2 NETWORK DESIGN AND APPRAISAL

Because hydrological networks, whether concerned with rainfall, evaporation or river flow, have much in common in the way they should be designed and analysed, it is convenient to discuss them in this chapter rather than in separate chapters dealing with specific aspects of the hydrological cycle.

It should be emphasized that advice on hydrological data collection and siting of instruments is not included in this book. These topics are discussed in many basic texts, and sound practical advice is provided by WMO (1994) and Gunston (1998).

SAMPLING OF VARIATIONS IN TIME AND SPACE

Guidelines exist for the numbers of hydrological gauges required in an area or basin, expressed as densities, or numbers of raingauges and river flow gauges per 100 km^2. However, Moss (1982) argues that general criteria cannot be specified for the design of a network, and that these should vary between different processes, geographical contexts, and levels of water resources development. Few studies have compared the values of networks with their cost, and in practice network development grows from a minimum network in the light of correlations obtained in use.

The estimation of the water resources available at a given site on a river, or over an area containing a number of rivers, depends on the sampling and subsequent analysis of flow variations over both time and space. Thus hydrological networks should be designed to be adequate to monitor variations in time and also differences over an area. In developing countries the planning of national networks must be based on the assumption that long-term records will not be available at every project site. The networks should be planned in accordance with the location of likely water resources demands, but should also cater for the unexpected development. The location of urban demand can be predicted from population densities and trends, but the future locations of industrial demand may require fuller economic analysis. The assessment of hydroelectric potential will require a more complete monitoring of the river network, and may need to be based on a preliminary assessment of potential sites. In countries where irrigation forms an important sector of the economy, the scale of demand may require monitoring of all major rivers; however, in more arid countries where irrigation is vital, the number of significant rivers may be limited. This is the case in the Sudan, where the key sites depend strongly on the river network. The criteria for gauge density can benefit from statistical analysis; the cross-correlations obtained within the initial network will indicate the number of gauges required, consistent with the economic development of the country.

Type of variation

Between rainfall, evaporation and river flow, variations in time may most easily be detected in rainfall and river flows. Although rainfall stations are easier to operate, a single record may not fully represent the variability of available water over a basin because of measurement errors, random incidence and altitude effects. It is usually necessary to combine a number of records to monitor variations over time, whether over seasonal, annual or longer time scales.

On the other hand, river flow measurements are more complex and expensive to initiate and maintain, as a gauging station must be constructed and monitored, with usually the need to calibrate the station by regular measurements. However, because river flows are the residual of the water balance process, they are more sensitive to variations in water availability and therefore a series of flow records will make it relatively easy to detect changes over the years. Indeed, the outflows from Lake Victoria in East Africa are so sensitive to relatively small changes in rainfall that some hydrologists have not accepted the validity of the flow records and have put forward a variety of alternative explanations.

Moreover, river flows are the main subject of most water resources studies, so that variations are more directly relevant to the long-term yield of projects and direct measurement provides the most accurate estimate. The advantage of rainfall networks is that their length of record is in general longer than those of river flow stations. However, once estimates of areal rainfall have been derived by combining a number of records, the time series need to be related to river flows by some form of rainfall–runoff model.

Variations in time

The geographical distribution of gauging stations is not the only consideration. The sampling of variations of river flows with time over a region has become more important with increased knowledge of the extent of periodic droughts or fluctuation of supply over wide parts of Africa, for example. It is increasingly understood that the climate and water resources of large regions can vary between successive decades or longer periods. Whether these variations are random, cyclical or result from climate change, it is important to monitor them and thus to assess water resources potential over as long a period as possible. It is therefore extremely important for rainfall and river flow stations to maintain complete and consistent measurements at a number of core stations which can be used to sample variations with time. These basic stations can be used to extend shorter records by correlation to estimate time variations at the short-term stations; therefore the correlation matrix between stations is an important indication of the consistency of rainfall and river flow and thus the density of stations required.

Although measurements or estimates of potential evaporation can be made at a number of sites, it is generally accepted that evaporation varies much less from year to year and from site to site than other hydrological variables. Although seasonal fluctuations are significant, evaporation appears to be much more conservative than other variables and rather fewer observations are needed to sample the variations.

