

5 SOIL MOISTURE STORAGE

Soil moisture storage has a physically important role in the hydrological cycle, and it has a vital influence on the amount of rainfall which becomes runoff and groundwater recharge. The problems of measuring soil moisture volume and the equivalent depth of water contained in the soil reservoir have led to various indirect methods of measurement. The role of soil moisture storage in maintaining vegetation or crop growth during dry periods is important and it plays a key part in controlling runoff in a monsoon climate; soil moisture investigations played an important part in an investigation of basin water balance and groundwater recharge in central India, which is described here and later. The role of soil moisture state in converting storm magnitude to flood volume is illustrated by evidence drawn from British studies.

PHYSICAL CHARACTERISTICS OF SOIL MOISTURE STORAGE

Soil moisture storage is a key factor in the water balance of a basin, as it provides a short-term reservoir maintaining the continuous outputs to basin evaporation and transpiration from the discontinuous rainfall inputs. The volume, or equivalent depth, of soil moisture storage between the ground surface and the lower limit of the rooting zone is an important indicator of the state of the basin at any given time. In simple terms, as illustrated in Fig. 5.1, soil moisture varies between field capacity, i.e. the maximum quantity of water which can be held in the soil against gravity, and wilting point, below which vegetation cannot extract further water. Both water content limits may be expressed as percentages of the total soil volume; the water content held at these two limits depends largely on soil characteristics. The total water volume within a soil profile which is stored and available to vegetation between these two limits also depends on the rooting depth of the specific vegetation; this volume is known as the root constant. The soil moisture deficit, or the depth of water required at a given time to bring the soil moisture reservoir to field capacity, largely controls the runoff response of the basin to a given depth of rainfall. In general, the rainfall infiltrates into the soil layer and brings the storage to field capacity before significant runoff occurs, though surface runoff can occur over short periods if the intensity of the storm exceeds the maximum infiltration rate of the soil surface. Any rainfall input when the soil is at field capacity soon drains, i.e. forms recharge if the sub-surface is permeable, or, on impermeable strata forms runoff to streams.

Thus the soil moisture state to a large extent determines how much of the rainfall input is immediately released as river flow. This is often expressed as a runoff coefficient, or the fraction of rainfall which runs off, though this is not a physically accurate concept; runoff is more truly a residual of the rainfall–recharge process. Soil moisture storage may be measured in various ways, or may be estimated by the indirect method of soil moisture modelling. Examples of both soil moisture measurement and modelling are described.

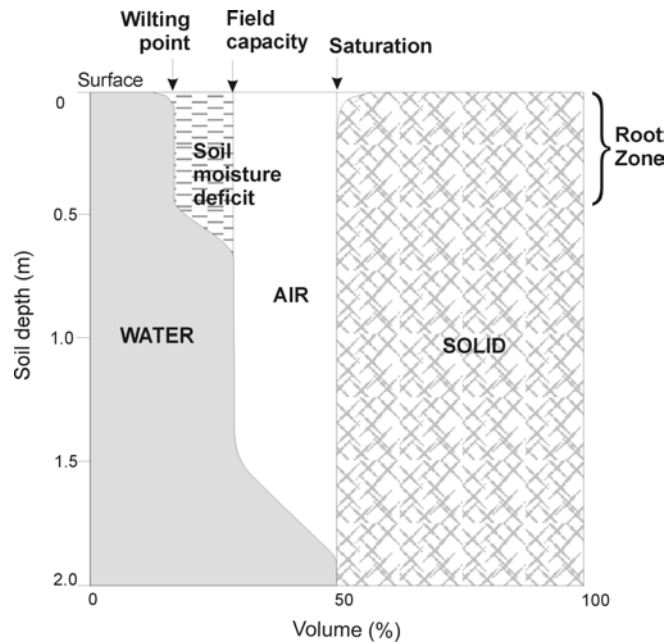


Fig. 5.1 Soil moisture: field capacity, wilting point, soil moisture deficit.

SOIL MOISTURE MEASUREMENT

Early observations of soil characteristics in wet conditions were included in the flood plain survey of the Bahr el Jebel or White Nile in the southern Sudan during 1951–1952. Soil pits were dug to a depth of 1.8 m at kilometre intervals along cross-sections. Samples were collected to supplement visual observations and notes of the soil characteristics, but in these field conditions soil moisture content could only be estimated by observing the depth at which standing water occurred in the pits. Chemical and mechanical characteristics of soil samples at 30 cm vertical intervals were derived by analysis, and a soil map (Jonglei Investigation Team, 1954) revealed the pattern of soil deposition across the flood plain, with the coarser material deposited near the river and finer material carried further.

