Indo-Gangetic river systems, monsoon and malaria

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The history of the Indo-Gangetic river systems from the late nineteenth to the early twentieth centuries can be reconstructed from the meticulous official records of the survey, meteorological and medical departments of the British Government of India. In contrast with the grand sweep of the geological evidence, these records indicate a complex narrative of floods, droughts and channel shifts. Similarly, the cumulative growth of the Ganges–Brahmaputra and Indus deltas was overprinted by the effects of the annual monsoon cycle on precipitation, temperature and winds. Malaria, the principal vector-borne disease of the Indian subcontinent, and the deadliest, displayed epidemiological types that ranged between the extremes of stable–endemic to unstable–epidemic as defined in the classic theory of equilibrium of George Macdonald. Variations in its transmission, incidence and prevalence were closely tied to the different deltaic environments of the Bengal and Indus basins and to the short-sightedness of many irrigation and related engineering schemes.

Keywords: Indo-Gangetic deltas; monsoon; malaria

1. Introduction

To H. F. Blanford, FGS, FRS (1834–1893), palaeontologist with the Geological Survey of India from 1855 to 1862 and Meteorological Reporter to the Government of India from 1874 to 1888, the subcontinent offered ‘many peculiar advantages’ for scientific enquiry. As a region defined, to the north, by the Himalaya and to the west and east by the Arabian Sea and Indian Ocean, it presented ‘in its different parts extreme modifications of climate and geographic features’ [1, pp. 563–564]. From the mid-1870s, systematic observations on geological phenomena and meteorological events were published in the surveys’ annual reports. Meanwhile, under the Registration Act of 1865, the district medical officers of the provincial Sanitary Commissioners’ departments collected monthly observations on births and deaths, with specific reference to climate and physiographic conditions. Deaths were registered inter alia by principal cause—chiefly fevers, of which upwards of one-third were ‘malarious’.

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One contribution of 10 to a Theme Issue ‘River history’.
Nowhere in British India was the range of variation in physiography and climate more striking, nor more closely observed, than in the north, in the great river basins of the Ganges–Brahmaputra system to the east and the Indo-Gangetic system to the west. Against a background of the geological past of these great river systems, as established by advances in geoscience, it is possible to reconstruct a recent history, from the mid-nineteenth century, of fluvial processes, their climate and their environmental diseases from technical records of the British Government of India, unique in their calibre and consistency.

Malaria was British India’s most deadly and debilitating disease. Predominantly a disease afflicting the rural poor, malaria was ‘responsible directly’ for at least 1,000,000 deaths each ordinary year, increased, in epidemic years, by another 25,000. At least 100,000,000 suffered from malaria each year. It probably accounted for an ‘additional indirect morbidity’ of 25–75,000,000. It had a marked adverse effect on the birth rate, and was ‘probably the greatest single cause in retarding the natural increase of the population’ and ‘the greatest factor in lowering the health, vitality and physical development of the people’ where it prevailed. Malaria accounted for annual financial losses ca £80,000,000 to the individual and the family alone. While direct and indirect losses could not be accurately evaluated, there was ‘little reason to doubt that they must run into unbelievable millions of pounds sterling each year’ [2, p. 158].

When systematic registration of mortality began in 1865, environmental conditions—dampness, defective drainage, waterlogging and swamps—had long been regarded as the direct cause of ‘malarious fevers’, and were given prominence accordingly in the Sanitary Commissioners’ reports. Laveran’s identification of the parasite Oscilla (later renamed Plasmodium malariae) as causative organism in Algeria, in December 1880, established an intermediate step between environment and human host. By the end of the decade, two further plasmodia had been discovered in the blood of malarious patients and the association of each species with periodicity of malarial fever—Plasmodium vivax with benign tertian, P. falciparum with malignant tertian and P. malariae with quartan—determined. The passage of plasmodium to host, and the role of environmental conditions, awaited elucidation. In China, in 1878, Patrick Manson, parasitologist—the ‘father of tropical medicine’—had shown how the agent of filariasis, the parasitic worm, Filaria sanguinis hominis, was transmitted by Anopheles mosquito—the female, since ‘the anatomical arrangement of the male’s proboscis and appendages prevented it from penetrating the skin’. The mosquito ingested the filarial embryos, ‘nursed’ them to maturation, then reinjected them into the animal host [3]. Might not the female Anopheles, favoured by the environmental conditions long associated with malarious fevers, be the ‘nurse’ of the malarial parasite? In discussions from 1894 to 1897, Manson discussed his hypothesis with Surgeon-Major Ronald Ross, Indian Medical Service, physician, artist and mathematician. In Calcutta, in August 1897, Ross demonstrated, by experiments of an elegance to match Manson’s hypothesis, the transmission of the plasmodium associated with benign tertian malaria (P. vivax) by the female Anopheles mosquito to an avian host [4–6]. In 1900, Manson, in association with Italian colleagues, confirmed by experiment the transmission of plasmodium by Anopheles to human host—his physician son, whose recording of his symptoms of benign tertian malaria daily and in detail perfected the demonstration [7].
Subsequent investigations into the parasitology and transmission of malaria, the environmental conditions that favoured it and pioneering efforts at control and prevention are described by Bruce-Chwatt [8].

