11 SEDIMENTATION AND ENVIRONMENTAL ISSUES

Some topics which are important to water resources studies do not fit easily into the sequence of processes of the hydrological cycle. These topics include the estimation of sediment transport in rivers, including both suspended sediment and bed load, and the assessment of the impact of water resources projects on the local environment and economy. A few examples are included, based on problems which have been encountered. The treatment is not as complete as the topics deserve; their inclusion is intended to draw attention to the need for such studies.

SEDIMENT TRANSPORT

The assessment of sedimentation is an important part of reservoir design, especially in the more arid parts of the world where reservoirs are vital. Reservoirs in such areas are particularly vulnerable to sedimentation, because the few intense flows are likely to be heavily sediment-laden. This can severely limit the useful life of reservoirs unless the sediment load is estimated with care and appropriate reservoir operation is designed.

However, sediment transport is not easy to measure or to estimate. Sediment load is linked to river discharge but is highly sensitive to variations in flow. Further, the relation between river flow and sediment load is not constant, as it depends on the supply of material eroded from the basin and is greater at the beginning of the wet season and after heavy storms. Sediment load is also sensitive to changes in basin vegetation, due for example to deforestation.

The load consists of two main components, suspended sediment and bed load. Suspended sediment can be sampled at river gauging stations, though it varies with depth; bed load is more difficult to measure, as it may only occur during high flows when it is not easy to sample. The problems are best discussed with specific examples.

Tana basin, Kenya

During investigation of the Tana basin in 1958 (Chapter 3; Sutcliffe & Rangeley, 1960a), it was necessary to estimate the sediment load within the basin as this would affect the economic life of any reservoir to be constructed. This was made possible by the fact that about 100 suspended sediment measurements had been made at each of a number of gauging stations in a recent research programme. These measurements were based on a depth-integrating sampler suspended from a cableway; the sampler was designed to be lowered from the water surface to the bed and raised at a constant rate so that the sediment intake would sample the total load over the profile. The measurement was repeated at three points on the cross-section, and the mean analysed

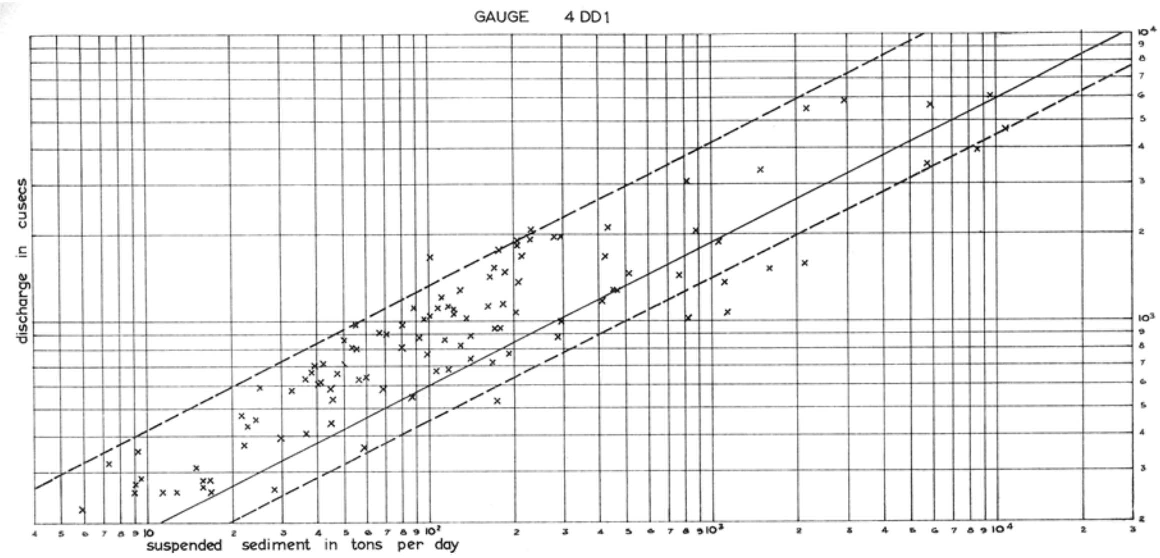

Fig. 11.1 *Thiba above Kamburu: sediment rating curve. Note that the units on the axes are log(cusecs) and log(tons per day).*

sediment concentration was calculated. This concentration could be multiplied by the river discharge to give an estimated suspended load in tons per day.

At ten stations sufficient results were available for sediment load to be compared with discharge. Although no account was taken of the season or whether the river was rising or falling, there was a clear correlation between sediment and discharge at each station. The relation appears as a linear band when plotted logarithmically; an example is illustrated in Fig. 11.1. At most sites the scatter was considerable and the range of loads for a given discharge was found to vary by an order of magnitude. Because of this scatter, and the effect of the logarithmic scale, a graphical approach was preferred to statistical correlation. Two parallel lines were drawn to envelop all but a few outlying points, and a third line was drawn to give the arithmetic mean of the two envelope lines, taking account of the logarithmic scale.

The estimation of total load involves the conversion of river flow to sediment load by means of the sediment rating curve. Because the sediment concentration is highly sensitive to flow, there had to be a compromise between conversion on a daily basis, which would have involved a considerable amount of calculation before the availability of computers, and the calculation of sediment loads on a monthly basis, which would greatly reduce the peak flows and concentrations. In this case the suspended sediment loads at six sites were calculated using 5-day or 10-day periods and mean flows were converted to sediment loads in tons per day. The total loads were deduced for each year. The annual sediment loads for the Tana at Kamburu, the most complete station, are compared with the annual flows in Fig. 11.2; it is evident that the transport of suspended sediment is extremely sensitive to high flows and that a large proportion of the long-term load is carried in years of high river flow. The annual average sediment load was calculated for the five tributaries and the main river at Kamburu; it was found that the total tributary load was higher than the downstream estimate, which may have

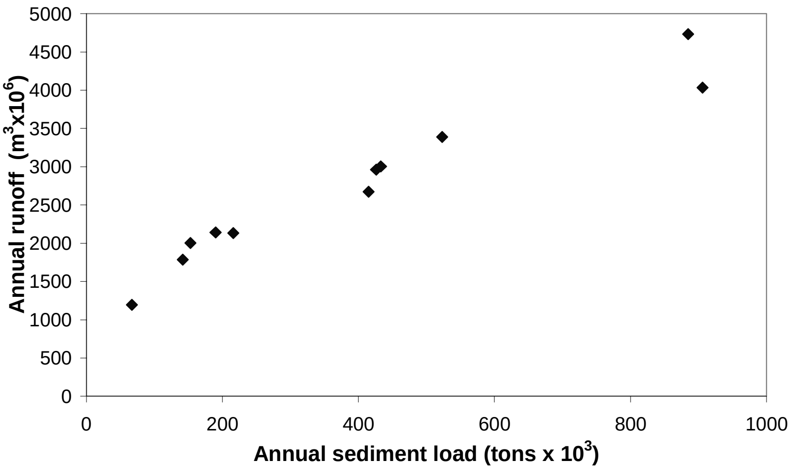

Fig. 11.2 *Tana at Kamburu: annual sediment and runoff:*

been due to the short period of sampling, the rating curves derived, or deposition above the lowest site. No information was available on bed load, so the results were confined to suspended sediment. The results confirmed the visual impression that the rivers flowing from Mount Kenya carried less sediment than the rivers draining the Aberdare range, while the tributaries whose basins had at the time a higher proportion of cultivated land carried more sediment than those which were primarily used for grazing.

