Historical water resources in South Asia: the hydrological background

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Abstract

The development of historical water resources in the South Asian subcontinent has been largely dependent on the hydrological background. The runoff patterns are derived from climate statistics and the historical developments in different areas are related to these patterns.

Keywords

South Asia; climate statistics; runoff patterns; historical water resources

Introduction

The dominant feature of the climate over most of South Asia is the contrast between the short monsoon season, when rainfall is abundant, and the longer dry season, when water is in short supply. As demonstrated in this paper, a number of strategies have been used to provide water supplies to historical communities. Their characteristics have varied with regional climate and geology of populated areas. Because in most areas the rainfall was concentrated into one season, the challenge is to retain sufficient seasonal supply throughout the year. There are two possible solutions: if the topography is suitable, storage can be constructed to a depth greater than evaporation and percolation during the dry season; alternatively, if the near-surface geology can store water below the level from which it could evaporate, a well can be dug below the water-table and water extracted as required. In such areas, sources of water have developed into the village reservoir or the village well.

As argued elsewhere (Shaw and Sutcliffe 2001), small populations could have relied initially on rainfed cultivation, where sufficient rainfall and soil moisture storage could supply a single crop. As populations grew or spread into new regions, the use of irrigation could become necessary. Because of the greater water requirement, more storage would be needed. Irrigation may depend on run-of-river water supply where significant dry-season river flow is available. Where river flow is available for a limited period, seasonal runoff could be spread over an area by a low embankment, so that the soil moisture storage is saturated, or alternatively stored and applied to an irrigated area downstream. It may be necessary to divert river flows to overcome water shortage or avoid flood damage. Perennial irrigation, depending on overyear storage to meet shortages in dry years, would need more sophisticated control structures and spillways than seasonal storage systems.

There are few studies emphasising the physical background to historical water use. In areas dominated by the seasonal monsoon, like South Asia and West Africa, a simple hydrological model can be used to estimate available runoff or surplus. It will be shown that hydrological factors affect the form of water resources development. The aim of this paper is to describe the influence of hydrology on the development of historical water resources across South Asia.

Typical climate of Central India

Before discussing how historical populations have approached the problems of water supply and irrigation in different regions, it is useful to discuss a typical climate in terms of seasonal availability of water. This account is based on a detailed investigation of the water balance of a hard-rock basin in central India, undertaken in 1976–1980 as a joint research project between the Indian Central Groundwater Board, the British Geological Survey, and the Institute of Hydrology (Indo-British Betwa Groundwater Project 1981).

The climate of the Betwa basin is highly seasonal, with over 90% of the annual rainfall concentrated in the monsoon months between June and September. During the initial phase of the study (Sutcliffe *et al*. 1981), the surface water balance of the basin was analysed. Sixteen rainfall records for the Betwa basin (20 600 km^2) were combined to give a monthly series for the years 1926-1975; the average annual rainfall for the basin was 1138 mm. Climate records were used to estimate open water evaporation and potential evapotranspiration from vegetation by the Penman method. Average monthly estimates of rainfall and potential evapotranspiration in Fig. 1 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 evapotranspiration for two to four successive months, while potential evapotranspiration is greater than rainfall for the rest of the year. The period of soil moisture recharge, indicated in Fig. 1, is followed by a period of water surplus or runoff; after the monsoon the soil moisture is used for evapotranspiration until the soil moisture storage is exhausted. This is followed by a period of water deficit after this storage has been used; the soil moisture recharge equals the subsequent soil moisture use. In the Betwa basin, the soil moisture storage is at field capacity at the end of the monsoon and always reaches wilting point, when the storage is empty, before the end of the dry season; thus the annual recharge brings the storage from wilting point to field capacity throughout the rooting zone. This difference in terms of depth is the “root constant”. The soil moisture recharge should be reasonably constant from year to year in the absence of land-use change and is a first charge on the net rainfall, the surplus of rainfall over evaporation. In this climate, one may assume that evaporation continues at the potential rate until the soil moisture storage reaches wilting point.

The root constant, or the depth of the available soil moisture reservoir, can be estimated simply by comparing annual net rainfall with runoff. This is illustrated in Fig. 2, where the runoff was estimated by converting annual total inflows to reservoirs at the lower end of the basin, to mm depth over the basin. The annual soil moisture recharge is shown to be about 200 mm while the mean runoff is 351 mm. Gross and net rainfall may be compared with runoff to illustrate the increasing variability of the water balance. The gross rainfall has a mean of 1138 mm with a coefficient of variability of 18.5%, the net rainfall and runoff have corresponding values of 583 mm and CV of 29.2%, and 351 mm and 44.7%, respectively.

This early phase of the investigation drew attention to the important role of the soil moisture storage in providing moisture to crop cultivation, and in controlling the conversion of rainfall to runoff (Sutcliffe and Green 1986). A network of soil moisture observation points was established (Hodnett and Bell 1986) over the cultivated plain in the centre of the basin, where black cotton soils average about 2 m depth. Moisture profiles were measured at weekly intervals by neutron probes and revealed the successive drying of the soil profile when the crop water supply was derived entirely from the soil moisture storage. This storage was sufficient, with minor contributions from winter rainfall, to maintain growth of the dominant wheat crop from the end of the monsoon to crop maturity in February. Equally importantly, the key role of the soil moisture reservoir in absorbing surplus rainfall at the beginning of the monsoon until recharge is complete was confirmed, as was the transfer of the subsequent surplus to runoff and groundwater recharge. In other words, the simple picture implied by Fig. 1 was shown to be realistic. A simple storage model (Sutcliffe 2004, pp. 108–114) was found to predict the timing and amount of both soil moisture recharge and runoff. To a large extent, this simple model of seasonal rainfall and runoff illustrated by the water balance of the Betwa basin is valid over the whole of the subcontinent.

Climate data of the subcontinent

A generalised water balance of the subcontinent can thus be derived from climate data available in the FAO publication *CLIMWAT* for *CROPWAT* (FAO 1993). For India itself 160 stations are included, and also 17 stations in Bangladesh, 23 in Pakistan and 14 in Sri Lanka, with details of latitude, longitude and elevation. For each station, based on 30 years of records, monthly average values are listed of rainfall, and reference crop evaporation or ET calculated from meteorological records using the FAO Penman-Monteith method. It is possible to carry out a similar analysis to that of the Betwa basin for those stations where the climate is similar. Starting the analysis at the beginning of the year, it is assumed that when the monthly rainfall first exceeds potential evapotranspiration, the initial soil moisture deficit is 200 mm; the deficit is reduced by each rainfall surplus until the deficit is eliminated, when the cumulative net rainfall is taken as runoff until evapotranspiration again exceeds rainfall. This analysis provides an estimate of mean annual runoff for each station.