Distilling field and experimental observations on malaria as the prototype of vector-borne disease into a probabilistic theory of transmissibility, generalized as ‘pathometry’, Ross [9,10] laid the foundations of the mathematical epidemiology of vector-borne disease.

Some 40 years later, George Macdonald, malariologist and mathematician, followed Ross’ probabilistic method in his classic paper on theory of equilibrium in malaria [11]. His theory was derived from half a century’s field and experimental observations, given mathematical expression and translated back into epidemiological terms.

Macdonald [11] identified three factors as essential to the epidemiology of malaria: (i) the duration of the extrinsic cycle of the parasite (in the vector); (ii) the vector’s biting habit—specifically, the frequency with which it fed on man; and (iii) the vector’s normal longevity. Factors (ii) and (iii) could be related as the average number of feeds on man that an insect took in its lifetime. These factors affected ‘the probability of an insect becoming infected and thus the density of insects needed to maintain continuous transmission’: they determined the ‘critical density of insects in relation to man, below which the disease tends to disappear’. If the critical density was exceeded, then Macdonald considered that these factors would act to curb ‘progressive multiplication of human cases’.

Macdonald [11, p. 824] described the variability of transmission of malaria between vector and host as a dynamic equilibrium, continually adjusted between stability and instability (see table 1):

according to the degree of the controlling factors, the epidemiology of the resultant malaria corresponds to some point on the scale between the extremes described as stable and unstable malaria.

In stable–endemic areas, transmission of malaria was more or less constant, building up a firm immunity in the host population and thus preventing epidemics. In areas prone to epidemics, transmission was interrupted and immunity fell. The resumption of transmission led to an epidemic, followed by a significant level of immunity for several years [11]. It was well recognized that endemic malaria, despite its relatively low death rate, sapped the strength of the population—and ‘may exercise in the long run a more harmful effect upon the public health than even the most severe epidemic’ [12, p. 418].

Recent exercises in the mathematical epidemiology of malaria have amended and enlarged on Macdonald’s analysis with a variety of modelling techniques [13]. A simulation of the dynamics of transmission of malaria in association with variation in weather, the Liverpool Malaria Model, designed by Hoshen & Morse [14], has lately been updated by Morse and co-workers [15].

From field studies throughout India on which Macdonald built his theory of equilibrium of transmission, with the rate of enlarged spleens and later parasitaemia in a given population taken as the index of malarial infection, variation between stable–endemic and unstable–epidemic types of malaria was localized to specific regions of the Indian subcontinent—a remarkable achievement of the Malaria Survey of India within 6 years of its establishment in 1920 (figure 1).
Table 1. Epidemiological types of malaria, according to Macdonald’s theory of equilibrium [11].

<table>
<thead>
<tr>
<th>Type</th>
<th>Determining Causes</th>
<th>Anopheles Density Required to Maintain Transmission</th>
<th>Endemicity</th>
<th>Seasonal Changes: Effect on Transmission</th>
<th>Fluctuations in Incidence</th>
<th>Immunity of Population</th>
</tr>
</thead>
<tbody>
<tr>
<td>I Stable</td>
<td>Transmission regular, by vector <em>Anopheles</em> of frequent man-biting habit, moderate longevity, at temperature &gt;15°C, favouring rapid completion of extrinsic plasmodial cycle, all altitudes, latitudes</td>
<td>Very low: ≤0.025 man-bites per night</td>
<td>Very high: anophelism without malaria also found</td>
<td>Slight: complete termination of transmission unlikely despite conditions unfavourable to breeding or prolonged adult survival (temperature &lt;15°C, low rainfall, low humidity)</td>
<td>Slight, seasonal: mean value of amount of transmission high, with seasonal and local variations. Virtual cessation of transmission rare. Epidemics unlikely</td>
<td>Regularity of transmission likely to ensure stable immunity with local variations. Experience of malaria and resistance throughout population, except youngest children</td>
</tr>
<tr>
<td>II Unstable</td>
<td>Transmission irregular, with gross variations, by vector <em>Anopheles</em> of relatively infrequent man-biting habit, short-lived, at low altitudes only</td>
<td>Relatively high: 1 to ≥10 man-bites per night</td>
<td>Variation, low-moderate, may be high</td>
<td>Very marked response to variations in temperature, low humidity, other unfavourable vector breeding conditions. Virtual cessation of transmission in some years. Seasonal, severe epidemics: abrupt onset at relatively high temperatures; rapid cessation as temperatures fall</td>
<td>Very marked: mean value of transmission moderate-low, seasonal epidemics exaggerated, endemicity exacerbated by increase in favourable breeding conditions. Major regional epidemics, invasion of previous non-malarial areas where/when climatic factor(s) favour vector longevity, breeding over large areas</td>
<td>Very variable: significant proportion of population not immune, no resistance to upswing in transmission in unstable conditions</td>
</tr>
</tbody>
</table>
The association of these contrasting epidemiological types of malaria and the great river basins of northern India is apparent. In the northeast (NE), humid subtropical region of the subcontinent of south Asia, the western part of the Bengal foreland basin (the oldest, least active region of the inland delta of the Ganges–Brahmaputra system) has a history of stable–endemic, stable malaria, with hyperendemic foci. The death rate was constant, but small, associated with a constantly high spleen rate and a relatively low birth rate [12]. Immunity levels were consistently moderate to high. The semi-arid region of the Indus foreland basin to the northwest (NW), characterized by recent, dramatic river shift particularly in its eastern part, has a history of unstable–epidemic malaria, with hyperepidemic foci. The death rate was high, but for short periods only, with a ‘remarkable freedom from mortality during inter-epidemic periods’ [12].