Some 20 years later this same estimate was used by others as the basis for the design of a proposed reservoir, as no subsequent analysis was apparently available. This was criticised on the evidence of more recent measurements, which suggested that the sediment load of the Tana tributaries had increased dramatically over the 20-year period, with greatly increased intensity of agriculture and changed land use in the headwaters following population pressure. This illustrates the sensitivity of erosion and sediment load to changes of land use, which had been investigated on an experimental basin scale upstream by the East African Agriculture and Forestry Research Organization (EAAFRO) and later investigators (Pereira, 1962; Blackie *et al.*, 1979).

Bed load estimation

In a field investigation on the River Tongariro in New Zealand in 1959 (Sutcliffe & Rangeley, 1960a), similar suspended sediment samplers were constructed and used to monitor sediment loads. Additionally, it was evident from the channel material that bed load movement was likely to be a significant component of the total transport of this mountain river and its tributaries. A bed load sampler was tested on the main Tongariro River, but its use was impractical during the periodic spates in which the load was concentrated. The bed load was therefore estimated instead at a water supply intake site below the main skiing area on Mount Ruapehu, where the intake basin had to be cleared of bed load, including boulders, at regular intervals. The average annual volume removed gave an estimate of the tributary bed load.

In a review of solid discharge estimates for the Tarbela dam project on the main Indus in Pakistan, it was noted that the bed load estimation had previously been based on a nominal percentage of the suspended load. This was tested by using semi-empirical formulae relating bed load movement to channel gradient, river velocity, and the typical size of bed load material; the last was measured during a field visit. This illustrates a recurrent theme of this book, that there is no single correct way to estimate hydrological processes; methods of investigation depend largely on the evidence which is already available or which can be assembled during the time available.

Reservoir operation to minimize sedimentation

The Blue Nile provides an example (Sutcliffe & Widgery, 1997) of a river where the sediment load is high, particularly compared with the size of the reservoirs which can be constructed within the Sudan to store water required for local irrigation and for hydroelectric power production. The sediment load of the Blue Nile above Roseires has been estimated as 140 million tonnes per year (El Moushid *et al.*, 1997). The distribution of sediment during the flood season is important. The concentration of suspended sediment reaches a peak in late July or early August before the peak discharge is reached, and decreases until the end of the flood; an example is illustrated in Fig. 11.3. The storage available at Roseires reservoir and at Sennar downstream is fairly limited and it is important to minimise the sediment deposition by careful operation of the reservoirs to pass the flow during the flood period. In 1995, after nearly 30 years of operation, the capacity of Roseires reservoir had been reduced by 0.9 km^3 to an estimated 2.4 km^3, compared with an average annual flow of 49 km^3. The strategy has been to delay the filling of the reservoirs until the peak of the flood has passed through the reservoirs, as the sediment concentration is greatest on the rising limb of the hydrograph. Flow forecasting from rainfall could be useful in postponing the filling as long as possible while minimising the risk of not filling the reservoir.

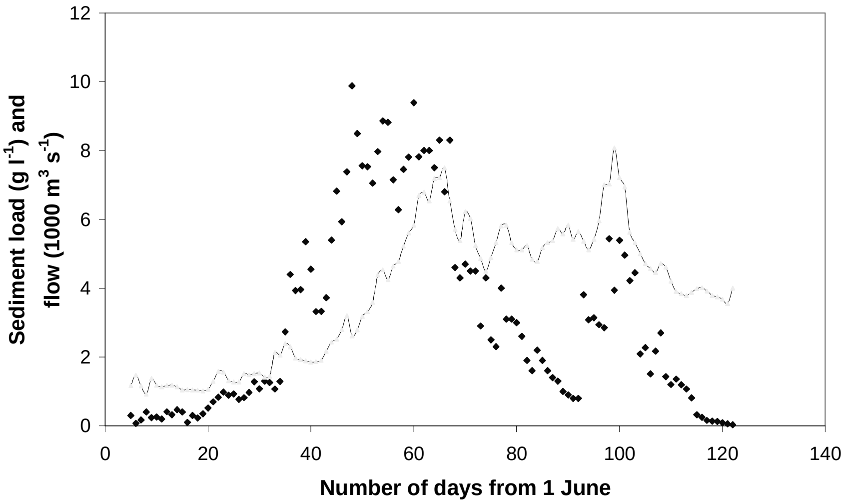

Fig. 11.3 *Blue Nile at Roseires: sediment concentration; ♦ sediment, – – flow.*

ENVIRONMENTAL ASPECTS

The following examples of environmental studies involve the effect of different types of projects on African wetlands. In one case, the project was the Jonglei Canal, whose purpose was the reduction of evaporation losses in the large Sudd wetlands in the southern Sudan in order to increase the flows of the White Nile downstream. In this case the emphasis of the study was the effect of the project on the natural flooding of the Sudd wetland, and the result which this would have on the vegetation of the flood plain. This study thus included the mechanism by which the seasonal flooding controlled the natural vegetation, and the change of vegetation which would result from the change of regime caused by the project. In another case, potential reservoir storage in Lake Albert would cause flooding of areas used for cultivation and also areas of wetland above and below the lake; the level to which flooding would reach was the subject of investigation. The proposed use of the River Kagera for hydroelectric power production would also result in flooding upstream of the reservoir and a change in regime through the wetlands on the lower Kagera; the ecological control of the wetland vegetation was similar to that deduced in the Sudd. In the lower Senegal valley, where natural flooding produced vegetation similar to that of the Sudd, areas of seasonal flooding were also used for cultivation when the flood had receded; a reservoir built upstream for power production and irrigation was operated initially to simulate the natural flooding but with greater reliability.

Study of Jonglei Canal and Nile wetlands

The assessment of the environmental impact of projects has become an essential part of most investigations in recent years. In 1950, when the author joined the Jonglei Investigation Team, the concept was relatively new. However, the team had been set up by the Sudan Government to investigate the potential effects of the Egyptian Government's proposals to increase the contributions of the White Nile by bypassing the Sudd. Its report (Jonglei Investigation Team, 1954) has been described as the first environmental assessment in the developing world. The scale of the effort resulting in this report may be illustrated by the fact that a team of ten expatriate professional staff, with local support including a Nile steamer (Plate 11.1), spent up to four years on the study. The following summary of the hydrological aspects of this and later studies is divided into accounts of the physical background, the effects of successive projects for the Jonglei Canal, and the prospects for mitigating these effects.

Because it had been noted early in the 20th century (Garstin, 1904) that the outflow from the Sudd was only about half the inflow of the major channel, it was suggested that a diversion channel could reduce the evaporation losses. For this reason the flows through the Sudd have been measured and the hydrology investigated over much of the 20th century. After the economic importance of the dry season grazing provided by seasonal inundation had been noted, complementary ecological studies of the area were combined with hydrological work in, for example, the research of the Jonglei Investigation Team.