Variations in space

Estimates of spatial variations of water resources are particularly important where the resources of an area are being assessed, or where there is a choice between different project locations. The primary criterion for the viability of a project is usually the mean and variability of river flows at or near the site. Therefore, the hydrological network should be designed to sample the variation of runoff over a region which may exhibit differences in climate and geology, and thus enable the hydrologist to estimate the water available at a number of ungauged sites within the region.

Because a dense network of long-term river flow stations would be expensive to establish and to maintain, it is preferable to use a network of rainfall stations and flow stations to monitor the variation of water resources over a region. Indeed, it could be argued that it is easier to compare rainfall records over an area in order to deduce regional trends, because the records are not confused by variations of basin area, geology, and thus runoff coefficient, which complicate comparisons of flow records. It is essential to support the spatial distribution of runoff with that of rainfall. Although rainfall distribution is subject to influences like distance from the moisture source and the orographic effects of topography, the rainfall depths are more easily comparable than runoff depths. The spatial distribution of rainfall can be more easily mapped than that of runoff, and it is common to describe this by means of an isohyetal map, or preferably to map net rainfall, and then to relate runoff depth to this map. It follows that a combination of long-term and short-term stations is necessary to define the spatial distribution of rainfall.

In fact a combination of the records of rainfall, evaporation and runoff is also necessary to understand the water balance of an area, and therefore all three hydrological components need to be monitored by a network of measuring stations. The links between these components may be treated as simple comparisons, or compared by statistical comparisons or by conceptual modelling, but at this stage we are considering the planning, operation and monitoring of the different networks.

QUALITY APPRAISAL

If hydrological records are to be used in assessing available water resources over a region, it is of course necessary that they should be as accurate as possible, but it is probably more important that they should be consistent, both over time and from one site to another. Recent short-term flow records at a project site are often extended to cover a longer and more critical period, using long-term rainfall or flow records in the vicinity. Bias will be introduced if the recent records at the long-term sites have been measured or processed differently from the earlier records, even if the recent records are in fact more accurate as a result of the change. It is therefore essential that reviews of hydrological records should be applied consistently over the whole period.

The appraisal of rainfall and evaporation records must start with the investigation of sites and measuring techniques. These may change over the years even if the record is published as a continuous series. However, changes are usually recorded in station files or annual reports and may require adjustments to the basic series. Double-mass or cumulative comparisons over time between single stations and either adjacent stations or groups of stations can reveal the dates and directions of significant changes which require detailed investigation.

Accuracy and precision

An example of the way in which consistent records may be more important than precision is illustrated by the problem of the water balance of Lake Victoria. The coverage of raingauges around the lake and its basin has improved considerably over the years, especially since the establishment of gauges on islands within the lake after 1967. However, the contribution of the heavy rainfall of 1961–1964, which led to a significant rise in the lake, was more easily reproduced (Piper *et al.*, 1986) by using the small number of long-term gauges around the lake, after adjusting for site changes, than by using the whole increasing but non-homogeneous network. This problem is discussed in more detail in Chapter 8.

RATING CURVES

River flow stations are more complex to maintain as a homogeneous record, even though standard measurement techniques are used. At sites where river level records have been collected over a long period, the quality of the derived flow records is likely to depend on the use of discharge measurements to derive rating curves, or curves relating water level and discharge, at the site. The factors affecting the quality of flow records include the range of gaugings compared with the range of level and flows experienced at the site, the methods used over the years to derive successive rating curves, and the stability of the site itself in terms of control. For example, at gauging stations with sand beds in Botswana, the river bed may change shape dramatically after each significant flow event.

The overall quality and consistency of the record can be assessed by using all, or samples of, the historical discharge measurements to derive rating curves by consistent computer-based methods for the whole period of records, divided if necessary into relatively stable periods. The advantage of treating all the gaugings at a site in one comparison is that a more consistent set of rating curves is likely to result. In any single year of gaugings, it is not likely that sufficient high floods will have been measured to define the rating curve precisely for high flows; the upper part of the calibration is normally defined by channel control which varies little from year to year, and thus gaugings from a longer period can be combined to derive a high flow rating in a form compatible with the geometry of the site. For example, in a study of about 40 years' flow on the Nile below Lake Kyoga in Uganda, it was evident that in individual years the range of levels and flows was inadequate to derive a precise rating, as the flows were highly damped by storage in Lake Victoria and Lake Kyoga. However, analysis of all gaugings over a period allowed a family of curves to be derived, which allowed for changes in control level from year to year. In addition to minor annual changes in control, there was a major shift in the rating curve after the rise in Lake Victoria level and outflow after 1961; both these changes could be incorporated in the rating curves (see Fig. 7.4).