In the Indo-Gangetic river systems, a dynamic equilibrium between relative stability and instability is adjusted and readjusted by phases of progradation and aggradation, at rates of greater or lesser activity according to the balance of forces—fluvial and, at the coastal deltas, tidal processes, on a seasonal, interannual and interdecadal scale, complicated by the anomalies of the Asia monsoon cycle and constrained by tectonic movements. The systems arose in

*Phil. Trans. R. Soc. A* (2012)
the Himalaya–southern Tibet with the progressive collision of the Indian and Eurasian plates during the Tertiary. The convergence of the plates, together with gravitational spreading, unleashed forces that uplifted the Himalayan ranges and east Asian plateaux—movements that continue at the present day. In the Himalayan–south Tibetan drainage basin, the action of eroding forces towards the head of the rivers is counteracted by northward migration of rivers north of the rising Himalaya [17]. In their passage south, the forerunners of the Indo-Gangetic system have cut great gorges in the south Tibetan plateau and in the foothills through which they debouch, abruptly into the plains of the northern subcontinent, to form vast, braided fans of inland and coastal deltas. Delta building continues, in phases of greater or lesser activity and forcefulness of fluvial and tidal processes, subject below to tectonic movements and above to the vagaries of the monsoon (figure 2; table 2).

Figure 2. The Asia monsoon cycle. From data in Pithawala [18] and Kump et al. [19].
Table 2. History of the Asia monsoon system [20,21].

<table>
<thead>
<tr>
<th>chronology (Ma)</th>
<th>events</th>
</tr>
</thead>
<tbody>
<tr>
<td>9–8</td>
<td>aridity in Asian interior increases</td>
</tr>
<tr>
<td></td>
<td>onset of Asian, East African monsoons</td>
</tr>
<tr>
<td>ca 5</td>
<td>intensification of Asian monsoon</td>
</tr>
<tr>
<td>3.6–2.6</td>
<td>intensification of East Asian NE and SW monsoons continues</td>
</tr>
<tr>
<td></td>
<td>dust transport to North Pacific Ocean increases</td>
</tr>
<tr>
<td>ca 2.6</td>
<td>increased variability in monsoons: continued strengthening of East Asian NE monsoon, weakening of Asian and East Asian SW monsoons</td>
</tr>
</tbody>
</table>

The modern Asia monsoon system is a complex, cyclical weather system in dynamic equilibrium, varying with regular or irregular regularity about a relatively stable norm to unstable anomaly in wind speed and direction, barometric pressure, precipitation, temperature and relative humidity, over years, decades, centuries and aeons [21–25]. But ‘the defining variability of a monsoon system is its seasonal character’ [26, p. 203]. The strongly defined seasonal cycle marks out the Asian monsoon system from others with their weaker annual cycles [27]. The NE monsoon of the Asian cycle, in the NE and NW of the Indian subcontinent, a relatively low-grade wind bringing gentle patchy precipitation, associated with mild temperatures, is in evidence at the turn of the calendar year and dies away through March into a transitional phase, abruptly interrupted, during May–June, by the onset, commonly tumultuous, of the southwest (SW) monsoon winds, in an east to NW progression, the date of regular onset varying according to location. The SW monsoon provides up to ca 80 per cent of the annual discharge of the Indo-Gangetic rivers, augmented by snow-melt. In September, the SW winds are exhausted and come gradually to cessation. A transitional phase follows, to the close of the year. Within the cycle, there is much intraseasonal variability—in onset and duration of monsoon wind, between weak and strong spells, in amount and distribution of precipitation, in coincident temperatures and in relative humidity [23,26].