Inspection of the rainfall records reveals that over most of the subcontinent the assumption of a single rainfall season is valid. In southwest Sri Lanka there are two rainfall seasons, and in southwest India near the Western Ghats there are some stations with evidence of a second season. For these stations the estimation of runoff may be carried through the drier period between the two rainfall seasons with a temporarily increasing soil moisture deficit; the runoff will be lower for a given annual rainfall.

The geographical pattern of annual runoff is illustrated by summarising the results of this analysis in the form of a map (Fig. 3). This shows where irrigation is needed for crop cultivation, and areas where runoff is available for storage. This map reveals great contrasts between different parts of the region, and presents a key to the discussion of early water resources development. The distribution of high runoff is concentrated along the coast and foothills of northeast India, and along the Western Ghats. In the mountainous regions of northeast India, where the monsoon comes into contact with the high ground, the mean annual runoff is of the order of 1000–2000 mm, and much higher at some sites. This high runoff continues in a line to the northwest along the foothills of the Himalaya.

Across the plains and plateaux of Bihar, Uttar Pradesh and Madhya Pradesh, the mean runoff is lower, but varies between 300 and 700 mm, decreasing generally from the coast towards the northwest, to about 100 mm at Ahmadabad in Gujarat. There are exceptions where local topography induces higher rainfall.

Along the west coast and the Western Ghats, the runoff is high, of the order of 1500–2500 mm, with some higher values. However, the runoff decreases rapidly to the east of the Western Ghats, with a few exceptions near local hills. In Andhra Pradesh, Tamil Nadu and Karnataka, the runoff is likely to be confined to occasional storms except along the coast. The Central Highlands of Sri Lanka give rise to significant runoff. The plains of Pakistan, on the other hand, rely on runoff from the mountains to the north and west.

Key climate stations

This account is further illustrated by histograms of rainfall and evaporation for selected stations (numbered in Fig. 3). In Fig. 4(a) three stations in north India illustrate the modification of the monsoon from the east coast: Sagar Island, Bhopal and Ahmadabad. Although these stations share the single monsoon season, the duration of the rainfall season decreases steadily from east to west; in turn the runoff season, after the soil moisture deficit is replenished, decreases sharply from about five months to three and to one month. In Fig. 4(b), where the climate in south India is illustrated by Mangalore, Mysore and Chennai (Madras), there is a clear contrast between the intense rainfall near the Western Ghats, the bimodal rainfall at Mysore where the rainfall is divided between two seasons and the runoff reduced, and the late rainfall at Chennai.

A useful map of Indian climate (Fig. 5) is included in Rao's (1981) *The Climate of the Indian Subcontinent*; it illustrates water availability duration in days. This is the period when the rainfall and soil moisture storage are together able to meet the losses due to potential crop transpiration, in which the duration of the rainfall season and the water storage capacity of regional soils have been taken into account. It clearly illustrates the duration of water availability in the plateau near Bhopal, and by contrast the limited availability of moisture to the east of the Western Ghats.

To generalise about water resources potential in India, the areas of moderate runoff in Bihar, Orissa, Uttar Pradesh and Madhya Pradesh are favourably placed, though potential decreases to the west. Peninsular India is reliant on rivers rising in the Western Ghats and flowing towards the east, like the Krishna and the Kaveri (Cauvery). There is a wide area to the east of the Western Ghats where local runoff is very low, where local village tanks are likely to be viable, but runoff from inflowing major rivers is required to maintain major irrigation areas in the deltaic plains. In general, ancient local irrigation is likely to be viable in north or northeast India, while major rivers draining the Western Ghats are needed to maintain large irrigation areas in southeast India.

The three rainfall stations in Sri Lanka in Fig. 4(c) reveal the humid climate at Nuwara Eliya in the Central Highlands, the intermediate climate at Kandy, and the comparatively dry climate at Anuradhapura, which have given rise to the complex system of river diversions and storage reservoirs to compensate for the variability of climate. The stations in Fig. 4(d), on the other hand, reveal the semi-arid conditions of the lower Indus basin, where the water resources provided by external rivers are vital.

A map of net annual evaporation, or annual evapotranspiration less mean annual rainfall, which is closely related to irrigation demand, is shown in Fig. 6; the distribution is less variable than local runoff. The total decreases steadily from over 2000 mm over the plains of Pakistan to less than 500 mm in southwest and eastern India and in Sri Lanka.

Historical water resources development

The historical exploitation of water resources in South Asia has been influenced by the natural distribution of rainfall and runoff; because they are so closely linked to the unusual topographic control, the geographical pattern is likely to have remained similar to the present pattern over recent history. The variation of rainfall magnitude, on the other hand, over recent millennia is beyond the scope of this paper. As noted by Rao (1981), *"Perhaps in no other part of the world has physiography determined the climate as in the Indian* *subcontinent. The significant features are the very high mountains in the north with broad plains below them, the tapering peninsula to the south, hill ranges to the northwest and northeast and a lower range running along the west coast of the peninsula."* Within this context, examples from different regions illustrate the diversity of water resources methodologies. Figure 7 shows some of the major river systems and historical sites discussed.

A summary of regional water resources systems (Agarwal and Narain 1997) draws on British-era gazetteers and recent ethnographic studies, and illustrates many traditional structures. Although most systems included wells and "village tanks" or small storage structures, there is also evidence for diversion dams and feeder channels. The relative importance of these features varies with climate and topography.

For example, in the arid climate of Baluchistan and the Kutch peninsula, there is archaeological evidence for wells and stone dams to store water from local runoff. These ancient structures, known as *gabarbands*, are sloping stone rubble structures sited to intercept intermittent storm runoff and alluvium from hillsides. By contrast, in the Himalayan foothills, terracing and contour canals leading to cultivation plots are used to maintain agriculture. On the Indo-Gangetic plains, wells and feeder canals are used to convey water from streams in the foothills. In south Bihar, where slopes are low, irrigation has since ancient times depended on low rectangular embankments known as *ahars* which were flooded by canals from seasonal runoff; these reservoirs were used either to irrigate downstream or to grow rice within the reservoir itself. In Gujarat and Rajasthan groundwater is accessed by deep step-wells or *baolis*, which have been excavated with a series of steps up to five or six storeys deep.