In the initial stages of the investigations leading to the *Floods Studies Report* (NERC, 1975) for the British Isles, a countrywide investigation was made of all the gauges with at least five years of record; the rating curves were compared with high flow gaugings and consistent curves were derived, either for the whole period or for shorter periods. In addition to ratings which were used to derive flood flows from peak levels, an assessment of the quality of each flood record was made on the basis of the precision and stability of these ratings and other factors.

The use of measurements from single years may produce high flow ratings based on extrapolation which are inconsistent from year to year, and in some countries may determine a high proportion of the annual runoff. On the other hand, low flow ratings

Fig. 2.1 *Rating changes for Bahr el Jebel at Mongalla; flow corresponding to the gauge level of 12.25 m.*

at sites with mobile beds are likely to change from flood to flood; the simultaneous study of a number of years of measurements should make it possible to date changes and to monitor progressive movements of bed controls. An example of such progressive changes is illustrated in Fig. 2.1, where successive discharges of the Bahr el Jebel at Mongalla in the southern Sudan, corresponding to a gauge level of 12.25 m, reveal changes of rating which are consistent with measured bed levels.

Assessing rating curves

The direct assessment of ratings can be supported by indirect techniques like double-mass analysis and inter-station correlation. The double-mass comparison of flow records at upstream and downstream sites on the same river, or draining adjacent basins, should reveal a linear relation with minor variations, and the dates of any changes of slope should draw attention to the dates for detailed investigation of critical non-homogeneity.

An example is given in Fig. 2.2. The cumulative annual flows of the Bahr el Jebel at Mongalla are compared with outflows from Lake Victoria at Jinja, where the natural and stable rating curve at the Ripon Falls, linking lake level and outflow, has been maintained since the construction of the Owen Falls dam at the outfall. There are other tributaries between the two sites, which are about 900 km apart, but the relationship between the two sites has been reasonably stable; the flows at Mongalla may have been over-estimated in the early years before regular discharge measurements began. Inter-station correlations of annual flows should reveal stations to which particular attention should be paid. Even simple comparisons of rainfall and runoff depth over a region can identify stations whose records merit particular attention; such a comparison in the central mountains of Sri Lanka (Fig. 8.2) showed that most stations were reasonable but that at least one was an outlier in terms of water balance.

If these or other analyses show that there are likely to have been faults in the original rating curves, these can be improved retrospectively by assessing the whole

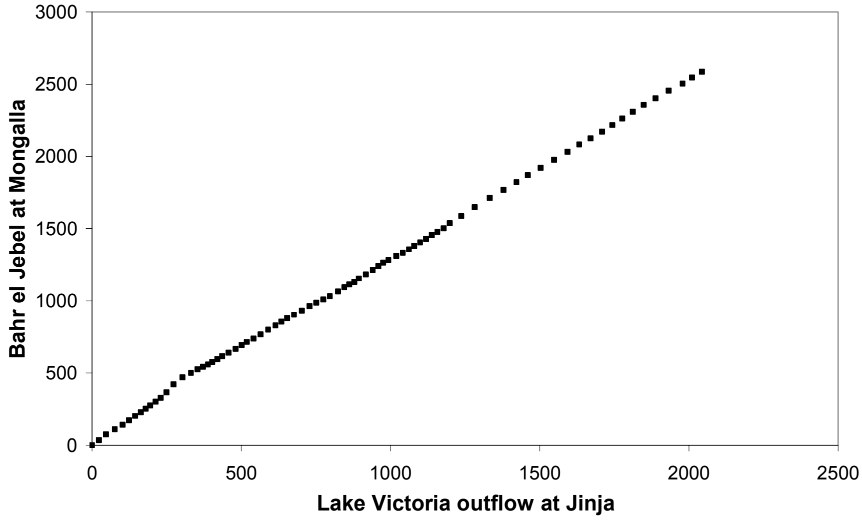

***Fig. 2.2** Double mass curve: cumulative annual flows (km^3) of the Bahr el Jebel at Mongalla vs outflows from Lake Victoria at Jinja, 1905–1982.*

period of discharge measurements, provided that the sites are either reasonably stable or progressive in their changes.

