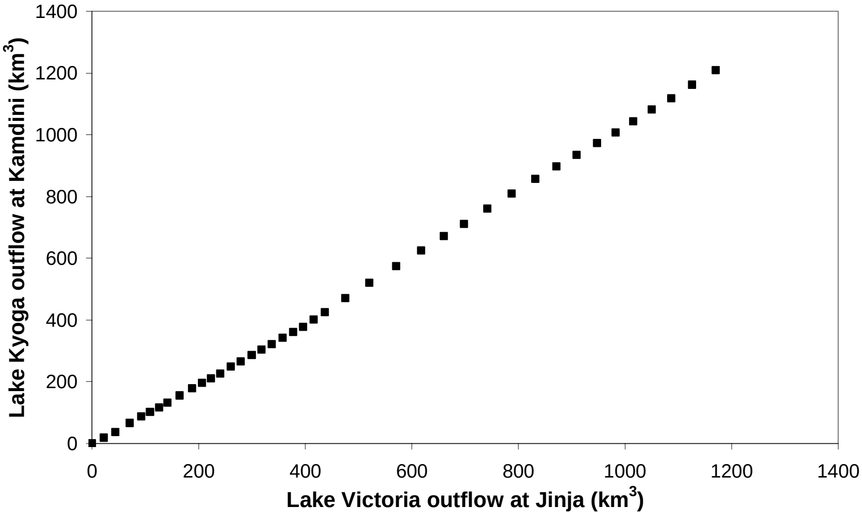

Fig. 7.9 *Cumulative flow comparison: Lake Victoria outflow at Jinja and Lake Kyoga outflow at Kamdini, 1940–1980.*

In general double-mass curves are the most popular form of comparison. The cumulative flows of different records are compared, or alternatively cumulative flows are plotted against time. An example comparing the outflows from Lake Victoria at Jinja with Lake Kyoga outflows at Kamdini (Fig. 7.9) suggests that both sites provide reasonable and consistent records. However, comparisons between stations on different tributaries may reflect different regimes rather than inconsistent records. For example, comparisons between the flows of the Bahr el Jebel at Mongalla and the Blue Nile at Khartoum show a distinct change after 1961–1964, but this is related to the rise in Lake Victoria and the doubling of outflows down the White Nile which was not reflected in the flows of the Blue Nile.

Double-mass curves can also be used to compare rainfall and river flow records, and can be useful in a number of cases to confirm the validity of records. However, where there is a discontinuity of rainfall and thus runoff over a period of years, there may be an apparent change in the double-mass curve. This is illustrated by the records of the Kagera which flows into Lake Victoria as its largest tributary. The Kagera basin was subject to an increase in rainfall after 1961, which also affected the rest of the lake basin; however, the runoff increased more than the rainfall in relative terms, and therefore the cumulative comparison of the two factors showed a distinct change of gradient (Fig. 7.10). This is of course due to the fact that the difference between rainfall and runoff is due to evaporation, so that runoff, as the residual, is extremely sensitive to changes in rainfall. If the rainfall over a basin is 1600 mm and the evaporation 1500 mm, the runoff will be 100 mm; if the rainfall increases by 10% without any change in evaporation, the runoff will increase to 260 mm, and the double-mass curve will show an apparent discontinuity.

One example where a comparison between rainfall and runoff provided the date of a discontinuity in level measurement, which was reflected in the flows of the Tongariro at Turangi in New Zealand, has already been described in Chapter 2. An example where such a comparison provided an assurance that flow records were valid was met