In central India, a number of different approaches were common until the recent onset of pump irrigation. In Madhya Pradesh rectangular embankments were located in areas of the clay-rich "black cotton soil" important for winter wheat production. In the Deccan plateau, wells and earthen dams were the main sources of irrigation, but diversion weirs with storage structures were also used. In the Western Ghats *qanats* or horizontal tunnels tapping groundwater from hillsides were used in various areas. A number of large rivers flow into the low-lying deltaic plains of Bengal and the eastern coastal plains of Orissa, Andhra Pradesh and Tamil Nadu. In general the lands were below the river channels and rice irrigation depended on flooding, supplemented by diversion canals and storage tanks and by monsoon rainfall. Rivers flowing through the plateau were difficult to control directly, but historical sites like Vijayanagar and Seringapatam were irrigated by means of diversion dams or *anicuts* leading to storage tanks.

North India

The authors' interest in the topic of ancient Indian irrigation was stimulated by the investigation of a group of 16 dams located during the Sanchi Survey, an archaeological study carried out between 1998 and 2005 (Shaw 2000, 2007, Shaw and Sutcliffe 2001, 2003a, 2003b, 2005). The study centred on Sanchi, a Buddhist monastic site with World Heritage status in the Betwa basin in Madhya Pradesh, and covered an overall area of about 750 km^2. In addition to Sanchi, the survey included four other known Buddhist sites of Morel-khurd, Sonari, Satdhara and Andher, all established between *ca* 3rd and 2nd centuries BC (Cunningham 1854, Marshall *et al*. 1940). The study which resulted in the documentation of numerous ritual sites related to the Buddhist and Brahmanical traditions, as well as habitational settlements and the dams which form the focus of this study, was aimed at assessing the relationship between religious change and broader political, economic and agrarian developments, particularly the issue of agricultural intensification and irrigation. Combined archaeological and hydrological research has shed light on aspects of the dams' construction, irrigation function, land use, chronology and their relationship to nearby settlements and ritual sites.

Within the study area the distribution of dams has been shown to be largely determined by the availability of suitable terrain. The area to the west of Sanchi with a mixture of hills and short valleys, is particularly suitable for dam construction, while to the east, the dams are confined to the hilly area at the edge of an agricultural plain. The dams were constructed of earthen cores, with stone facing on the relatively steep upstream faces, and with flat downstream faces which were presumably designed to reduce damage from overtopping; their heights varied from 1 to 6 m and their lengths from 80 to 1400 m. Their reservoir volumes range from 0.03 to 4.7 x 10^6 m^3, and their reservoir volumes are closely related to the runoff generated from present hydrological conditions and their upstream basins, which could be estimated on the basis of the earlier hydrological investigation of the region (Sutcliffe and Green, 1986); this correspondence (Fig. 8) suggests strongly that the set of dams were built on the basis of a sound knowledge of the principles of water balance. In addition to the design of the reservoirs, the presence of spillways (Shaw and Sutcliffe 2003b, Fig. 8) on at least two of the larger dams, which would pass floods of about 50 years' return period, suggest that flood protection was also taken into account.

Initial chronological indicators in the form of *naga* (serpent) sculptures (Shaw and Sutcliffe 2003b, Fig. 6) on or near some of the embankments have provided dates between *ca* 1st century BC and 5th century AD (Shaw 2004); other chronological pointers were provided by stone-facing type, and by the dates of associated settlements and Buddhist sites. Subsequent dating of sediments from dam material has supported these dates and the hypothesis that the dam construction coincided with the rise of urbanisation and the spread of Buddhism in central India (Shaw *et al*. 2007). It has been suggested that the dams were built to provide irrigation, principally for wet-rice cultivation as opposed to wheat, the staple crop today. This hypothesis is based on the fact that the present-day rainfall and the soil moisture capacity are adequate to maintain wheat from the end of the monsoon to maturity. Recent investigation has suggested that some of the dams were used for irrigation by inundation upstream of the dam, and that others were used for downstream irrigation (Shaw *et al*. 2007).

The relative positioning of the dams within the archaeological landscape, with the majority being situated near a monastic settlement and habitational settlement, suggests strongly that the dams were part of a cultural package that accompanied the spread of Buddhism and urbanisation. Similarities with inter-site patterns in Sri Lanka, where there is evidence for monastic landlordism from *ca* 2nd century BC, support the suggestion that the Sanchi dams were sustained by a similar system of exchange between Buddhist monks and local agricultural communities. The construction of a sophisticated set of water resource structures over a relatively short period of time suggests that the capital and design capability was central to the incoming monastic communities' patronage-generating strategies whereby local farmers were granted access to irrigation in exchange for a form of religious taxation.

In Gujarat, Mehta (1963) has described a series of ancient dams in the foothills northeast of Ahmadabad, with average annual rainfall of 800 mm and runoff of about 100 mm. Those near Devnimori consist of series of dams across the same stream, and in total there are some 18 dams of various sizes along four streams; a number of the dams have spillways. In one case, a relatively large dam (62 m long, 37 m broad, and 9 m high) was constructed across a narrow gorge. The earthen embankment was protected on its upstream face by large quartzite boulders, and its downstream face is relatively gentle; it would have formed a large reservoir with runoff from its steep basin. Two additional dams were built on the flatter ground downstream.

About 2 km to the south, eight dams were built along another pair of tributaries; their heights range from 2.8 to 6.3 m. In view of the construction of series of dams along the same stream, it is not clear whether these dams were built for upstream or downstream irrigation, or whether some were built as silting ponds or for groundwater recharge. Most of the dams may be dated to early in the first millennium AD because of the bricks used and a related image of the 5–6th century AD. On the other hand, a step-well constructed within one reservoir suggests that the dams had gone out of use by *ca* 15th century AD.

Another major dam, near Junagadh further west in Gujarat, well known through inscriptions, was investigated by Mehta (1968) and Shaw and Sutcliffe (2003a). A vivid description of the dam, and the devastating storm which destroyed it, occurs in the well-known inscription of the Ksatrapa ruler Rudradaman (150 AD), which describes his repair of the Sudarsana dam following its destruction, and its original construction during the reign of Chandragupta Maurya (*ca* 320–335 BC). A subsequent repair by Skanda Gupta in 455 AD is also recorded in an inscription on the same rock (Kielhorn 1905–1906).