The physical background

The basin of the Bahr el Jebel at Mongalla, at the upper end of the Sudd, includes Lakes Victoria, Kyoga and Albert (Fig. 11.4). The inflow to the Sudd combines a lake-

Plate 11.1 *Papyrus swamp on the Bahr el Jebel.*

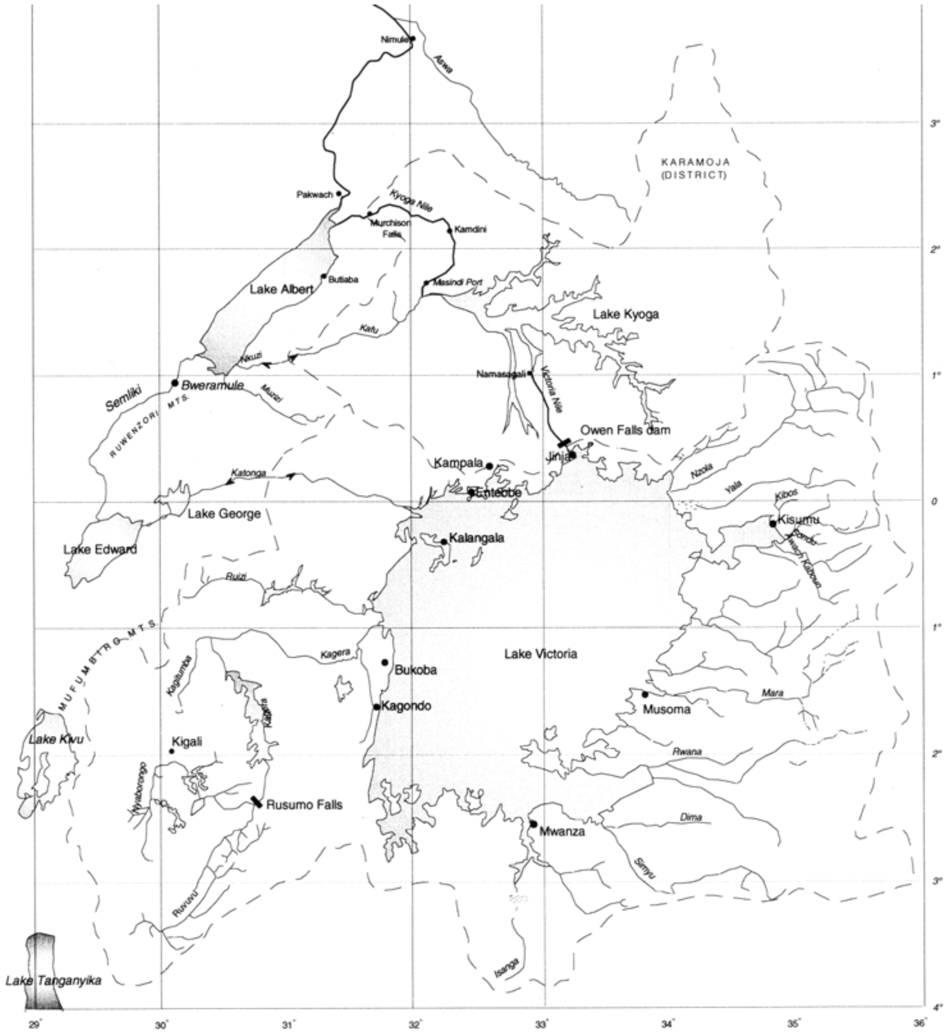

Fig. 11.4 *Map of the upper Nile basin (from Sutcliffe & Parks, 1999).*

fed component with the highly seasonal torrent inflows below Lake Albert. The outflow from Lake Victoria was controlled by lake level at the Ripon Falls until the Owen Falls dam was constructed in 1951–1953; since then the dam has been operated to mimic the natural outflow. The lake level (Fig. 8.26) was fairly stable between 1896 and 1961, but rose 2.5 m in 1961–1964 and the outflow doubled (Fig. 8.27). The average rainfall over the lake is very similar in amount to the lake evaporation. Thus an increase in lake rainfall, which occurred after 1961 with the associated rise in tributary inflow, had an exaggerated effect on lake level and outflow. After the dramatic rise in 1961–1964, this increase in rainfall continued to affect lake level and outflow though the lake level has fallen. There is evidence, from eyewitness accounts and from downstream flows, that high levels also occurred around 1878 and 1895, though the reversion to lower levels was faster than in recent years (Tate *et al*., 2001).

The net effect of Lakes Kyoga and Albert has been to enhance the variations of the outflows from Lake Victoria. Before 1961 there was a small decrease between inflows and outflows through Lake Kyoga; since 1961 there has been higher outflow than inflow. A similar change occurred in the regime of Lake Albert; after 1964 there was a net contribution from the lake basin. The torrents below Lake Albert reflect their single rainfall season and provide the highly seasonal element of inflow which causes the seasonal flooding of the Sudd.

The water balance of the Sudd

Within the Sudd, the Bahr el Jebel flood plain (Fig. 11.5) is incised several metres below the surrounding woodland. This valley widens from about 5 km near Mongalla to 15 km north of Bor, some 120 km downstream, and further north the woodland and the incision disappear. The alluvial river channels are built up above the flood plain; these channels are inadequate for all but the lowest inflows. Higher flows spill through or over the alluvial banks and flow down the flood plain and partly return to the river channel downstream. As the inflow to the Sudd increases seasonally or after upstream lake rises, wider areas are inundated and evaporation from these areas increases. As a result the channel flows decrease steadily through the Sudd and the eventual outflows (Fig. 11.6) lose their seasonal variation and are only about half the inflows.

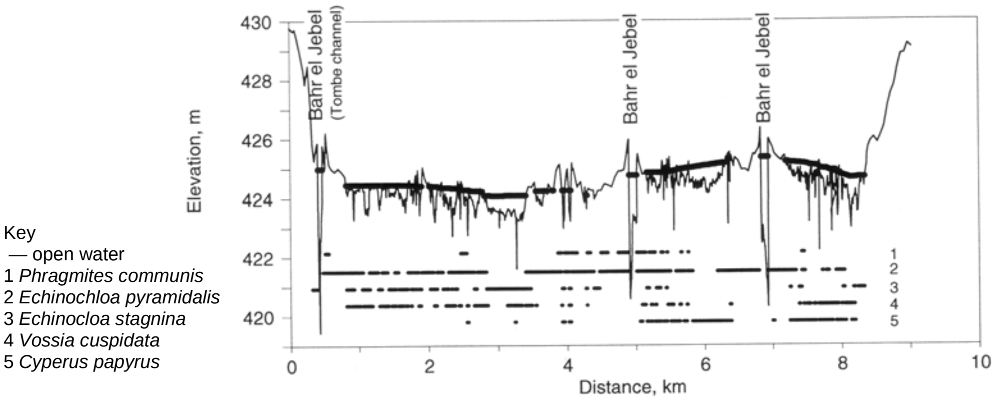

Fig. 11.5 *Bahr el Jebel flood plain: cross-section* L *on Fig. 11.7 (from Sutcliffe & Parks, 1999).*