COMPARISON OF RAINFALL AND RUNOFF

Comparisons of river flow series with the corresponding series of basin rainfall or preferably net rainfall can also be used to monitor or improve flow record quality. For example, a single abrupt change in the relation between stations or between rainfall and runoff might be explained by a simple unrecorded change of gauge zero. During an investigation of hydroelectric potential in the volcanic area of the North Island of New Zealand (Sutcliffe & Rangeley, 1960a), the only river gauge was that of the Tongariro at Turangi, which had been used for subjective forecasting for hydroelectric power generation. It was known that the gauge zero had been changed by a misplacement of the float connection, but the precise date was not known. Cumulative differences between basin rainfall and runoff depth were used to derive a time series of apparent basin loss (Fig. 2.3), and the date of the change, June 1952, was revealed by this simple comparison and the flow data adjusted before analysis.

USE OF RECORD NETWORK IN TIME AND SPACE

Once the networks of rainfall and runoff records have been appraised, and adjusted where necessary, they may be used to extend short-term flow records by correlation with long-term flow or rainfall records. Alternatively, a comparison of flow records for a standard period with rainfall distribution over the region can lead to an assessment of the water resources of an area. As will be seen in later chapters, these extensions and regional studies are much easier to carry out in humid rather than arid climates.

At this stage it is appropriate to discuss the influence of their use on the number of gauges required. The numbers of rainfall and flow gauges required for water resources assessment cannot be linked simply to area, though tables of this type may be a useful

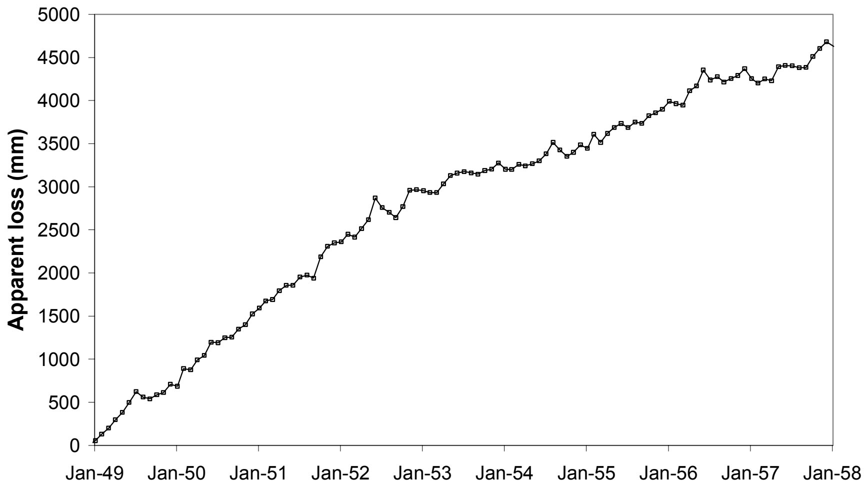

Fig. 2.3 *River Tongariro at Turangi: cumulative apparent basin loss (1949–1957) (after Sutcliffe & Lazenby, 1990).*

preliminary indication. Factors to be taken into account include topography, population density and the degree of economic development, and the variability over the region of climate and geology. For example, in arid regions with few major rivers, e.g. Sudan or Botswana, flows may be measured at key sites without a high density of gauges. The centres of population and likely water resources requirements must be taken into account in network planning, but higher gauge densities will be required if the areal variations of rainfall and geology make runoff from ungauged basins difficult to predict. Correlation analyses on basin characteristics can be used to assess this predictability and indicate the density required, in the same way as correlation between gauges can be used to assess the period of extended record needed to estimate mean runoff with a given precision. However, there must in most cases be a compromise between the optimal network judged on hydrological criteria and the resources which are allocated by the authorities of a developing country. The gap between these may be reduced by the understanding of the importance of records in developing water resources, but the role of the hydrologist must be to provide more effective ways of collecting, appraising and processing data, and using them in resources assessment.

CONCLUSION

Whatever the climate and water balance regime of the region, and the scale of the water demand in relation to water availability, the need for hydrological records remains. The requirement for precise water resources assessment is a network of reasonably accurate long-term rainfall and river flow records which can be used to sample variability of river flows in both time and space. For this purpose consistent records are of greater importance than absolute precision, and a careful appraisal of the consistency of both rainfall and river flow records is an essential preliminary to reliable water resources assessment.