In order to measure soil moisture directly networks of sites would need to be sampled regularly, by digging or soil augering, with the moisture content of samples determined by drying in ovens and the weight loss measured (ISO, 1993, 1997a). In the absence of such facilities, a subjective test of soil moisture was devised by the soil specialist of the team; samples were thrown up to the office ceiling and observed whether they stuck or fell! Various more practical devices, including tensiometers and electric resistance gypsum blocks, were developed to measure soil moisture *in situ*, and these were used in basin experiments, e.g. Pereira, 1962. Gardner *et al.* (2001) provide an overview of current soil water content measurement methods.

Neutron probe

The regular large-scale *in situ* measurement of soil moisture was made practicable when the neutron probe was developed for the purpose (Bell & McCulloch, 1966; Bell,

1976; Gardner *et al.*, 2001). This is used to measure the vertical moisture content profile by lowering a probe with a fast neutron source down an aluminium tube and counting the back-scattering of neutrons near the source; this reflects the moisture content of a sphere about 50 cm in diameter around the source and can be calibrated using local soil samples.

This technique was used to monitor the moisture content at a network of sites in the experimental basins of the Institute of Hydrology on the Ray at Grendon Underwood in central England and the upper Severn and Wye basins at Plynlimon in Wales. The Ray experimental basin was set up to monitor the water balance of the basin in order to develop modelling techniques (Nash, 1960; Mandeville *et al.*, 1970), while the Wye and Severn basins were monitored to observe the differences in behaviour of adjacent basins with contrasting land cover of forest and grass (Kirby *et al.*, 1991). It was therefore important to measure or estimate the soil moisture at regular intervals at the same time as other components of the water balance were measured. After a reasonable set of soil moisture data had been measured, it was found possible to calibrate a soil moisture deficit model for the Plynlimon basins which gave reasonable estimates of soil moisture conditions.

Betwa study, central India

An investigation of groundwater conditions and recharge in a hard-rock basin in the Betwa basin in central India was undertaken from 1976 to 1980. The study was a joint research project between the Indian Central Groundwater Board and the British Geological Survey, and the Institute of Hydrology was responsible for the surface water and soil moisture aspects of the study.

The climate of this basin is highly seasonal, with rainfall concentrated in the monsoon between June and September, with over 90% of the annual total occurring in this period. An analysis of the water balance of the basin was carried out at an initial stage of the study (Sutcliffe *et al.*, 1981). Rainfall records for the whole Betwa basin were combined, as described in Chapter 3, to give a monthly series for the years 1926–1975. Meteorological records were used to estimate open water evaporation and potential transpiration by the Penman method. Average monthly totals of rainfall and potential transpiration are compared in Fig. 5.2 to illustrate the seasonal regime.

The annual water balance may be simplified by considering the seasonal cycle as a single period of water surplus during the monsoon and a single period of deficit during the rest of the year. During the monsoon period, monthly rainfall exceeds potential evaporation for two to four successive months, while potential transpiration exceeds rainfall during the rest of the year. The period of soil moisture recharge is indicated in Fig. 5.2, and is followed by a period of water surplus or runoff; after the monsoon ends soil moisture is used for transpiration until the soil moisture storage is depleted. This is followed by a period of water deficit after the storage has been used; the soil moisture recharge equals the subsequent soil moisture use. In the Betwa basin, the soil moisture storage is full at the end of the monsoon, and always reaches wilting point before the end of the dry season; thus the annual recharge brings the storage from wilting point to field capacity throughout the root zone. This difference is the “root constant”. The soil moisture recharge should be reasonably uniform from year to year in the absence of land-use change and may be considered as a first charge on the net rainfall, the surplus