Mehta (1968) suggested that the original dam looped from the present Uparkot past the Khapra Kodia caves and across the Sonrekh stream to join a ridge on the east bank; the dam would have risen some 22 m above the stream bed. He pointed out a gorge in the ridge with an artificial bank within it which could have acted as a spillway. Shaw and Sutcliffe (2003a) confirmed this location by showing that the bank on the east of the stream was artificial.

The location of the dam, with its basin on the slopes of Mount Girnar which rises to 1100 m above the town of Junagadh, is probably one of the few possible dam sites in Saurashtra, with the average rainfall at Junagadh of 844 mm rising perhaps to 1000–1100 mm on the basin of 20.5 km^2. The area of the reservoir is estimated by Mehta to have been about 1 km^2, and its volume with an average depth of about 10 m is tentatively estimated as 5 x 10^6 m^3, which would be filled with a runoff of 250 mm. No traces of control structures or irrigation canals have been found, but Mehta points out that ample ground would have been available to the east and south of the reservoir.

A prominent water resources feature of Gujarat is the step-well or *baoli*, where series of steps or spiral staircases lead down to a well which may be over 30 m below ground level. In Junagadh there is one within the Uparkot citadel: the Adi Chadi Vav (11th century) with 172 steps and a spiral staircase. There are several in Ahmadabad, including the Dada Hari (1499 AD) and the Mata Bhavani well which is reputed to date from the Solanki period (1063–1093 AD). These underground wells would be more likely to be adequate for domestic water supply than for irrigation.

Chakravarty *et al*. (2006) published a number of accounts of “traditional” historical water management systems from Madhya Pradesh, Gujarat, and Maharashtra, all areas where irrigation is useful for crop cultivation. For instance, excavations at the Chalcolithic settlement of Inamgaon (Pune) (Dhavalikar 2006) revealed that barley and wheat were both cultivated between 1500 and 1200 BC; because wheat requires winter moisture, which is not available in Maharashtra, this indirectly suggests irrigation. In addition, excavation revealed an embankment and suggested that an irrigation canal, some 420 m long and 6 m wide, was used to divert water from an adjacent stream, which was stored in a tank and used for irrigation.

In northwest Maharashtra (Patil 2006) a system of low diversion weirs (known as *bhandaras*) was built obliquely on west-flowing rivers in the Tapti basin to divert water to distribution channels when there was flow in the river. Tradition attributes their construction to the time of the later Farukki rulers (1370–1600 AD). The canal system was elaborate and could exceed 10 km; the allocation system for irrigation water was communally based.

Kirtane and Gandhi (2006) describe historical water management techniques in Bundelkhand, which included parts of present-day Uttar Pradesh and Madhya Pradesh, in a relatively dry hard-rock area of central India with an average rainfall of about 800 mm. Under Chandela rule, after 831 AD, large tanks were built at such sites as Khajuraho and Chanderi, as well as numerous smaller tanks; almost every village had at least one tank. They depended on earthen embankments with broad bases, typically 7:1 breadth to height, with stone pitching at least on the upstream face, and a natural spillway. Most tanks have a temple on the embankment or on a nearby hilltop. The *bhandi* system of cultivation was also used for traditional irrigation in the black soil areas. During the monsoon, rainfall was impounded in bunded fields which were sown after the impounded water had infiltrated or run off. Step wells or *baolis* were also used for water supply or irrigation.

In the Bhandara district within the Wainganga basin southeast of Ramtek, more than 40 000 tanks were built, mostly 250–300 years ago, to provide irrigation (Rajankar and Dolke 2006). The district has the largest proportion of irrigated land in Maharashtra, with nearly 80% of the land under cultivation of rice, wheat and sugarcane. The embankments are constructed of black cotton soil, reinforced by stones where water pressure is high. Water is drawn from the reservoir using tunnels which are blocked by stones or logs.

An exotic system (Raghuwanshi 2006) was introduced by the Mughal emperor Shahjehan in the early 17th century to contribute to the water supply to Burhanpur on the Tapti. With the advice of a Persian geologist, a system of eight *qanats* was constructed to exploit the groundwater of the Satpura basin and converge through rectangular tunnels; parts of the system, some 400 years old, are still functioning.

A potentially larger scale project has been investigated at Ramtek near Nagpur on the boundary between Madhya Pradesh and Maharashtra (Bakker 2008, Shaw and Sutcliffe 2011). An inscription refers to the dedication of an ancient dam near Ramigiri hill near Ramtek, and provides a date of *ca* 550 AD. Satellite imagery and topographic maps led to a modern irrigation dam which was built before 1933 to span a gap about 225 m wide between two ridges which currently gives rise to a large reservoir which supplies a feeder canal to an area of rice irrigation downstream. The topography is so distinctive that the site of the ancient dam must have been almost identical, but the fact that the site is buried by the modern dam means that the height of the ancient dam and therefore the reservoir volume cannot be estimated. However, the basin of the River Sur at the dam site has a contributing area of some 237 km^2, and the present annual average rainfall of the basin is about 1150 mm; analysis of local rainfall records suggests that the average runoff would be about 306 mm or 72 x 10^6 m^3, with considerable variation from year to year.

Within north India these examples suggest that traditional systems of storage have been adapted to the different topographic and geological conditions in different parts of the region. At Sanchi the topography was suited to small-scale structures designed to supply individual sites, while the unique climate regime at Junagadh led to a single structure. The site at Ramtek lent itself to a single structure, which could supply water to a wide area downstream.

South India

Esha Shah (2001) describes the irrigation systems of south India, concentrating on the dry region of Karnataka. Tanks were first constructed in the eastern deltas to store the diverted flows of perennial rivers, probably from 600 AD. Around 1300 AD they began to dominate irrigation in the drier interior region. The simple tanks included earthen dams with stone revetment upstream, a sluice with a tunnel closed by a plug, an overflow weir and a canal network. In Karnataka both northeast and southwest monsoons contribute rainfall but water supply has been uncertain, and that vulnerability has led to the construction in modern times of major dams and irrigation projects. In fact the vulnerability of water supply to the earlier tanks is explicable in terms of the discussion of climate; because the annual rainfall is divided between two monsoon seasons the runoff is lower than would be expected from the total rainfall.