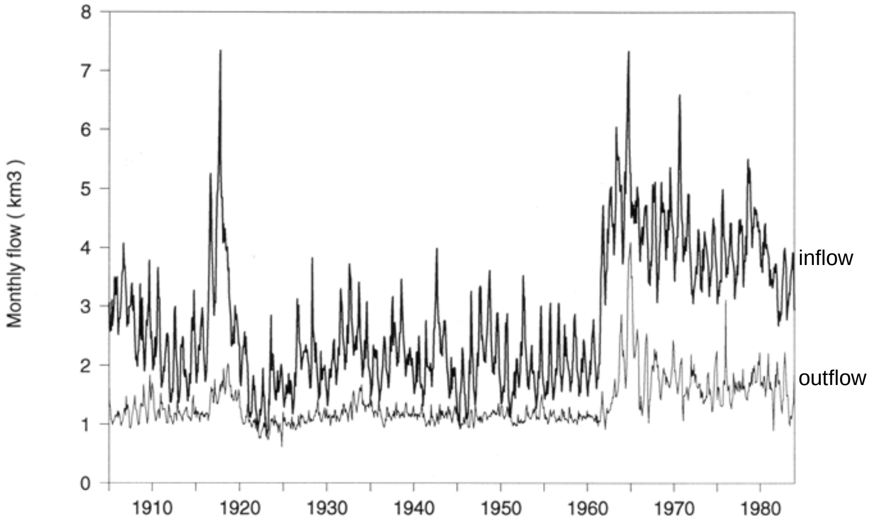

***Fig. 11.6** Sudd inflows and outflows (from Sutcliffe & Parks, 1999).*

From measurements of inflows and outflows for either a sample reach or the whole of the Sudd, together with estimates of rainfall and evaporation over the flooded areas, a water balance can be used to estimate the areas inundated over the period of records. This also requires information on the relation between areas and volumes of flooding. In 1951–1952, the Jonglei Investigation Team carried out a survey of the southern Sudd between Juba and Bor, which included 16 cross-sections of the whole valley (Fig. 11.7), 15 sections of the Aliab valley to the west of the main river, and 12 sections of the Mongalla basin to the east; these surveys of sample areas included longitudinal surveys of the alluvial banks of the river, transects of the vegetation and soils along the cross-sections, and also studies of the use of the flood plain for grazing.

Hydrological control of vegetation

A water balance of the Mongalla basin, between Mongalla and Gemmeiza, showed (Sutcliffe, 1957, 1974) that the volume of water in transit through the basin was directly related to the inflow, and therefore the volume of seasonal flooding could be related to the flow records at Mongalla. From the recorded vegetation along each cross-section (Fig. 11.5), the distribution of species with elevation could be deduced along each cross-section and down the flood plain. It was evident (Fig. 11.8) that there was a distinct elevation boundary between the deep-flooded flood-plain species (*Echinochloa stagnina*, *Vossia* and *Cyperus papyrus*) and the shallow-flooded species (*Echinochloa pyramidalis*, *Oryza* and *Phragmites*). This vegetation boundary was traced along the river profile and shown to be parallel to the high river level; it was deduced that this boundary was controlled by the maximum depth of flooding. From the statistics of flooding volume it was estimated that this maximum depth of flooding was 1.30 m. Because papyrus was limited to the lower end of each basin, and the elevation range of flooding increases from the lower to the upper end of the basin, it was also deduced that the presence of papyrus, anchored by fragile rhizomes, is controlled by the range of flooding; the limiting vertical range was 1.50 m. These conclusions on how the hydrological conditions

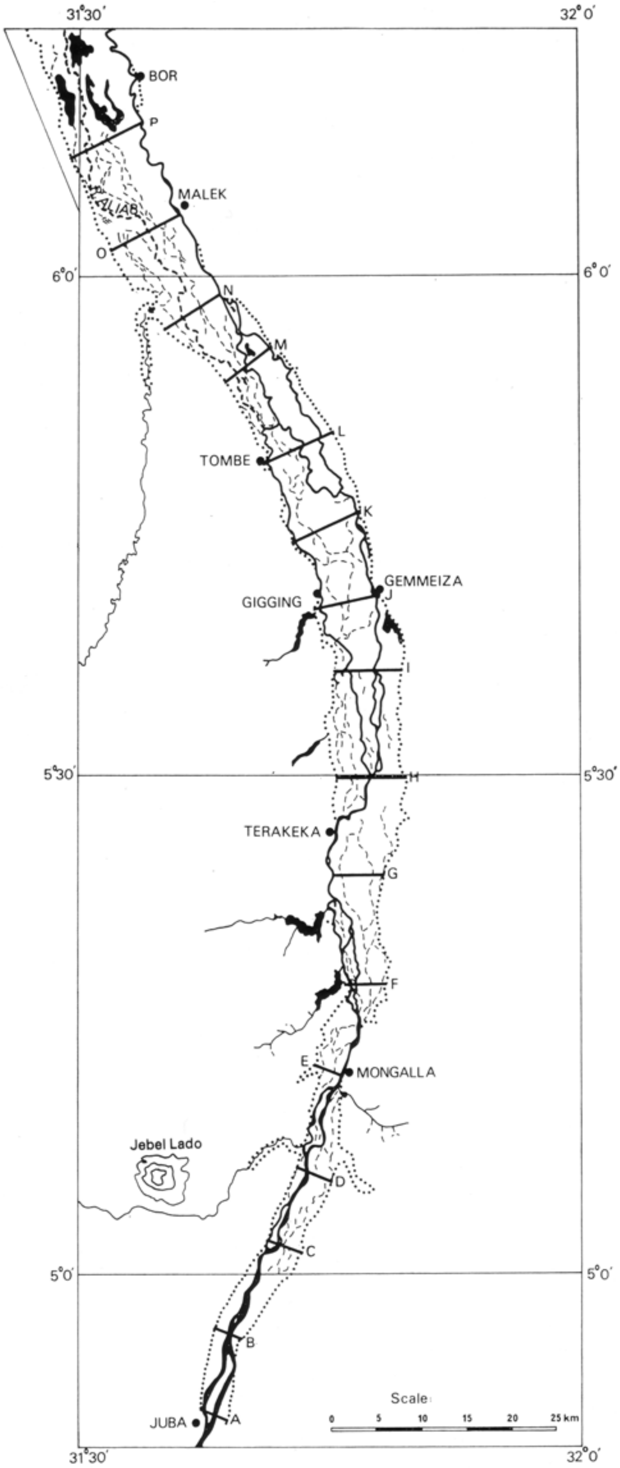

Fig. 11.7 *Map of the Bahr el Jebel flood plain between Juba and Bor (from Sutcliffe & Parks, 1999).*