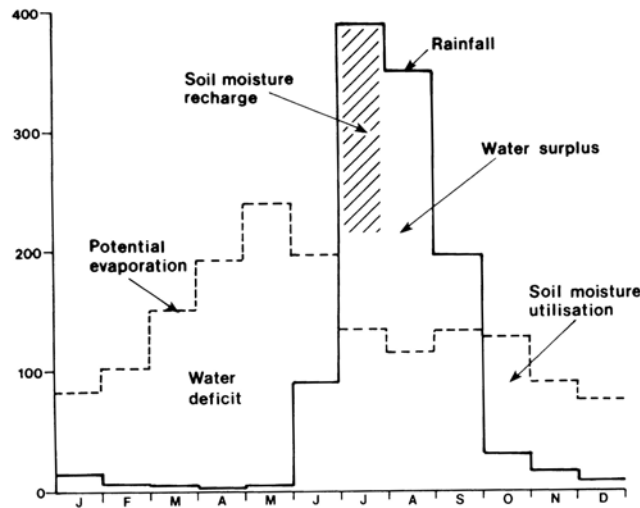


Fig. 5.2 Betwa basin: net rainfall, soil moisture recharge and runoff, mm (after Sutcliffe *et al.*, 1981).

of rainfall over evaporation. In this seasonal climate it is possible to assume that basin evaporation continues at the potential transpiration rate until the soil moisture deficit reaches wilting point. The root constant, or the available soil moisture reservoir, can then be estimated by comparing annual net rainfall with annual runoff.

This net rainfall, or gross seasonal rainfall, was calculated by subtracting monthly potential transpiration from monthly rainfall, and by adding the surplus monthly figures to give the net rainfall for the year. If one accepts that soil moisture recharge is a fixed charge on the net rainfall, it is possible to deduce the annual recharge by comparing seasonal net rainfall with annual runoff. The intercept on the horizontal axis provides an estimate of the annual soil moisture recharge. In the case of the Betwa basin of 20 600 km², annual total inflows to reservoirs at the lower end of the basin over the same 50-year period were converted to runoff depths and compared with net rainfall in Fig. 5.3. The soil moisture recharge is shown to be just below 200 mm, while the mean runoff is 350 mm over the basin. Gross and net rainfall may be compared to runoff in mm to illustrate the increasing variability of the water balance.

It was evident during this early part of the study that the soil moisture storage formed a crucial part in the water balance of the whole basin. Apart from maintaining crop growth after the monsoon period, it was also a key to the conversion of rainfall to runoff. In fact the measured values of soil moisture in part of the Betwa basin may be used to monitor the partition of rainfall during the monsoon season between transpiration, soil moisture recharge, groundwater recharge and finally runoff, as described in Chapter 8. The groundwater recharge was found to be small and equal to the dry season river baseflow.

Soil moisture network

Once the key role of the soil moisture storage was recognised, a network of soil moisture observation points was established (Hodnett & Bell, 1986) in the very flat plain across the centre of the basin (Plate 5.1). Deccan Trap basalts are found over

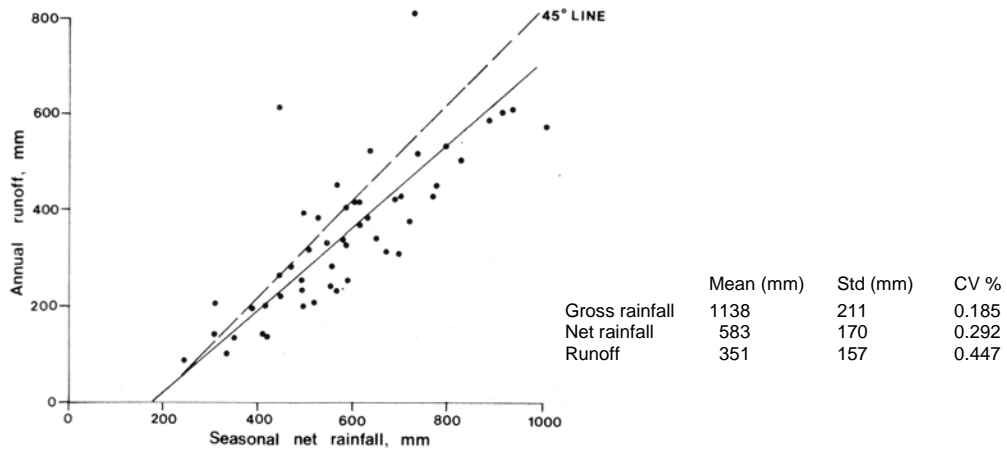


Fig. 5.3 Betwa basin: seasonal net rainfall and runoff (mm), and annual totals (after Sutcliffe et al., 1981).