2. Bengal: the Ganges–Brahmaputra river system

The dynamic equilibrium of the Bengal delta (figure 3; table 3) is most evident where it is least stable, at its margins—south, in the tidal delta of the Bengal coast; north, where the mountain torrents emerge from the gorges into the plains. In the tidal delta, as Hunter, Statistical Officer to the Government of Bengal observed in the course of his field surveys of Bengal (and every district in British India) for the Imperial Gazetteer [32, p. 20]:

An eternal war goes on between the rivers and the sea, the former struggling to find a vent for their columns of water and silt, the latter repelling them with its sand-laden currents.

From the Early Holocene, the shoreline has lost ground to the rivers and retreated south over some 80 kyr, with marked acceleration in pace between 80 and 6 kyr, to its present position (figure 3). The sluggish end-streams of the
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Ganges now debouch into the NW reach of the Bay of Bengal. The deposition of their sediment load varies with their rate of discharge by an order of magnitude corresponding to the seasonal variation in precipitation of NE and SW monsoons. Fluvial processes are here counteracted by the eroding forces of tides with a diurnal variation of 1.9m range, compounded by a periodic variation at 14–15 day intervals, stirred alternately by the clockwise and anti-clockwise gyre of the monsoon wind systems and funnelled 8km or more into the estuary and the network of tidal creeks, relicts of the old Ganges in its migration east–northeast [33].

*Phil. Trans. R. Soc. A* (2012)
Table 3. History of the Ganges–Brahmaputra river system, Bengal delta. Sources: Lindsay et al. [28], Kuehl et al. [29] and Goodbred & Kuehl [31].

<table>
<thead>
<tr>
<th>age</th>
<th>geological era</th>
<th>stage in delta formation</th>
<th>events</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;126 Ma</td>
<td>Early Cretaceous</td>
<td>initial</td>
<td>fragmentation of Gondwanaland: delta formation begins from slow sedimentation at Indian plate margin, northward drift of Indian plate, colliding with Eurasian plate; great increase in rate of sedimentation</td>
</tr>
<tr>
<td>126–49.5 Ma</td>
<td>Cretaceous–Early Eocene</td>
<td>proto-delta</td>
<td>deposition of carbonate–clastic associations: early, in high-latitude, restricted marine environment later, in low-latitude, open marine equatorial environment</td>
</tr>
<tr>
<td>49.5–10.5 Ma</td>
<td>Early Eocene–Mid-Miocene</td>
<td>transitional delta</td>
<td>formation of deep-sea fan from increased sediment load</td>
</tr>
<tr>
<td>10.5 Ma–present</td>
<td>Mid-Miocene–Holocene</td>
<td>modern delta</td>
<td>sea-level high; small deltas form around inner boundary of basin; with successive falls in sea-level, deep dissection of delta sediments</td>
</tr>
<tr>
<td>1.5 Ma</td>
<td>Early Pleistocene</td>
<td></td>
<td>upper delta plain: accretion of major fluvial and flood basin sequences delta depositional sequences largely aggradational depositional sequences mostly progradational; alluvial sands widely distributed across coastal plains</td>
</tr>
<tr>
<td>11–7 ka</td>
<td>Early Holocene</td>
<td></td>
<td>progradation most prominent in western delta, where Ganges system discharging</td>
</tr>
<tr>
<td>7 ka</td>
<td></td>
<td></td>
<td>eastern delta: Brahmaputra shifts eastward, into Sylhet basin, depositing most load inland, not delta front</td>
</tr>
<tr>
<td>&lt;7 ka</td>
<td></td>
<td></td>
<td>Brahmaputra shifts to westward, coastal depositions revived</td>
</tr>
<tr>
<td>7.5–6 ka</td>
<td>Mid-Holocene</td>
<td></td>
<td>In Brahmaputra, further cycle of east–west shift, main Ganges course shifts eastward. Subaerial depositions extend to modern coastline</td>
</tr>
<tr>
<td>by 6–5 ka</td>
<td></td>
<td></td>
<td>east delta: progradation of coastline begins</td>
</tr>
<tr>
<td>&lt;5 ka</td>
<td></td>
<td></td>
<td>Brahmaputra shifts to modern, western, course</td>
</tr>
<tr>
<td>&lt;3 ka</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>150 years</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The NW shoreline of the Bay is distinguished by a series of tidal lakes where, as Hunter observed, ‘the strong monsoon and violent currents which sweep from the south during eight months of the year have thrown up ridges of sand’ [32]. The largest of these, Chilka Lake, a pear-shaped ‘inland sea’ at the southern extremity of the Mahanadi delta of Orissa, measured over 70 km long in Hunter’s time, with a surface area varying from a minimum of 891 km$^2$ during the eight dry months to a maximum of 1165 km$^2$ in the rains. The lake was joined to the sea by a narrow neck much silted up since 1780, when the opening in the bar—more than 1.5 km wide—had had to be crossed in boats. Forty years later, the neck was ‘choked up’ and an artificial mouth had had to be cut, which was now silt ing up [32, p. 23]. Hunter observed how the seasonal variation in the dominance of tidal as against fluvial forces was reflected in the composition of lake water [32, p. 20]:

The narrow tidal stream which rushes through [the neck, now a few hundred metres broad] is speedily lost in the wide interior expanse and produces a difference never more than 1.2 m between high and low tide and at times barely 0.45 m, while the tide outside rises and falls 1.5 m. It suffices to keep the lake distinctly salt during the dry months, December to June. But once the rains have set in, the rivers come pouring down upon [the lake’s] northern extremity, the sea-water is gradually pushed out and the Chilka passes through various stages of brackishness into a freshwater lake.