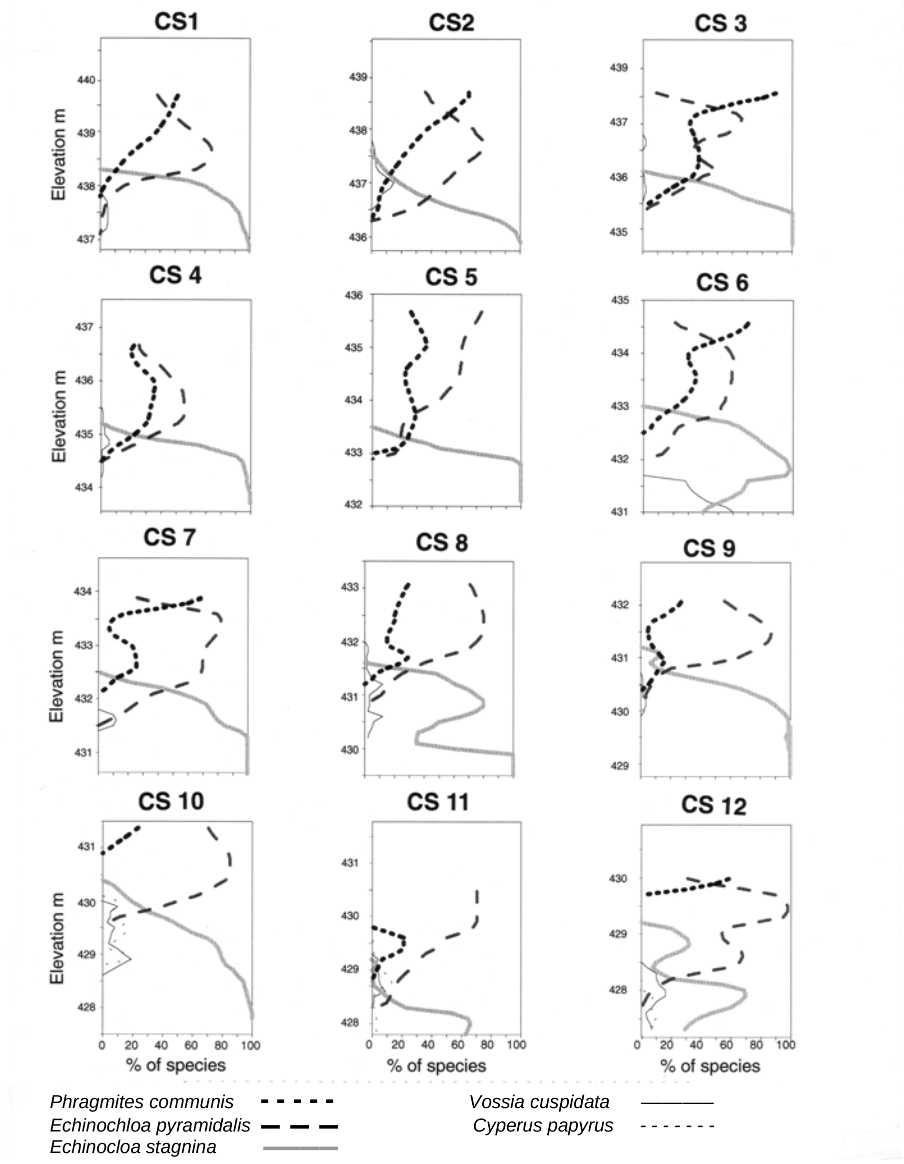

Fig. 11.8 *Vegetation distribution in the Mongalla basin: cross-sections in order from south to north (after Sutcliffe & Parks, 1996).*

control the vegetation (Sutcliffe & Parks, 1996) were consistent with the areal distribution of species, and also with observations elsewhere in the Sudd of the flood depths recorded where species were found.

The distribution of these vegetation species on the flood plain was important since the pastoral economy relied on the dry season grazing provided by the *Echinochloa* species and *Oryza* (Plate 11.2). At the wet end of the distribution, the papyrus swamp provides no grazing, while the *Phragmites* at the dry end is unpalatable. The local economy was based on the annual migration to the flood plain during the dry season,

Plate 11.2 *Cattle grazing on the Bahr el Jebel flood plain.*

and on rainfed vegetation during the rest of the year. The maintenance of the annual inflow regime, resulting in the annual inundation of the flood plain through the torrent flows, and its uncovering during the course of the dry season, was essential to the pastoral economy; alternative agriculture on higher ground was difficult because of the frequency of either drought or excessive flooding.

Impact of the Jonglei Canal

Because of the Bahr el Jebel losses in the Sudd, there have been several proposals since 1904 to reduce the losses of flow downstream by carrying part of the flow past the Sudd in a channel. Some proposals included regulating the inflows by storage upstream in Lake Albert or Lake Victoria. Others were confined to banking the Bahr el Jebel, but most recent plans have been based on a canal, known by its offtake site as the Jonglei Canal.

Detailed proposals for the Equatorial Nile Project were published by the Egyptian Government in 1946 (Hurst *et al*., 1946). These proposals included storage in Lake Albert controlled by a dam, either immediately below the lake at Mutir, or at Nimule some 200 km downstream, together with a regulator at Jinja on Lake Victoria. This would have allowed the control of Lake Albert outflows, including the virtual storage of the torrent flows, and their release at a time when they were required for irrigation in Egypt. To reduce transmission losses in the Sudd, flows of 55 $m^3 \times 10^6$ day^{-1} would be diverted through the Jonglei Canal and the balance passed down the natural river. It was planned that the storage could be used at a later stage to increase flows down the main Nile during years of deficit on the Blue Nile, with the Jonglei Canal expanded to pass these flows. The Jonglei Investigation Team studied the impact of these proposals and concluded that the associated reversal of seasonal flows above the canal intake, the maintenance of low flows throughout the year in the natural river below the intake, and of high flows below the canal outfall, were unacceptable. A Revised Operation was proposed which would have greatly reduced the adverse effects of the project.

After 1956 attention turned to the Aswan High Dam, with overyear storage at one site. This removed the importance of the flow timing for irrigation demand in Egypt, which had led to the planned reversal of flows below Lake Albert. Revised plans for the Jonglei Canal were agreed between Egypt and Sudan, aimed at increasing annual downstream flows by 4 km^3 by reducing flows through the natural river. This did not involve the reversal of flows, and the environmental issue was the reduction of the extent of the inundated areas, particularly the important seasonally flooded area.

The construction of the revised Jonglei Canal (Fig. 11.9), which had little similarity to the earlier project, began in 1978 but has been interrupted since 1983 to the present. Its potential effects were studied by Mefit-Babtie, with a hydrological assessment by the Institute of Hydrology (Sutcliffe & Parks, 1982, 1987; Howell *et al.*,