Plate 5.1 Neutron probe soil moisture measurement in the Nion basin.

most of the basin infilling the pre-existing landscape of Vindhyan sandstones. Over the centre of the basin, the soils developed from the basalts are dark swelling silty clays, known locally as black cotton soils. On the fringe of the plain, the cotton soils are from 0.5 to 2.0 m deep, and directly overlie the weathered basalt. Over the central part of the basin, the black cotton soils are about 2 m deep and merge down into the silty yellow clay from which they developed. The combined depth of the black cotton soil and

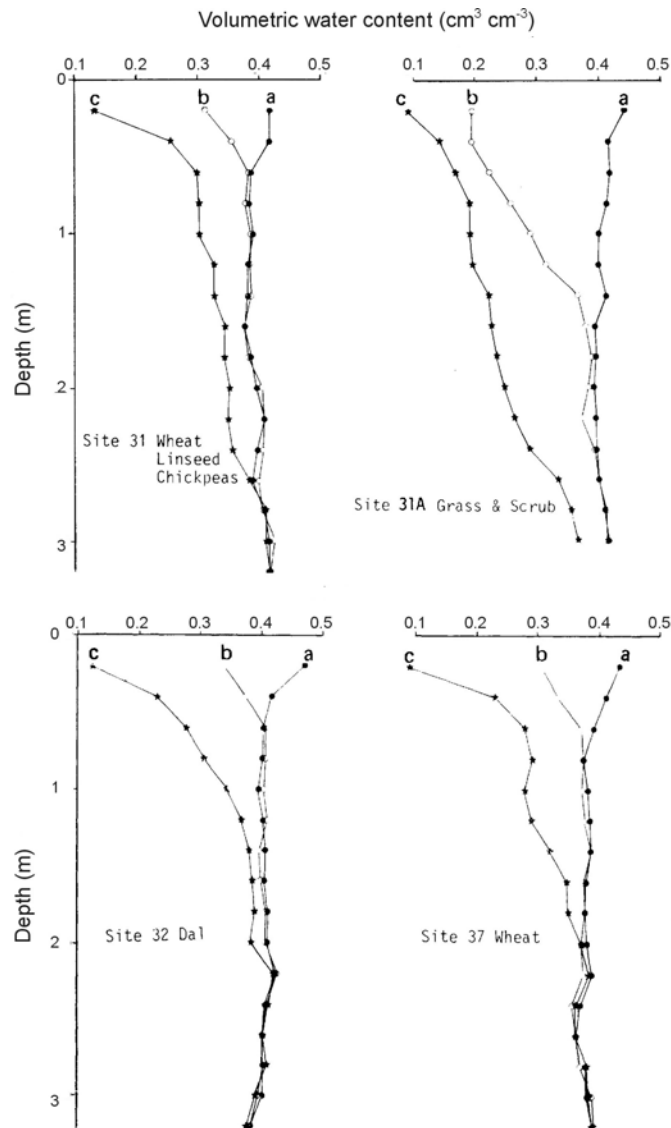


Fig 5.4 Betwa basin: soil moisture profiles (from Hodnett & Bell, 1986).

yellow clay overlying the weathered basalt varies from 5 m to over 20 m. The soils are remarkably uniform and are stone-free; they shrink and crack extensively during the dry season. About 85% of the area was cultivated, with wheat, pulses and linseed the main crops grown in the post-monsoon season. The local mean annual rainfall of about 1200 mm is slightly higher than the basin average.

At 24 sites along a 120-km transect across the basin, soil moisture was measured to sample the different soil depths and typical crop types of the area. Neutron probes were used in tubes which were up to 3.2 m deep, and measurements were made at weekly intervals over a complete year, starting at the end of the wet season. The moisture content was monitored at each site at vertical intervals of 0.2 m and profiles