The subtropical tidal deltas of the northern Bay of Bengal, as exemplified today in the World Heritage Site of the Sunderbans, are swamp–creek–lake ecosystems. Their predominant vegetation, forests of mangrove, harbour a wide variety of fauna, not least arthropods, and flora. Mangrove is adapted to the hydrodynamic circumstances peculiar to estuaries. Its swamps are aquatic at high tide, terrestrial at low and subject to discontinuous flow given the wide diurnal and seasonal variation in tidal and fluvial volumes. Trees and roots act as a brake on tidal and fluvial forces and by creating eddies, enforce non-laminar flow. Mangrove is halophilic and adapted to seasonal variation in the saline concentration of creek and lake water [34, pp. 27–42].

The youngest, most active and unstable sector of the lower Bengal delta inland from the coast lies to the east, at the apex of the Bay of Bengal, where the Meghna, carrying a combined sediment load of Ganges and Brahmaputra south from their confluence, enters the Indian Ocean. In the NE monsoon season, the Meghna’s sediment load at a discharge rate of ca 10 000 m$^3$ s$^{-1}$ is easily kept at bay by the tides. During the SW monsoon, when the Meghna increases 10-fold or more, a freshwater layer 50–100 m in thickness displaces the sea water in the north of the Bay [28,29,35].

At the northern margins of the Bengal basin, rivers rising from the eastern Himalaya, still uplifting since the Asia–Eurasia collision of the Cretaceous, pour through steep gorges in the foothills to fan out at the sudden, drastic change in gradient on meeting the plains in great, unstable deltas, their courses shifting direction within the constraints of terraces thrown up by tectonic forces. One such is the Kosi river, one of the great Ganges tributaries to the NW of the basin, in modern Bihar. Draining a catchment of some 61 869 km$^2$, the Kosi is braided throughout the 209 km of its course. Its fan, ca $154 \times 147$ km in maximum width, slopes from 0.89 m km$^{-1}$ at the apex of the cone to 0.06 m km$^{-1}$ at its base [36, p. 291]. Its discharge may vary by ±50 per cent, from 0.006 to 0.024 m$^3$ s$^{-1}$ from NE to SW monsoons, with an average annual sediment load of 118 000 000 m$^3$. 

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ranging in content from boulders towards the apex of the fan to coarse pebble and shingle over the base, the more coarse sediment contributing to relatively rapid rates of aggradation [29]. The recent history of the Kosi fan is exceptionally well documented. A series of observations from Rennell’s survey of 1731 to the present day shows a shift of 113 km 50° to the west in some 250 years [37,38].

The Kosi’s stepwise migration to the west is less likely to reflect sudden, cataclysmic events, earthquakes and floods but rather ‘stochastic and autocyclic’ shifts [38], irregular ‘oscillations’ by the sediment-laden river, which from time to time is forced out of its course and migrates laterally, overwhelming smaller streams in its path to leave a succession of dead and dying rivers in its wake. The history of delta building in the great plains of the western Bengal basin is written in the intricate networks of obsolete and obsolescent channels: ‘like fossils’, the geologist James Fergusson observed in his survey of the Bengal delta in the mid-nineteenth century. The shallow pools and streams of these remnants of river shift have been transformed into wetlands, bogs and lakes and refreshed seasonally, but irregularly, by the monsoon [38,39].

The onset of NE monsoon sea-winds was first felt in February–March. This winter–spring precipitation, ‘less regular and lighter’ than elsewhere in northern India, continued through April. The transitional phase, in May, was brief [1, p. 600]. From the first or second week of June, the SW monsoon current ‘pours into the funnel-shaped opening occupied by the delta, then turns westward and passes up the Ganges Valley towards the Punjab. The Bengal basin is thus the recipient of most of the moisture it carries’. The SW monsoon phase ended in late ‘autumn’ rains, in October, initiating a turbulent transitional phase when winds over Lower Bengal—the delta—were ‘conflicting and variable and calms (alternating with storms) at their maximum frequency’. From the end of October and November, the NW wind current of Upper India combined with NE winds of north Bengal in a continuous stream over the Bengal basin, heralding the next NE monsoon phase. Temperatures were generally more equable in humid, subtropical Bengal than in the semi-arid NW. From a mean of 66°F (19°C) in January, there was a gradual rise to a mean of 85–90°F (29–32°C) in April, with a further, slight increase in May. Temperatures decreased through the SW monsoon phase from June. Regions where the rains were most copious, such as Bengal, were the coolest. By early October, as the rains ceased, mean temperature was a near-uniform mean at 81–82°F (27–28°C) [1, pp. 584–585]. Humidity, higher in every season in the tidal than in the inland delta, varied in relation to the prevailing winds. During the driest months, humidity increased, more so in the east than the west, and decreased from the onset of the SW monsoon in June, more so in the west than the east [1, p. 597].