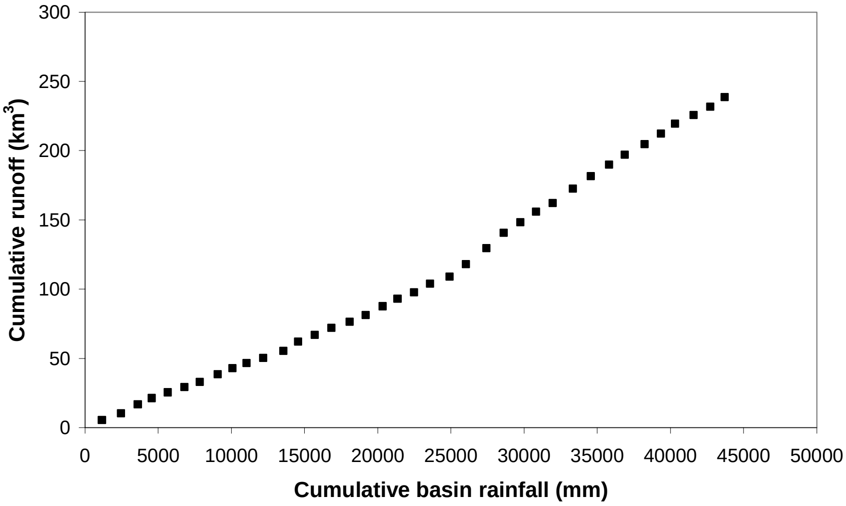

Fig. 7.10 *Kagera basin: cumulative rainfall and runoff, 1940–1977.*

in a similar climate on the fringe of the Andes in Argentinian Patagonia. Here the inflows to a hydroelectric station after the construction of the dam were lower than in the previous period of recorded flows. However, double-mass comparisons of flow records with independent gauging sites showed that the two sets of records were consistent (Fig. 7.11), but also comparisons with long-term rainfall records confirmed that there had been a significant decrease in the regional water balance. This comparison was made easier by the fact that the construction of the reservoir would not in itself have affected the runoff; an examination of the basin showed that it was full of glacial lakes surrounded by dense rain forest (Plate 7.2), where evaporation including interception could approximate to open water evaporation, so that the reservoir would not have resulted in increased basin evaporation. These examples underline the fact that careful interpretation and incorporation of local knowledge are vital when using analytical techniques to understand hydrological regimes.

Comparisons of rainfall and runoff form a common means of extending flow records using long-term rainfall records in the area. The process of correlation which forms part of such analysis (see Chapter 9) will often provide an opportunity of testing the consistency of flow records. This is particularly useful in humid areas, where the basin evaporation loss is likely to be constant from year to year.

Regional comparisons can also draw attention to stations where flow records appear to be suspect, and where attention to rating curves should therefore be concentrated. An initial appraisal of the water balance of a number of sites in Sri Lanka, where a humid climate over most of the project area made comparison simple, quickly revealed (see Fig. 8.2) that certain stations were inconsistent with the others in the region.

Cross-correlation matrices for groups of stations can also identify those stations which are inconsistent with other stations; this may be because the regimes of some basins are different from others, or because the records are not compatible. Knowledge of the hydrology of the area should reveal which of these hypotheses is the more likely.