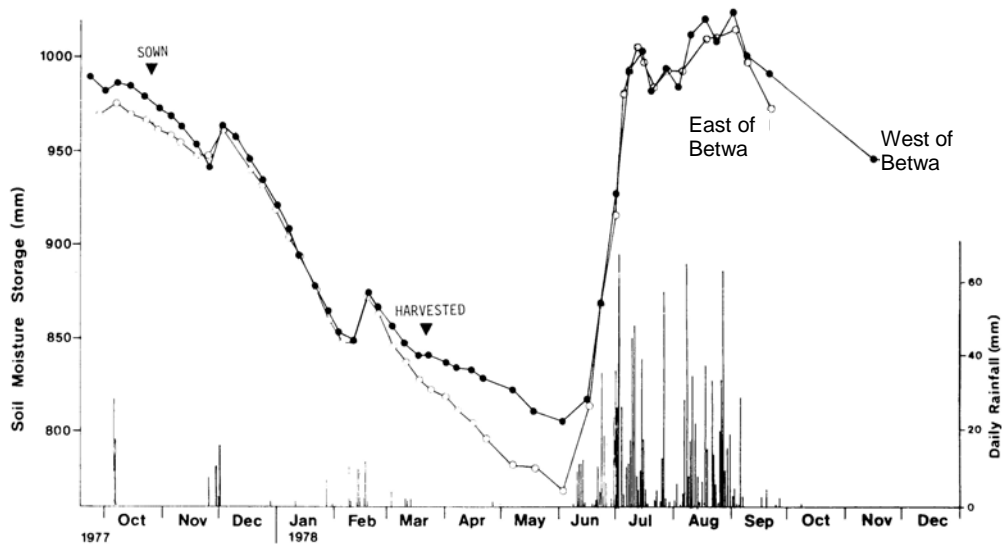


Fig. 5.5 Betwa basin: soil moisture storage and daily rainfall, September 1977–December 1978 (from Hodnett & Bell, 1986).

were plotted to show the total moisture content. The successive drying of the soil profile could be observed during the course of the post-monsoon season when the crop water supply was derived entirely from the soil moisture storage. Examples of three states are illustrated in Fig. 5.4 for four sites in the area of deep soils with: (a) the wettest conditions, (b) those when the water table had fallen below the measured profile, and (c) the driest conditions shown at three cropped sites with one under grass and scrub (Hodnett & Bell, 1986).

The wet season profiles at different sites in the region of deep soils were extremely similar, with very little variation in total moisture content. Under cropped sites, the soil moisture content was reduced during the season of crop growth after the monsoon over a depth of about 2 m, and the mean decrease in moisture content was 230 mm. The depletion below the site with a permanent cover of scrub and grass was 550 mm and extended below the maximum depth of measurement (3 m). This detailed measurement was successful in monitoring the soil moisture reservoir which maintains annual crop growth after the monsoon in this region of highly seasonal rainfall supply. The soil moisture storage from September 1977 to December 1978, including the crop period from October 1977 to March 1978, is compared with daily rainfall in Fig. 5.5.

Supplementary measurements of soil moisture content by neutron probe, and of soil water potential by tensiometers, were carried out in 1978 and 1979. Profiles of soil moisture content and potential, together with estimates of hydraulic conductivity derived from gradients of hydraulic potential, enabled the downward flux to be estimated.

APPLICATION TO OTHER AREAS

The simple approach to seasonal water balance derived from the Betwa basin is also appropriate to areas with similar climate, especially seasonal rainfall distribution. The approach was applied (Sutcliffe & Piper, 1986) to the problem of assessing runoff in

Guinea, where the West African rainfall is highly seasonal, with rainfall between June and September but rather higher in total than in the Betwa basin. The annual rainfall varies from over 4000 mm along parts of the coast to about 1300 mm in the northeast of the country where the upper Niger flows into Mali. Much of the basin is covered with deciduous woodland, which suggests that similar processes occur to the Betwa basin, and the same assumption could be made that a single wet season is followed by a single dry season during which the soil moisture store is drawn down to wilting point. Estimates of annual river flows were required for reviews of potential hydroelectric power resources at a number of sites over the country, and long-term rainfall records were available for analysis at a number of sites, supported by flow records for different periods.

Monthly rainfall series at all stations were converted to net rainfall series in the same way as in the Betwa example, by subtracting potential transpiration and summing the seasonal surplus. Net rainfall series for individual basins were deduced from the available rainfall stations, and annual totals of net rainfall were compared with measured annual river flows. As Fig. 5.6 shows, this comparison was reasonable where an adequate number of rainfall stations was available; the relationship has a slope of about 45° and an intercept of about 300 mm. Another comparison (Fig. 8.23) showed that the mean annual runoff depth at all stations was related to the net rainfall of their basins with a loss, corresponding to an annual soil moisture recharge, of about 300 mm. This suggested not only that annual runoff series at stations with short periods of record could simply be extended by means of annual net rainfall series by subtracting the same annual loss, but also that river flows at ungauged sites could be deduced from mean basin net rainfall in the same way.