The defective drainage of mature, and more especially moribund, regions of the western–central Bengal delta, the oldest, least active sectors, was highlighted annually, during and after the SW monsoon. These regions correspond, on the malaria map (figure 1), to stable–endemic areas, where malaria of varying intensity was ‘practically never absent…largely a reflex of a multiplicity of natural features of the country…rainwater collections, streams and rivers, swamps, ponds, lakes’ [16]. The spleen rate was rarely above 50 per cent, maximum, largely confined to young children, with a ‘relatively low rate in
resident adults who have had considerable immunity to malaria and suffer little from its effects’, in contrast to the high incidence among—non-immune—immigrants to the region. The map shows extensive areas of high- and hyperendemicity in the deltaic plains within the endemic tracts and ‘apparently associated with secular changes affecting the physiographic conditions’ favouring transmission of malaria: ‘decayed rivers’. Smaller such foci were found where old-established malaria was slowly enhanced in intensity over years. Hyperendemic foci were also associated with forested hills to the north, jungle and terai, boulder-strewn marsh at 305–900 m in altitude at the debouchement of foothill streams [16]. In marked contrast to the western deltaic plains, malaria in the eastern, active delta was markedly lower in both incidence and prevalence, particularly in the tidal delta, which had not lost its mangrove forests [40–42]. The stripping of mangrove from much southern reaches of the old delta from the eighteenth century [39] may well have contributed to a rise in endemic malaria. In these stable–endemic areas, epidemics were rare [16].

The association of malarious fever and its seasonality with physiographic conditions peculiar to the old inland delta of the western Bengal basin—the lie of the land and the effect of the SW monsoon—was well recognized by the Sanitary (public health) Commissioners of Bengal through the later nineteenth century. Observations abound in their annual reports as to how the districts of the old delta constituted ‘a vast alluvial plain intersected by six large rivers, numerous smaller channels and by a labyrinth-like network of forsaken river-beds and old rivers in every stage of decay and effacement. . . . The regularity of the slope of the country is broken up by the tangle of rivers and river-beds that cross and recross one another and obstruct the natural lines of surface drainage. . . . The high mortality in October, November and December is undoubtedly due to malarial fever caused [sic] by the marshy and waterlogged state of the country after the rains. . . . worst in dense jungles and along drying-up river-beds, converted in the monsoon to a series of still pools’ [43]. Jessore district, in the heartland of endemic–hyperendemic malaria, was typical of the moribund delta—‘seamed with the beds of extinct rivers, with a languid vitality during the rains and in dry weather a chain of foetid swamps’ [44, appendix III].

Ross’ and Manson’s experimental confirmation of the mosquito–malaria hypothesis in 1897–1900 was matched before long by field observations. After the (annual, June–August) Ganges floods, the Sanitary Commissioner commented in his report for 1904 that there were ‘large collections of stagnant water [freshened by the recent rains] . . . and as these became breeding places for anopheles, so malarious fever became rife during the latter months of the year’ [45].

Over the next four decades, officers of the Indian Medical Service and, from 1920, of the Malaria Survey of India compiled a mass of field and experimental observations on the transmission of malaria, unique in the annals of epidemiology, identifying Anopheles, their habits and habitats, specific to the several regions of the subcontinent (table 4).

The work of control by the distribution of quinine from local dispensaries and post offices, which had begun in the nineteenth century, was stepped up. But tens of thousands of doses distributed per annum for a population of upwards of some 70 000 000 had little impact on annual mortality. Experiments in prevention by spraying kerosene on breeding pools were sporadic and confined to occasional villages. Throughout the 1930s, the death rate from malarious fevers continued to
Table 4. Bengal basin. Distribution of *Anopheles* species identified by mid-twentieth century [46].