It is no coincidence that major centres, like Vijayanagar and Seringapatam, are located on major rivers flowing east from the Western Ghats. For example, the city of Vijayanagar (fl. 1336–1565 AD) was supplied by the River Tungabhadra, which rises near Mangalore, and is tapped by aqueducts and canals feeding the city tanks and local irrigated village areas (Davison-Jenkins 1997).

The major rice-growing areas on the major deltas on the east coast are dominated by early cities. For example, Vellore and Kanchipuram are situated on the River Palar, which spreads over an extensive and densely populated irrigated delta. Although irrigation was mainly supplied by diversion canals, there are a number of shallow tanks on the plain, which store water. Some of these date back to the Pallava period (6th–8th centuries AD) but were also built by the Chola kings. Just south of Chengalpattu, near the coast, the Chembarambakkam tank is bounded by a 9-km embankment. Tiruchirapalli and Thanjavur respectively at the head and centre of the rice-growing Kaveri delta, depend on flow from the Nilgiri hills. Thanjavur was the capital of the Chola Empire from the 9th to 13th centuries AD. Madurai, an ancient city which was the capital of the Pandiyans (6th–10th centuries AD), near the head of the agricultural delta, is fed by the River Vaigai which rises near Kodaikkanal in the Palni hills.

Sri Lanka

The irrigation systems in Sri Lanka have received much attention, as the scale and complexity of the storage reservoirs and diversion and feeder canals are exceptional. The importance of irrigation in the island is due to the combination of topography and hydrology. The topography is dominated by the Central Highlands, rising up to 2500 m, from which about 100 rivers and streams radiate in all directions. The highland massif is surrounded by a zone of upland ridges and valleys, which is in turn surrounded by a lowland zone, especially in the north. The southwest quadrant of the island benefits from two monsoons, the northeast and southwest, which supply rainfall in May–August and October–January, respectively. Average annual rainfall exceeds 5000 mm on the western slopes of the central massif, and is generally high in the southwest of the island. The runoff from the Central Highlands exceeds 1000 mm. By contrast the rainfall in the northern "Dry Zone" is much lower; the average at Anuradhapura is about 1450 mm, but with a much longer season of rainfall, the surplus or runoff is only about 100 mm. The contrast between the areas of high runoff in the centre and the relatively dry conditions in the agricultural plains of the north and east is responsible for the high demand of water for irrigation and the availability of water within a relatively short distance. On the other hand, the variety of seasons when heavy rainfall occurs has led to a greater variability of flood magnitudes in Sri Lanka, compared with central India, so that dam designers have to plan for the higher possibility of severe floods in Sri Lanka.

While attention has been focused on the larger reservoir structures, a very large number of small tank cascade systems have been constructed by communal enterprise, and according to oral tradition have been in use as long as the larger projects. Some typical cascade systems have been investigated by Panabokke *et al*. (2002); they estimate that a total of 7600 small tanks currently exist in the various provinces of Sri Lanka, and that an additional 7700 abandoned tanks can be observed to give an overall total of over 15 000 tanks, which are markedly concentrated in the Northwest and North Central Provinces. These systems consist of networks of linked small reservoirs designed to irrigate rice, provide water supply for humans and livestock, and to induce groundwater recharge. There is evidence of integrated development by regulating flow from tank to tank, and thus reducing flood inflow and breaching. According to tradition, the siting of main dams depended on location of a rock outcrop suitable for a natural spillway. Evidence of major dams at the lower end of valleys showed that all had ideal spillway sites, some chiselled and lowered in elevation. The main difference between major and minor dams was in design of sluices; the major works depended on dressed stone cistern types known as *bisokotuwa*, while smaller works could rely on simpler devices.

The larger irrigation structures in Sri Lanka have received most attention in terms of their design and construction. The Basavakkulama tank at Anuradhapura is known to have been built around 300 BC. This was followed by a number of major irrigation works which have been described by Parker (1909), Brohier (1934) and Arumagam (1969). In terms of volume they range from 4 to 42 x 10^6 m^3, so they are an order of magnitude larger than the Sanchi dams. They reflect a sophisticated level of hydraulic engineering because their local basins are in a number of cases inadequate to fill the reservoirs, and a complex system of river diversions and inflow canals has been constructed, especially in the Anuradhapura and Polonnaruwa areas (Mendis 2002). For instance, in the Anuradhapura region, the important Kala Wewa reservoir is partly fed from the Dambulu Oya , and in turn feeds the Nachchaduwa tank, the Nuwarawewa, the Tissawewa and the Basavakkulama tanks by a series of feeder canals. Similarly, several reservoirs in the Polonnaruwa area are linked by feeder canals with the Mahaweli Ganga at Elahera, including Giritale, Minneriya, and Kaudulla tanks. However, those dams with local basins are vulnerable to extreme floods which can occur in the region. For example, Brohier (1965) notes that when Nachchaduwa tank was examined before its restoration in 1906, four large breaches in the embankment showed that the spillway had proved inadequate. After restoration this reservoir was subjected to a severe flood in 1957, and the embankment was overtopped by more than 300 mm and a breach 120 m wide occurred. Arumagam (1969) described the 1957 storm as unprecedented, with daily rainfall at Habarana on 24–26 December of 418, 477 and 345 mm. Although other serious damage occurred, a number of the ancient dams with small upstream basins supplied by river off-takes, survived intact.

Indus Basin

The analysis of climate reveals that the rainfall in much of Pakistan is such that external rivers are needed to provide water in sufficient quantities for irrigation. The plains of the Indus basin are reliant on the flow of incoming rivers for their water supplies. However, even before modern dams were built to provide storage to extend the period of dry-season flows, it was necessary to construct barrages along the lower reaches of the major rivers to raise water levels to divert flow into irrigation feeder canals. In the past much of the river flow was available to irrigate rice in the coastal delta. This suggests that much of the plains would have relied on groundwater supplies in ancient times. It is notable that the distribution of many of the Mature Harappan settlements *ca* 1900 BC (see Kenoyer, 1998) is concentrated on river courses away from the major rivers and along the foothills bordering the plains.