Isohyetal maps of gross and net rainfall, Fig. 5.7(a) and (b), were compiled from the series for individual stations, and mean annual net rainfall for basins with reasonably long flow records was compared with mean runoff. The mean runoff showed good correlation with mean net basin rainfall, and corresponded with mean

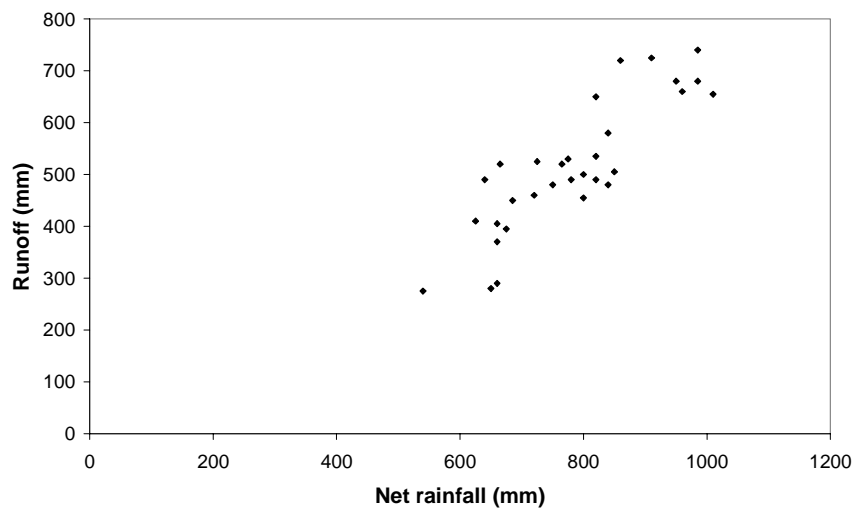


Fig. 5.6 Guinea: Niger at Tiguibery, annual net rainfall and runoff (after Sutcliffe & Piper, 1986).