<table>
<thead>
<tr>
<th>Epidemiological type of malaria</th>
<th>Region</th>
<th>Vector</th>
<th>Breeding site, seasonality</th>
<th>Adult feeding habit</th>
</tr>
</thead>
<tbody>
<tr>
<td>stable–endemic, hyperendemic where vector population density high</td>
<td>inland, mature, moribund delta</td>
<td><em>A. philippinensis</em></td>
<td>river relicts—pools, streams, swamps, clear water, in sunlight</td>
<td>chiefly domestic, anthropophilic</td>
</tr>
<tr>
<td>SE coastal deltas</td>
<td><em>A. sundaicus</em></td>
<td>lagoons formed by silting of river mouths, especially where mangrove cleared</td>
<td>anthropophilic &gt; zoophilic</td>
<td></td>
</tr>
<tr>
<td>SE coastal plains</td>
<td><em>A. aconitus</em></td>
<td>swamps, ponds, creeks, river-beds, where cattle abundant</td>
<td>zoophilic &gt; anthropophilic</td>
<td></td>
</tr>
<tr>
<td><em>A. annularis</em></td>
<td>still water with floating vegetation active at 12°C. Increased longevity in autumn clear, slowly moving water with grassy edges, death point 40°C</td>
<td>zoophilic, anthropophilic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>north, NE hills</td>
<td><em>A. minimus</em></td>
<td>clear, slowly moving water with grassy edges, death point 40°C</td>
<td>zoophilic, anthropophilic</td>
<td></td>
</tr>
</tbody>
</table>

...dominate registered annual mortality: at an average for 1937–1940, for example, of 15‰. ‘The total loss...inflicted on this province annually by this devastating scourge is colossal’ [47, p. 67].

3. Punjab: the upper Indus

From its debouchement at the Salt Range—the northwestern foothills of the Himalaya—the Indus river flows for some 1600 km through the semi-arid plains of Indian and Pakistan Punjab and Pakistan Sindh to its exit into the Arabian Sea southeast of Karachi. It drains a foreland basin of 970 000 km²—the world’s 12th largest, and forms the seventh largest known coastal delta of some 30 000 km². Its annual sediment load, deposited in the sea over aeons, some 60 per cent of it by the SW monsoon flood, has formed the gigantic Indus Deep-sea Fan, in its volume of ca 5 000 000 km³ second only to the Bengal (Ganges–Brahmaputra) Fan [48,49] (see table 5). An integral part of an Indo-Gangetic river system following the collision of the Indian and Eurasian plates before 126 Ma, the Indus is thought to have separated from the Ganges, which subsequently expanded eastward. The Indus, and its main tributaries, migrated west. The impetus may have been a strengthening in the SW monsoon from ca 5 Ma, increasing erosion in the Himalaya, bringing down a greater load of coarse sediments from increased erosion in the western Himalaya [48,52]. As the sediment-laden rivers of the western Indo-Gangetic system burst from the steep gorges in the Himalayan foothills into the low-gradient foreland basin, they overwhelmed old courses of the inland delta to form new streams successively to the west [50,51,53]—events similar to sequential river shift in the Bengal basin, as described above, to fetch up in their present course, further gross westward movement being forestalled by the mountain ranges rising northward from the SW.

*Phil. Trans. R. Soc. A* (2012)
Table 5. History of the Indus river system. Sources: Inam et al. [48], Clift & Blusztajn [50] and Schroder [51].

<table>
<thead>
<tr>
<th>age</th>
<th>geological era</th>
<th>events</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;126 Ma</td>
<td>Early Cretaceous</td>
<td>fragmentation of Gondwanaland: northward drift of Indian plate, colliding with Eurasian plate</td>
</tr>
<tr>
<td>75 Ma</td>
<td>Late Cenozoic</td>
<td>palaeo-Indus north, west of present location</td>
</tr>
<tr>
<td>57–37.5 Ma</td>
<td>Eocene</td>
<td>parallel, west-flowing streams south and north (palaeo-Indus) of Himalaya continued uplift of Himalaya, Suleiman Range—corresponding flexion of Indian plate, formation of Indus foreland basin</td>
</tr>
<tr>
<td>24.5–5 Ma</td>
<td>Miocene–Pliocene</td>
<td>ca 18 Ma: diversion of upper Indus south, through Himalaya close to Nanga Parbat massif, into foreland basin and east, into Ganges</td>
</tr>
<tr>
<td>&lt;5 Ma</td>
<td>Pleistocene</td>
<td>separation of Indus, Ganges</td>
</tr>
<tr>
<td>&lt;20 ka</td>
<td></td>
<td>last glacial maximum expansion of Ganges basin</td>
</tr>
<tr>
<td></td>
<td></td>
<td>contraction of Indus basin</td>
</tr>
<tr>
<td></td>
<td></td>
<td>westward migration of major Indus tributaries</td>
</tr>
<tr>
<td></td>
<td></td>
<td>main depositional lobe of Indus (coastal) delta</td>
</tr>
<tr>
<td></td>
<td></td>
<td>formed: westward shift in main channel</td>
</tr>
<tr>
<td></td>
<td></td>
<td>in westward shift, obsolete–obsolescent channels abandoned by main streams, forming riverains</td>
</tr>
<tr>
<td></td>
<td></td>
<td>shift of upper and lower Indus to west constrained</td>
</tr>
<tr>
<td></td>
<td></td>
<td>by uplifting western ranges running north from Karachi</td>
</tr>
</tbody>
</table>

The westward migration of the Indus (figure 4) has been the object of close attention from the early nineteenth century, when British Indian surveyors and administrators, learned in Sanskrit and with a bent for history, began to explore the abandoned riverains (jhils in the vernacular: obsolescent–obsolete river channels in Punjab, turned to ponds during monsoon) of the Indus basin for evidence of the ‘lost river Saraswati’ of Vedic times, the Ghaagar–Hakra–Nara Nadi river systems and the Indus (Harappan) civilization itself and subsequent settlements, successively abandoned and now identified from archaeological remains [54,56–58].