Summary

To summarise the findings of this study, the water balance has shown a variety of regimes of water availability. North India has a wide area where a reasonable depth of surplus water is available, where the construction of seasonal storage at selected sites could prolong the seasonal availability of irrigation water. Over South India the high surplus generated by the Western Ghats gives rise to a number of east-flowing rivers where water can be diverted to irrigate major centres or provide rice-growing deltas along the east coast. However, there is little local runoff for significant storage sites. In Sri Lanka major storage features could be filled by diversion from numerous rivers flowing from the Central Highlands with their surplus runoff, providing storage for irrigating suitable plains to the north or in coastal areas in the east and south. The Indus tributaries required modern techniques to provide embankments to raise river levels to supply canal offtakes and later large storage dams to provide large-scale irrigation. The development of water resources technology has spread the increase of irrigation in recent years.

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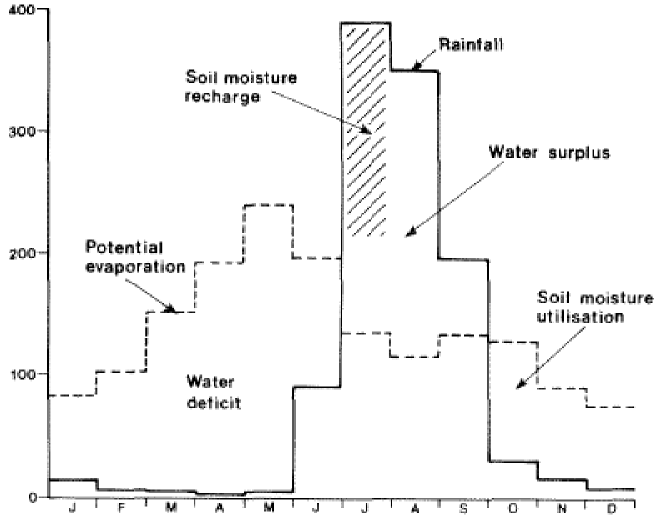

Figure 1: Monthly water balance of the Betwa basin, mm (after Sutcliffe et al. 1981).

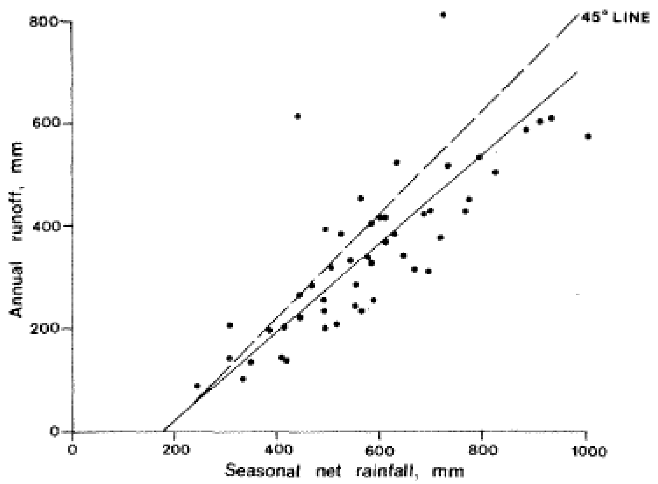

Figure 2: Annual net rainfall and runoff of the Betwa basin, mm (after Sutcliffe et al. 1981).

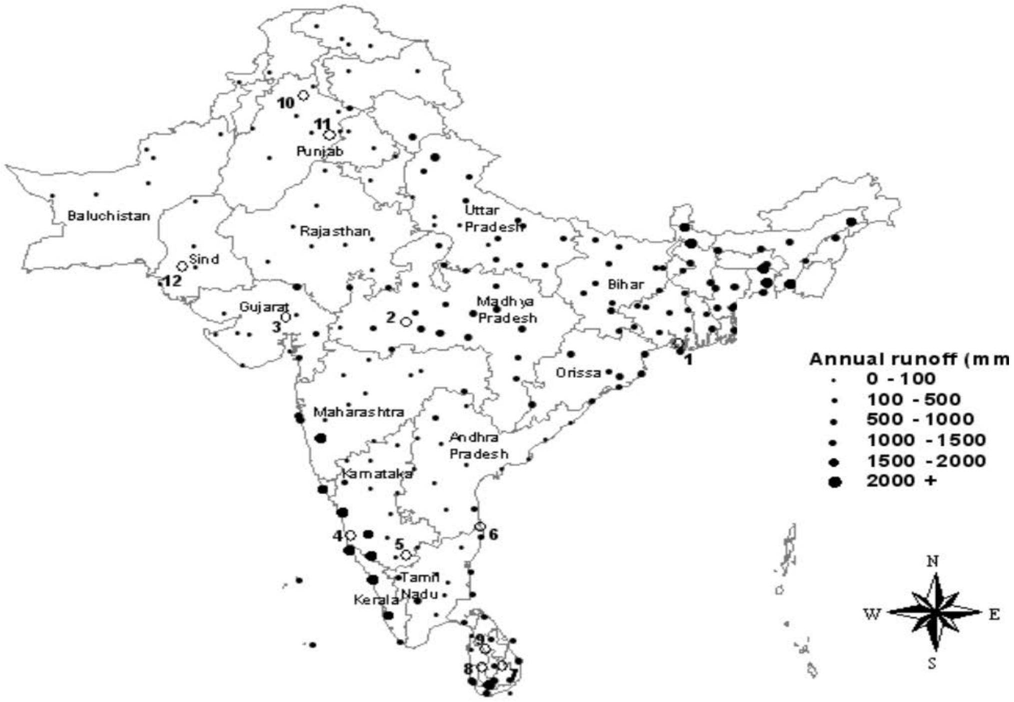

Figure 3: Estimated annual runoff over the Indian subcontinent, mm.