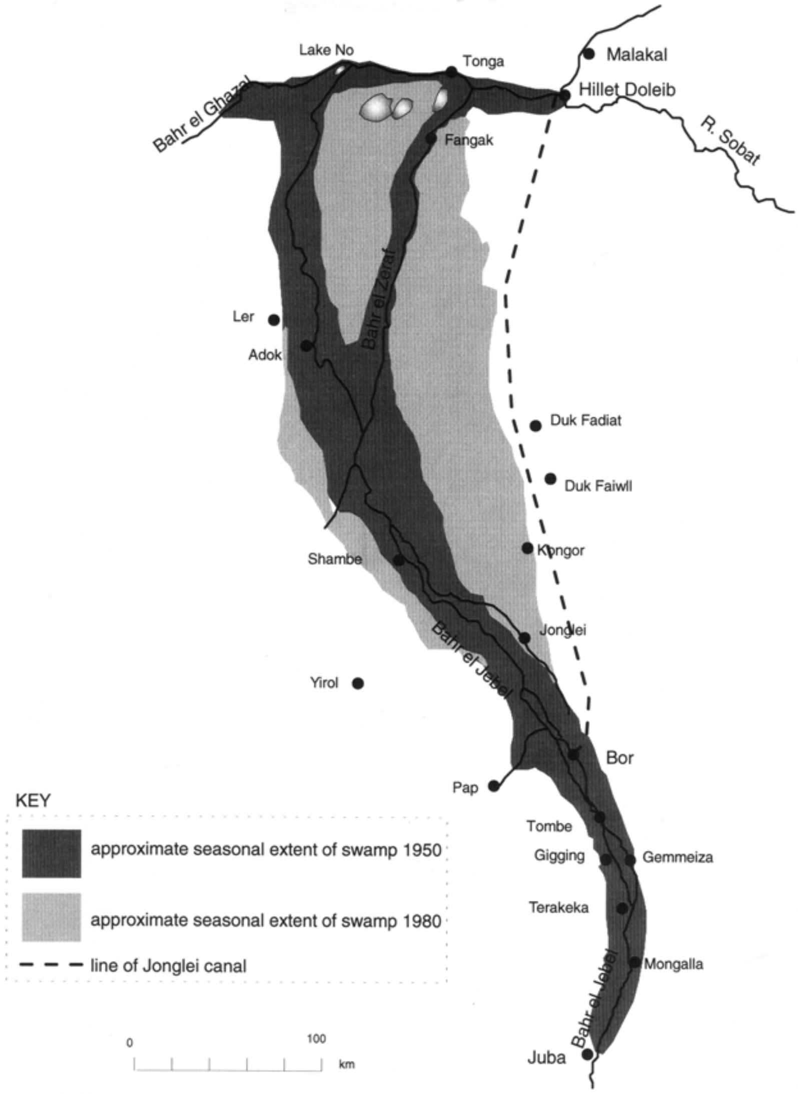

Fig. 11.9 *Map of the Sudd area (after Howell et al., 1988).*

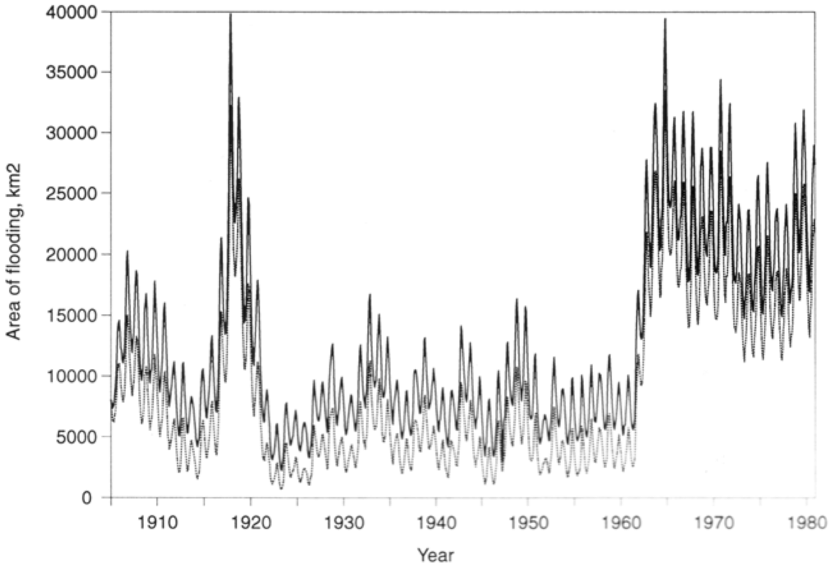

Fig. 11.10 *Effects of the Jonglei Canal: estimated areas of flooding below Bor, with and without the Jonglei Canal (20 m^3 x 10^6 day^{-1}) (from Sutcliffe & Parks, 1999).*

1988). The hydrological study was based on the water balance of the whole Sudd, using measured inflows and outflows for the period 1905–1980, rainfall measurements around the Sudd and evaporation from flooded areas using Penman estimates of open water evaporation. The model included soil moisture recharge of newly flooded ground, and used a simple linear relation between area and volume of flooding, which implies a constant depth as flooding spreads.

This model was run over the historic period to estimate the areas of flooding (Fig. 11.10), and reproduced reasonably well both the seasonal fluctuations and the changes after the rise in Lake Victoria. Using a relation between measured inflows and outflows and applying the same relation to river flows after construction of the canal, the model was used to predict the areas of flooding (Fig. 11.10) which would have occurred with the Jonglei Canal operating with a constant discharge of 20 $m^3 \times 10^6$ day^{-1}. This suggested that the areas of seasonal flooding would have decreased by some 26% in the lower flow period of 1905–1961, and by 17% in 1961–1980; the permanent swamp would have decreased by 46% and 21% respectively, in the same periods. It was important to note that the timing of the seasonal inundation and uncovering would not have been affected.

Mitigation of impact

The hydrological modelling also suggested that the adverse impact could be reduced by varying the canal flows seasonally. Trials suggested that altering the canal flow to 25 $m^3 \times 10^6$ day^{-1} from November to April and 15 $m^3 \times 10^6$ day^{-1} from May to October would lead to a decrease in seasonal flooding of only 12% in the early period and 10% in the later period. By varying seasonally the flow down the canal, the natural river flows would be increased during the wet season and decreased during the dry season; this would enhance the natural fluctuations and thus increase the areas of seasonal flooding at the expense of permanent swamp. Equally importantly, it would increase the range of depth of flooding, which would encourage the valuable grazing grasses rather than papyrus.

Observed changes, following the rise in Lake Victoria, in the hydrological regime of the Sudd and the resulting vegetation support the deductions about the links between flooding and vegetation. During the 1982 hydrological study, the opportunity was taken to observe the Aliab valley from the air at low level along the survey cross-sections, armed with vegetation and other maps of the 1951 survey. It was noted (Fig. 11.11) that *Vossia* and papyrus had spread over areas previously dominated with grazing grasses. Because the seasonal torrent flow volumes had not increased after 1961, while the area of flooding had doubled, the range of depth of flooding would have decreased to favour papyrus. The *Vossia* would have been encouraged by the higher flow velocities. In the drier Mongalla basin, the increased flooding had encouraged the spread of grazing grasses, and cattle were observed grazing areas which had previously been dominated by *Phragmites*.

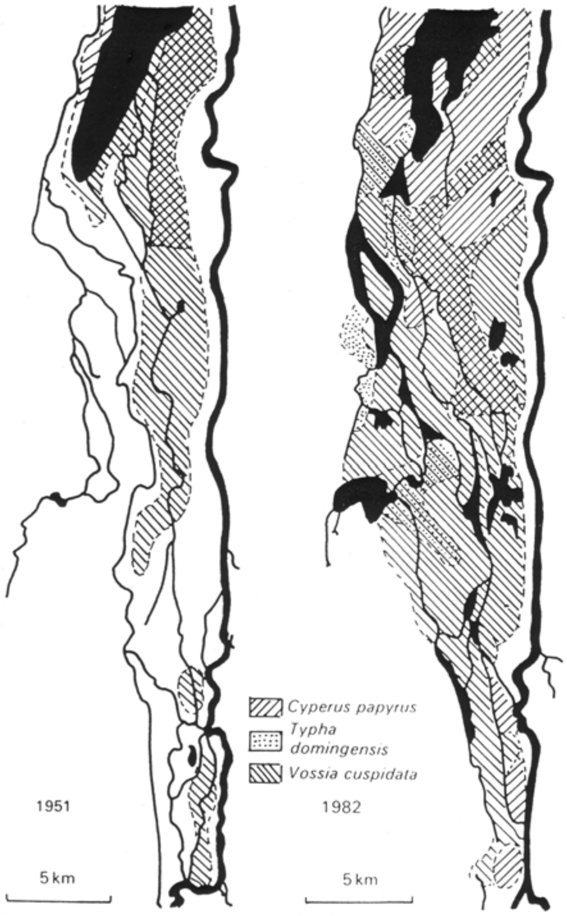

Fig. 11.11 *Vegetation changes in the Aliab valley between 1951 and 1982 (from Howell et al., 1988).*

Thus the potential effects of the Jonglei Canal project which was started in 1978 may be predicted in general terms. Above the canal offtake, the scheme would have no effect in the absence of upstream storage. Between the canal offtake and outlet near the Sobat confluence, the project would not affect the seasonal pattern of flooding but would reduce the areas of seasonal flooding; the effect would be less than on the less valuable permanent swamp. Indeed, it would be possible to reduce these adverse effects by suitable adjustment of the canal inflows. Below the canal outfall, the flows down the White Nile would be increased by the reduced losses in the Sudd; the seasonal distribution of flows down the White Nile is dominated by the Sobat inflows.