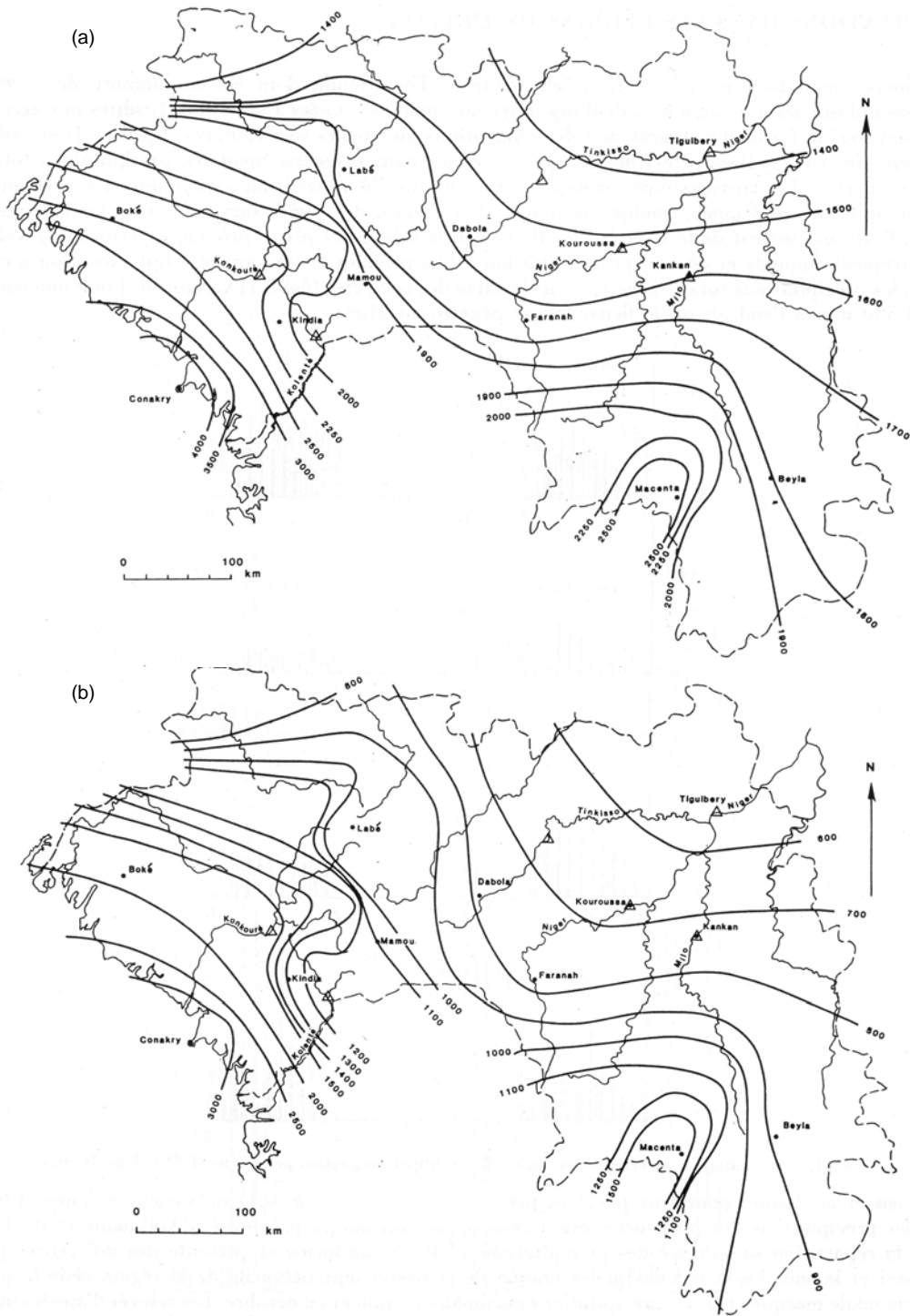


Fig. 5.7 Guinea: (a) gross annual rainfall (mm) 1951–1980; (b) net annual rainfall (mm); Δ river gauging station (from Sutcliffe & Piper, 1986).

basin net rainfall less 300 mm. Thus annual runoff series could be estimated with reasonable precision, even at ungauged sites, by deriving seasonal net rainfall series with an allowance of 300 mm for annual soil moisture recharge.

It is interesting to note that when the same approach was applied to Togo and Benin, the corresponding graphs linking annual runoff depths to annual net rainfall had slopes of 45° only in the north where a single rainfall regime is found, and not further south where two rainfall seasons occur.

Relevance to irrigation requirements

The importance to irrigation of soil moisture storage, and in particular the root constant, is that it largely determines the frequency with which irrigation applications are necessary. The rate of crop water use is related to net evaporation, or the potential transpiration and crop factor less rainfall; however, the time interval between water applications is also dependent on the volume of water on which the crop can draw, which is related to the root constant.

USE OF SOIL MOISTURE DEFICIT IN FLOOD STUDIES

During the investigations leading to the *Flood Studies Report* (NERC, 1975), a statistical comparison was made of flood statistics, in particular the mean annual flood, at over 500 gauged sites throughout the British Isles, with basin characteristics which could be measured from maps or derived from climate statistics. A major objective of this study was to develop a method of estimating the flood potential of ungauged basins. To this end a search was made for an index of flood-producing rainfall which should be more closely related to floods than indices used in earlier studies, like the mean annual rainfall or the daily rainfall of a given return period. It was thought desirable to take account not only of short-period rainfall but also of the antecedent conditions affecting the portion of the rainfall which runs off. In general annual rainfall is over 600 mm, distributed throughout the year; on the other hand evaporation, and therefore soil moisture deficit, is highly seasonal. It had previously been found that in British conditions (Mandeville *et al.*, 1970) the runoff volume could be predicted by subtracting the antecedent soil moisture deficit from the gross rainfall to give rainfall excess. Because the soil moisture deficit is the amount of water needed to restore the soil to field capacity, it was hoped that the basin rainfall excess would provide a realistic index of regional flood potential.

Although worldwide practice had been largely based on the premise that flood-producing rainfall depends on a rainfall intensity which exceeds soil infiltration rates, and thus gives rise to surface runoff, it was felt that climate conditions in the British Isles very rarely produced surface runoff in this way, as rainfall intensities were normally relatively modest. During lectures to an international course in Britain, it was interesting to note that almost all those who claimed to have seen surface runoff were overseas students!

During the development of unit hydrograph techniques of modelling flood events, records were compiled of storm characteristics and basin response in the form of immediate runoff volumes. These records were used in a qualitative statistical test (NERC, 1975, I.6.5.5) to see whether the water balance model, the infiltration model, or a contributing area model, best explained the relation between storm and response.

In the water balance model the loss between storm volume and immediate runoff was assumed to equal the soil moisture deficit; in the infiltration model the loss was related to storm intensity; with the contributing area model the runoff coefficient would vary with soil type and soil moisture deficit. By expressing these different assumptions algebraically and rearranging, it was deduced that the first concept implied that the loss, or difference between storm depth and immediate runoff, would vary with soil moisture deficit; in the second case the loss would be related to storm duration; in the third the loss would be related to storm depth and soil moisture deficit.