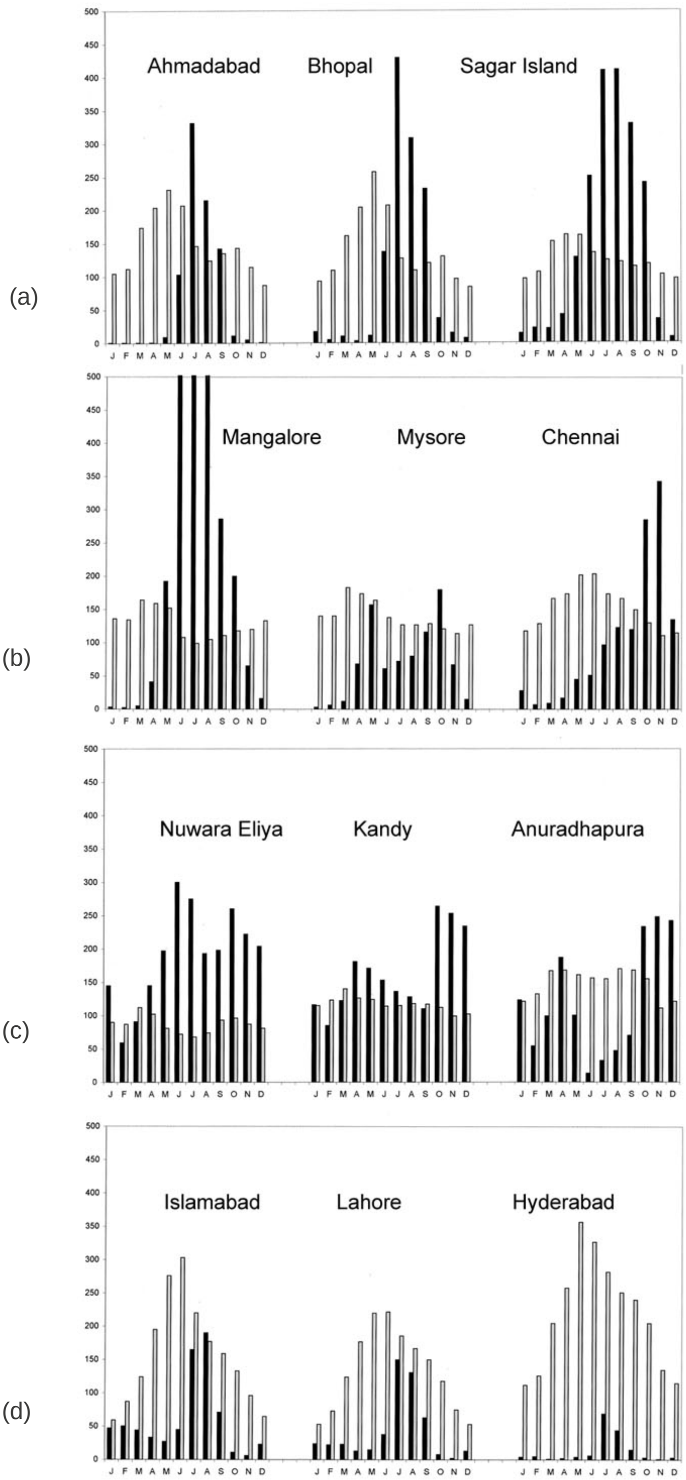

Figure 4: Monthly rainfall and potential evapotranspiration (mm) at selected stations: (a) Ahmadabad, Bhopal, Sagar Island; (b) Mangalore, Mysore, Chennai (Madras); (c) Nuwara Eliya, Kandy, Anuradhapura; and (d) Islamabad, Lahore, Hyderabad.

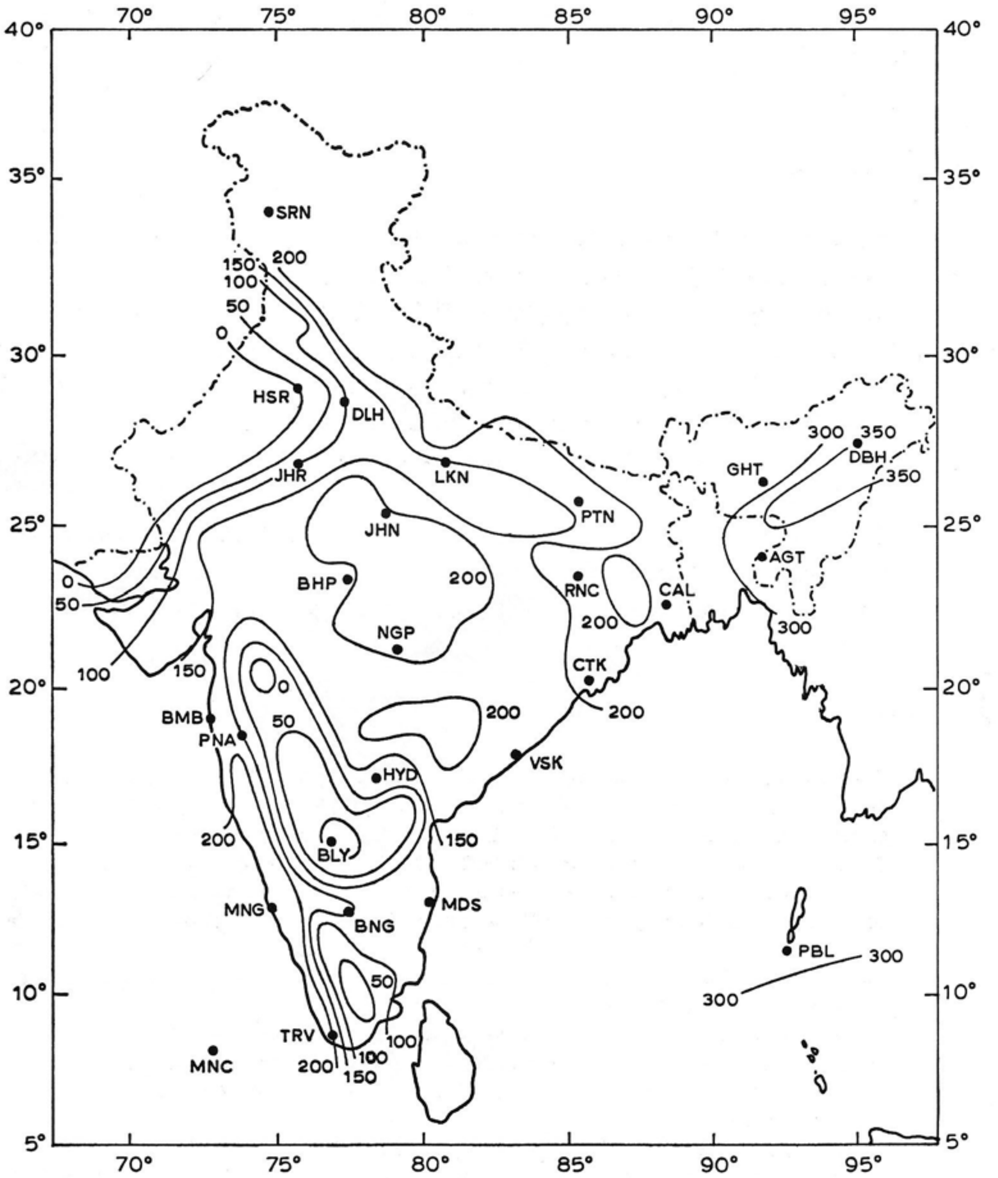

Figure 5: Water availability duration, days (after Rao 1981).