Local effects of storage in Lake Albert

After the report of the Jonglei Investigation Team (1954) had been published, negotiations between Egypt, Sudan and Uganda were due to take place over the use of Lake Albert as a reservoir to supplement the Jonglei Canal. For this purpose the Uganda Government needed information on the area which would be flooded by a dam at Mutir, below the exit from Lake Albert. This required a topographic survey of the area around the lake, supplemented by a study of the soils and crops and an estimate of the population involved. In order to carry out a rapid survey at this stage of negotiations, a simple instrument was used to measure cross-sections away from the lake; this consisted of two level staves with a transparent plastic tube inserted vertically and connecting the staves and filled with water. The water level in the tube was read against each level staff and the difference in level deduced. This procedure was continued along the section until the required elevation above the lake surface was reached, and thus a section could be plotted without the need to clear sightlines which form the main expense of conventional surveys.

A contour map was compiled by interpolation and the soils and crops were examined and classified within the limits of the land liable to inundation. The extent of wetland vegetation around the lake was also noted. In the event the negotiations were overtaken by the decision to investigate the Aswan High Dam, where Nile flows are now stored at a location with significantly higher evaporation. However, the Lake Albert dam is again being discussed. It is probable that the downstream effects along the Bahr el Jebel flood plain of operating such a dam could be more significant than the local inundation.

The Kagera flood plain

Proposals have more recently been made to develop hydroelectric power near the Rusumo Falls on the Kagera above Lake Victoria. There are lakes and wetlands above and below the falls, and the flood-plain vegetation species are similar to those on the Bahr el Jebel. It follows that the vegetation upstream and downstream would be affected by reservoir storage and in particular by changes in the depth and range of flooding. The general effects on vegetation could be predicted on the basis of the ecological controls deduced from the Sudd.

Control of Senegal flows to maintain flooding

An example of the control of a reservoir to improve the natural environment is given by the River Senegal. This river (see also Chapter 9), whose main sources are in the

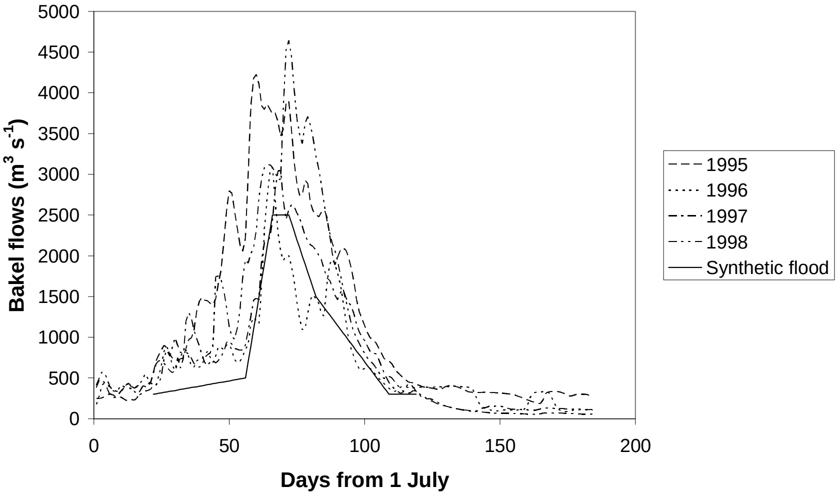

Fig. 11.12 *Senegal at Bakel: flows, 1995–1998.*

mountains of the Fouta Djallon in Guinea, in its natural state inundated an area of wetland in its lower reaches which averaged about 5500 km^2, but which varied from a very small area in a dry year to about 8000 km^2 in a wet year. The seasonal flooding provided the basis of the local economy, including dry season grazing for about a million cattle, recession agriculture on the area of flood plain where soil moisture was recharged by the annual flooding, and also fresh water fisheries. The area of recession cropping was sensitive to the flood volume and shape, with some 100 000–120 000 ha cropped in wet years but only 15 000–50 000 ha during the drought following 1970. The dry season flows were used to support commercially irrigated agriculture, including sugar cane.

The Manantali dam on the Bafing tributary was designed to provide hydroelectric power and irrigation for agriculture, as well as improving navigation. However, the change from recession agriculture to modern irrigation was expected to require a transition period. During this period it was planned to use the reservoir to provide an artificial flood which would provide a more reliable means of inundation than the natural river. The design of the artificial or synthetic flood was based on the shape of the hydrograph of the natural flood, but the flows of the uncontrolled tributaries would be supplemented by releases from the reservoir to give a duration and timing of inundation corresponding to the traditional system of agriculture. This control is illustrated by the flows of the Senegal at Bakel (Fig. 11.12) in some recent years.

DEAD SEA WATER BALANCE

The potential effects of a scheme to generate hydroelectric power by introducing water from the Mediterranean Sea into the Dead Sea were the subject of a review in 1982. The Dead Sea level had been falling steadily because of diversion of Jordan flows upstream, and the difference in elevation between the Mediterranean and the Dead Sea would enable hydroelectric power to be generated from water diverted into the lake, which would also raise the levels of the lake. However, potential changes in water quality introduced an unusual but important factor into the investigation of the water balance of the Dead Sea, as lake evaporation would vary with salinity.