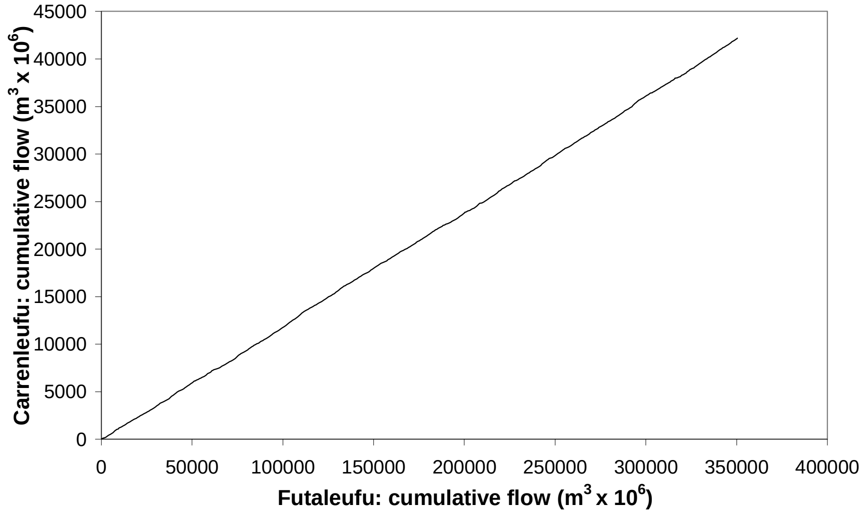

***Fig. 7.11** Comparison of cumulative flows of Futaleufu and Carrenleufu, Patagonia, 1954–1994.*

***Plate 7.2** Rainforest in Futaleufu basin, Patagonia.*

IMPORTANCE OF QUALITY APPRAISAL

It is essential that such checks of record quality should be carried out before time-consuming analyses of the river flow records of a region are embarked upon. Time spent on visiting key stations and examining gauging records and rating curves is seldom wasted, and can prevent a large amount of time being spent subsequently on investigating why certain sites and rivers behave differently from other sites in the region. During the initial investigation of records for the *Flood Studies Report* (NERC, 1975), visits were made to all gauging stations with representatives of the gauging authorities. Assessment of the high flow rating curves and other factors led to quality classification of each flood record.

Examples of flow gauging appraisal

One example where the accuracy of flow records dominated a project review was the Lesotho Highlands Water Project. This project was designed to divert water from the upper tributaries of the Senqu in Lesotho, where the mountainous headwaters provided significant runoff, towards the industrial complex of the Transvaal in South Africa. At the same time hydroelectric power could be generated at the dams through which diversion would occur. The economic value of the project depended on precise estimates of the flows available at key locations, but various estimates of these flows differed significantly. The accuracy of level records, of discharge measurements and rating curves were all examined, and the resulting flow records were subjected to tests of double-mass comparison, water balance derivation and statistical testing. The mean annual precipitation over the project area was closely related to topography, and varied greatly from 600 to 1600 mm as a result of the range of elevation. Consequently the water balance testing was difficult, so that the examination of individual gauging stations gained added importance. Once this quality control had been carried out, it was possible to extend the flow records using long-term basin rainfall records and a deterministic model to provide consistent flow series for system analysis.

The value of the inspection of gauging stations and of gauging methods may be unexpected. During a review of one hydroelectric project in central India, inspection showed that the flow records were based on gauging methods which could best be described as suitable for reconnaissance, though fortunately water balance checks showed that the results were not unreasonable. As part of the review of a second hydroelectric project, the first step was a visit to the key gauging station (Plate 7.1); an invitation to look at a nearby site on an upstream tributary was accepted. This turned out to be a former small irrigation offtake (Plate 7.3) which was the instrument of rapid river capture. The site had been gauged regularly over some 14 years; during this period the flow out of the main river into the channel (Fig. 7.12) had increased from 12% to 24% of the annual flow. Although the comparison was complicated by the fact that the percentage of outflow was higher in years of high flows, the outflow to an adjacent basin had doubled in less than 15 years. Thus a significant proportion of the resource was being lost to river capture at a remarkable rate. This information was taken into account in subsequent planning. It is essential to listen carefully to those with local knowledge and to follow up hints of unusual situations.

Plate 7.3 *Central India: Jawra nullah looking upstream to River Indravati offtake.*

Fig. 7.12 *Central India: Jawra nullah outflow as % of downstream Indravati flow.*

CONCLUSION

The network of gauging stations provides the primary evidence of the water resources of a country. The provision of accurate rating curves should ensure the validity of these records, and therefore the maintenance of a programme of discharge measurements and the monitoring of rating curves is vital to the knowledge and development of a country's water resources. Once the general validity of rating curves and flow records has been established, it is possible to analyse the hydrological behaviour of a region with some confidence. It is therefore most unfortunate that there has been a worldwide reduction in hydrological measurements at a time when the adequacy and stability of water resources come under increased scrutiny. The number of river gauging stations has been decreasing in many countries, and the number of discharge measurements being made to support these stations has fallen even more dramatically. This has occurred at a time when the availability of computer programs for routine analysis of gaugings should have made it easier for local hydrologists to improve the quality of flow records. It is equally important for the quality of records that the local gauging authorities should have the opportunity and resources to carry out water balance and other analyses on the flow records they hold.