Nearly 1500 actual events were used to test these approaches; records included storm depth and duration, runoff volume, soil type and a catchment wetness index, which combined antecedent soil moisture deficit and recent rainfall. The loss was found to be related to rainfall depth, soil type and antecedent conditions; the duration of the storm was not significant. It was deduced that soil moisture state rather than rainfall intensity had more influence on the proportion of rainfall which contributed to immediate runoff. Therefore, in the unit hydrograph modelling, the runoff coefficient was related to a wetness index based on soil type, the soil moisture deficit, and recent rainfall.

Development of net rainfall index

It was also decided that a net rainfall index, combining short-term rainfall and soil moisture deficit, should be developed as a basin characteristic for comparison with flood statistics in a countrywide statistical study. In the same way that an index of gross rainfall, of say 5-year return period, should be more relevant to flood statistics than mean annual rainfall, it was hoped that an index of net rainfall would be even more useful. The aim was to produce a map of daily rainfall less soil moisture deficit, of 5-year return period.

At the time, daily rainfall data for about 400 stations were being analysed by the UK Meteorological Office to provide rainfall frequency statistics over the country. Soil moisture statistics had also been calculated (Grindley, 1970) from meteorological records using a continuous water balance model based on Penman (1950), estimating soil moisture storage from rainfall and potential evaporation data; a typical basin was assumed with fixed proportions of short-rooted, deep-rooted and riparian vegetation with their appropriate root constants (75 mm, 200 mm, infinite). Evaporation was assumed to occur at the potential rate until the soil moisture deficit reached the root constant, and when the deficit was zero the rainfall excess was assumed to become runoff. Statistics of estimated soil moisture state were available for 180 stations covering periods up to 30 years.

It would have been possible to analyse records of rainfall excess by subtracting the soil moisture deficit on the date of each storm, but this would have limited the number and period of records available. The alternative was to analyse rainfall and deficit records separately and to derive the statistical distribution of their difference. It was found that the two variables could be rendered independent by considering storm events larger than a threshold exceeded on average 10 times a year, and by dividing the year into seasons. This meant that it was possible to deduce the distribution of the net rainfall from the two distributions of the gross rainfall and the deficit. It was also found that samples of daily rainfall above a threshold could be treated as drawn from an exponential distribution. These two findings greatly simplified the derivation.

It was shown (Beran & Sutcliffe, 1972) that if the distribution of rainfall is exponential, and the soil moisture deficit (SMD) is independent of rainfall amount, then the net rainfall or the difference between the two also has an exponential distribution with the same slope. It follows from the geometry of the exponential curve that the difference between gross and net rainfall of the same probability is a constant which is independent of probability. This theory was tested by examining the difference between gross and net rainfall, or the effective mean SMD, at different frequencies at a large number of stations; it was concluded that the value of the mean SMD at a return period of 5 years was valid from the mean annual event up to the 100-year event. This amount can be described as a weighted mean soil moisture deficit for the given location and season. Seasonal maps of mean soil moisture deficit could be prepared and used together with rainfall statistics to provide an index of flood-producing rainfall. A map of effective mean soil moisture deficit for the British Isles was derived from analysis of some 200 stations and published as part of the *Flood Studies Report* (NERC, 1975). The geographical distribution of this mean soil moisture deficit was clear; it increased from less than 2 mm in parts of northwest Scotland, central Wales and western Ireland to 10–20 mm in southeast England. This map was intended for use in combination with maps of rainfall of 5-year return period to give an index of net rainfall. Maps of rainfall excess of 5-year return period were later derived and published for the British Isles for use in flood estimation (Farquharson *et al.*, 1975).

Thus regional use of the concept of soil moisture deficit, viewed as a function of climate, was able to provide an additional tool to add to the normal analysis of rainfall statistics.

CONCLUSION

Several different examples of the use of measured or estimated soil moisture deficits to describe the conversion of rainfall to runoff illustrate the important role which soil moisture plays in the hydrological cycle. It is not an exaggeration to suggest that it is the key to understanding the difference between potential transpiration and actual evaporation, and thus the role of the basin in converting rainfall to soil or groundwater storage and river flow. It could be argued that the fairly recent ability to measure and thus to model soil moisture state was an essential condition to the ability to model the hydrological cycle with a degree of realism.