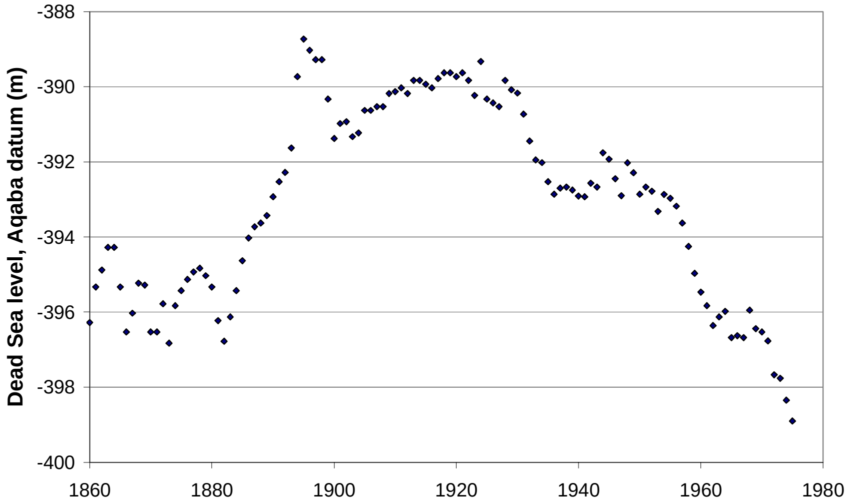

Fig. 11.13 *Dead Sea levels, 1860–1976.*

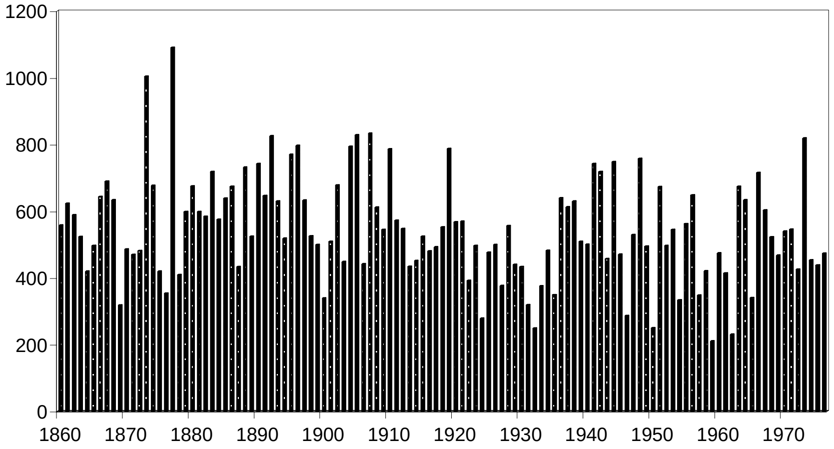

Fig. 11.14 *Jerusalem rainfall (mm), 1860–1976.*

Because the Dead Sea basin is a closed system, with the lake some 400 m below sea level and no outlet except evaporation, the lake levels reflect the balance between inflow and evaporation losses. Annual levels (Fig. 11.13) since 1860 (Klein, 1965; Underhill, 1967) revealed a range of about 10 m over the period of records. After a rise over the period 1880–1900, which must have been due to high rainfall and runoff and may have been linked to the same causes as the high Nile flows during the same period, the level of the Dead Sea has been falling steadily, especially since 1930. This was caused by periods of low rainfall, as recorded at Jerusalem (Fig. 11.14), exacerbated more recently by abstraction of the waters of the Jordan for irrigation.

The main inflow to the Dead Sea is the flow of the River Jordan (area 17 000 km^2), which was measured at the King Hussein Bridge (formerly Allenby Bridge) from 1932

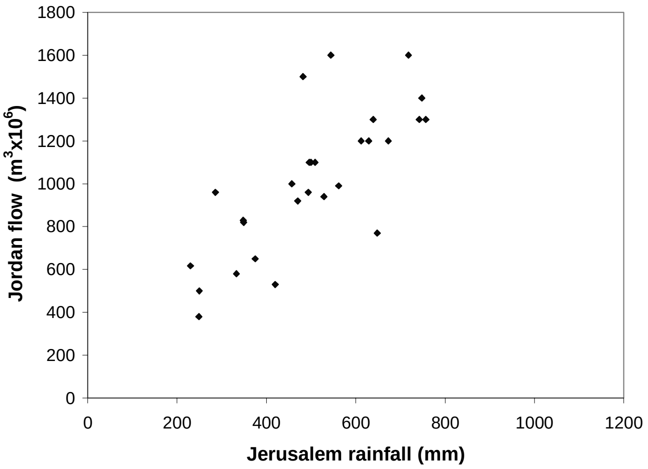

Fig. 11.15 *Jordan flows (at King Hussein Bridge) and Jerusalem rainfall (Old City), 1932–1963.*

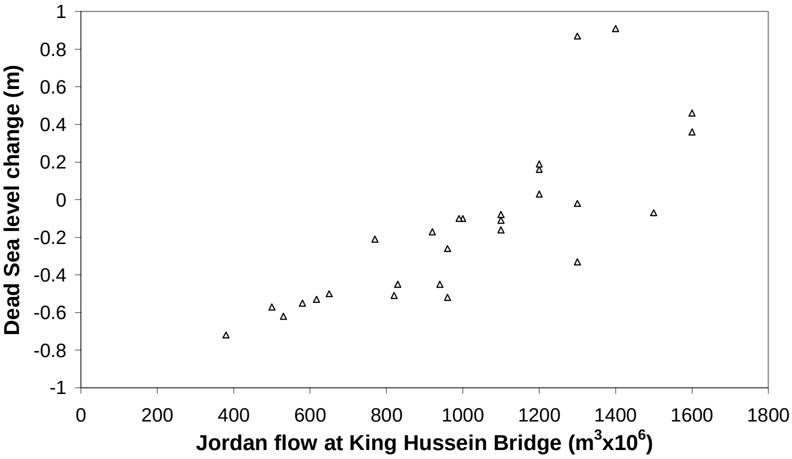

Fig. 11.16 *Jordan flows and Dead Sea level change, 1932–1963.*

to 1963, before irrigation abstractions reached their peak. These flows can be compared (Fig. 11.15) with the long-term rainfall station at Jerusalem to give a reasonable estimate of the long-term mean flow. The rainfall series date back to 1860, and show that recent records come from a relatively dry period; the long-term mean annual rainfall of about 550 mm corresponds to a mean runoff of about 1100 $m^3 \times 10^6$.

The lake balance may be illustrated by a comparison (Fig.11.16) between Jordan inflow and change in lake level, as this river flow forms most of the lake inflow and the evaporation will be more stable than the other components. It is clear that the fall will have been accelerated by a decrease in river inflow following upstream abstractions, which have been estimated to reach eventually 950 $m^3 \times 10^6$ (Weiner & Ben-Zvi, 1982) or most of the Jordan inflow. Alternatively, the lake balance could be illustrated by a comparison between Jerusalem rainfall and change in lake level, during a period when Jordan inflows reflected natural conditions before abstractions were significant.

Over recent years the water abstracted has been balanced by the decrease in lake area and therefore in lake evaporation, and by the stored water released by the lake decline. However, the surface salinity will have increased as the lake fell and the evaporation from the lake surface also decreases with increasing salinity. Evaporation varies with the vapour pressure difference over the water surface interface; the evaporation would almost halve if fresh water were replaced by Dead Sea brine (specific gravity 1.17 g cm^{-3}) at the same temperature, as could be tested by evaporation pans. However, in order to satisfy the energy balance a lake of fresh water would remain at a lower temperature than one of brine. The Penman approach was adapted by Calder & Neal (1984) to give the evaporation rate for saline lakes explicitly in terms of the usual meteorological variables. Whereas the evaporation from the Dead Sea with historic salinity would be 1498 mm with a surface temperature of 26.2°C, the evaporation if the surface water were substituted with Mediterranean Sea water would be 1969 mm at a temperature of 23.6°C.

Because the extraction of potash and other chemicals from the southern Dead Sea is an important contribution to the economies of both Jordan and Israel, the effect of the hydroelectric project on lake level and water quality formed a major component of the potential effects of the project. Alternatively, the rate at which water could be introduced to the lake would be determined by the level at which the Dead Sea level was to be maintained. The water contribution of the project could be equated with the quantity of water abstracted from the River Jordan for irrigation to maintain the long-term equilibrium in lake level, or the sum of the residual Jordan inflow plus the Mediterranean inflow could be compared with evaporation from the lake; this evaporation rate must depend on the resulting surface salinity of the lake. In fact, the Mediterranean-Dead Sea project was shelved, following criticism of its economic feasibility (*Financial Times*, 13 November 1984).

CONCLUSION

These examples illustrate the fact that projects involving changes in the flow or availability of water may have profound effects on the local environment and people. The links between water and environment are so strong that any water engineering project will have repercussions which may not be immediately apparent or straightforward. The example of the Sudd and the Jonglei Canal shows that the chain of effects may be subtle and require detailed research to clarify. The diversity of examples in this chapter hint at the many and wide-ranging effects that changes to the water regime may have on the environment which deserve investigation.