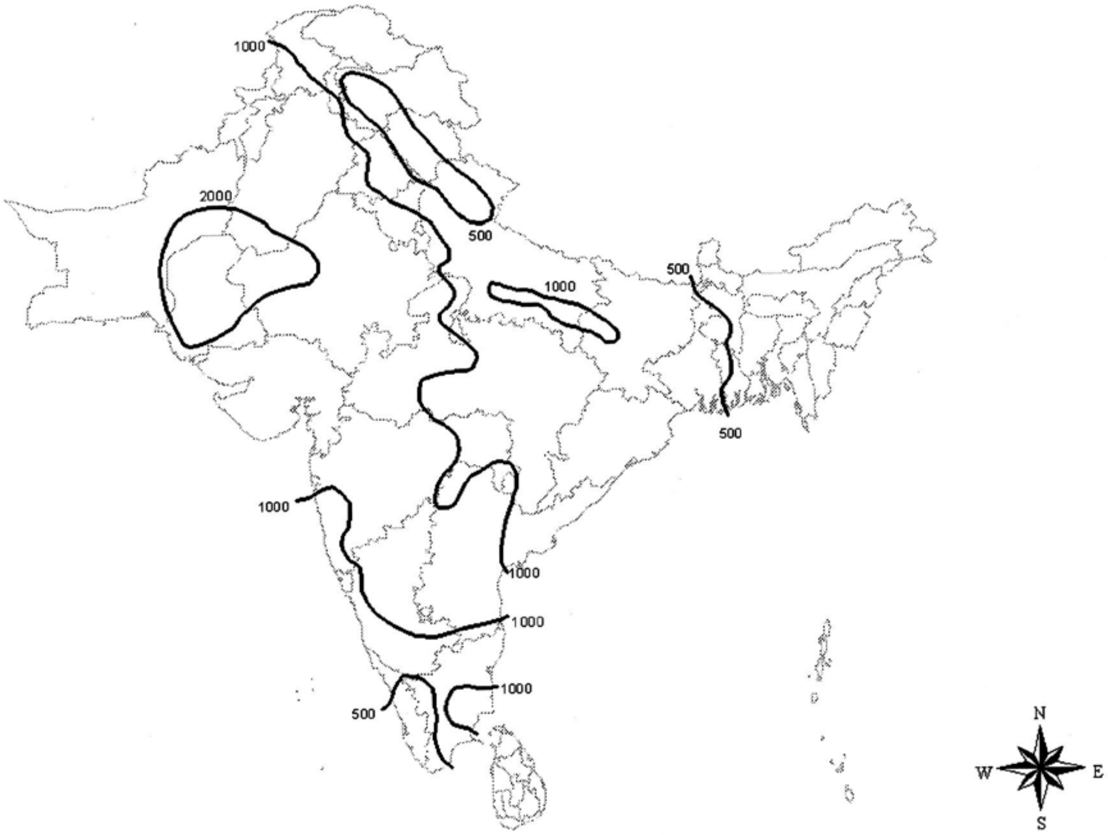

Figure 6: Annual net potential evapotranspiration (mm).

Figure 7: Map of the river system showing water resources sites.

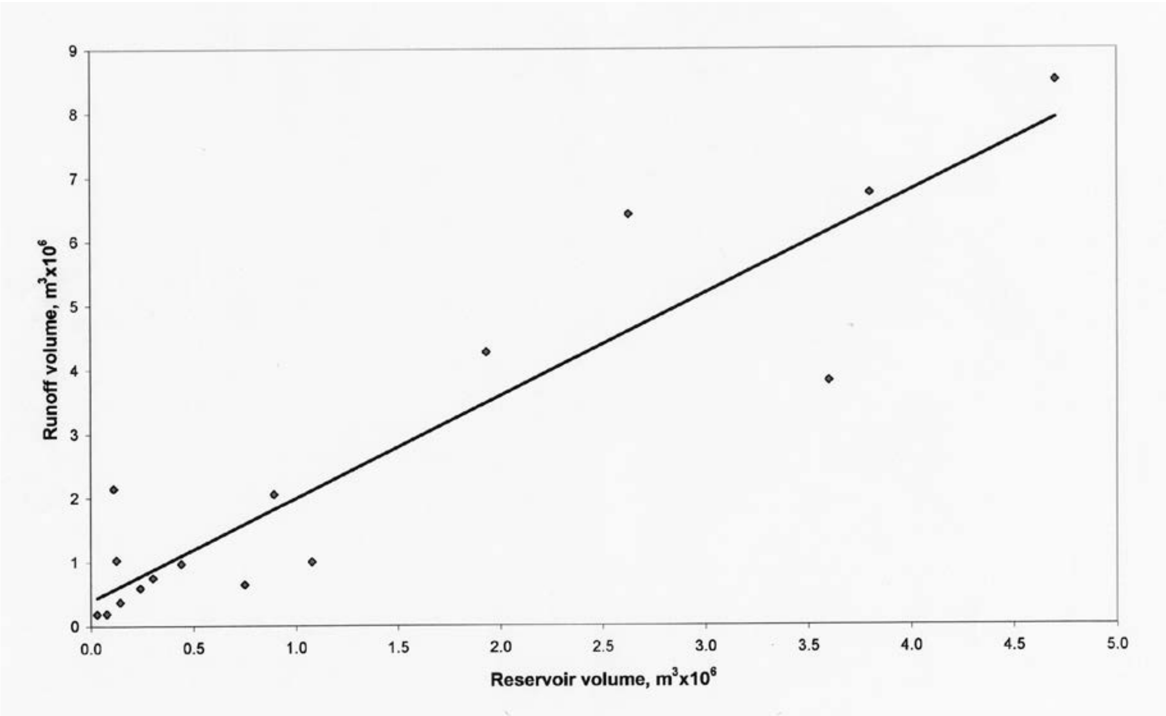

Figure 8: Reservoir volumes and mean annual inflow (x 10^6 m^3), Sanchi area (after Shaw and Sutcliffe 2003b).