With a resurgence of interest in the Indus civilization since the late twentieth century, professional exploration of the obsolete–obsolescent foreland basin has intensified, equipped with remote-sensing imagery and the latest geophysical and geochemical techniques [51,53,59–61]. As yet, there is no consensus on the exact courses taken by former Indus channels.

The annual monsoon cycle in Punjab was distinguished by its volatility. The NE monsoon, from December to March–April, was more regular and ‘copious’—at a mean monthly precipitation of ca 0.5–1.3 inches (13–33 mm)—than in the south and east Gangetic valley. A transitional phase followed, through April–May and into early June, marked by ‘scanty and uncertain rainfall from occasional thunderstorms’. Rainfall in the SW monsoon, from mid–late June to September, was in
Figure 4. The Indus foreland basin. Westward river shift, plotted from historical documents and archaeological remains. (a) 2000 BC; (b) AD 1940 (based on Wilhelmy [54]). For a critique of Wilhelmy’s reconstructions in the light of LANDSAT imagery, see Ghose et al. [55]. Dashed lines in panel (b) represent abandoned channels.

There was a similarly marked annual variation in mean temperature, from 55°F (13°C) in January, when Punjab was ‘the seat of greatest cold’, to a sharp rise in March–April to 95°F (35°C) and upwards. In the SW monsoon, Punjab became ‘the seat of the highest temperature’, at means of over 90°F (32°C) [1, pp. 586–588]. Humidity in the Punjab plains was at a minimum in May–June and at a maximum in December.

Dry winds were characteristic of Punjab’s weather, and drought frequent. In an examination of anomalies in annual precipitation in Punjab from 1845 to 1878 Blanford showed a complementarity between NE and SW monsoons. In 12 years...
of the series, the NE rains were excessive and SW deficient; in 13 years, the
converse was recorded; in 3 years, both NE and SW monsoons were excessive;
in 6 years, both were deficient. Further, in years of dry land winds and deficient
rainfall during the SW monsoon, an unusually heavy snowfall was recorded in
the NW Himalaya. From this, Blanford suggested that ‘the varying extent and
thickness of the Himalayan snows exercise a great and prolonged influence on
the climatic conditions and weather of the plains of North-Western India’ [62, p. 3].
A recent assessment by Fasullo [63] of Blanford’s hypothesis with satellite imagery
suggests that the association of Eurasian snow cover and the intensity of the
monsoon is complicated by the El Niño Southern Oscillation (ENSO). Northern
India showed the closest association between rainfall and snow cover, vindicating
Blanford.

The distinctive topographical features of the eastern Indus basin were well
recognized in official records of the Government of Punjab. These vast, semi-
arid plains, low in gradient and apparently featureless, were distinguished, on
closer inspection, by ‘great riverains’ lying slightly below the surrounding country,
which had been deserted by rivers migrating to the west. Soils were composed
mostly of fine silt sediments, laced with salts—especially CaCO$_3$, deposited in
concretions known locally as kankar in the desiccation of summer, which formed
an indurated layer a few feet below the surface. The riverains were peculiarly
liable to flood from mid-June to early September, during the SW monsoon. On
its cessation, surface pools formed by rainfall gradually dried out, ‘as much by
evaporation as by absorption’, where kankar layers prevented downward drainage
[64]. The SW monsoon gradually weakened in its progression northwestwards,
with the heaviest precipitation at the eastern extremity of the Indus basin and in
the submontane tracts to the north, and the least, even in a strong monsoon, in
the west.

In the malaria map (figure 1), the epidemic tracts in the NW region are roughly
co-extensive with the foreland basin of the Indus (Punjab), the upper Ganges
basin (Northwestern Provinces, from 1901 United Provinces of Agra and Oudh)
and the arid desert of Rajputana to the west. Christophers & Sinton [16] describe
the prevalence of malaria in this area as ‘markedly seasonal’, being enhanced
somewhat in early summer (March–April), followed by a lull on account of
widespread desiccation, with a marked increase in early autumn (late September),
following the cessation of the SW monsoon.

Within these tracts of unstable–epidemic malaria, the map shows a dense belt
stretching from the centre and east of the Indus basin on to the upper Gangetic
plain, roughly co-extensive with the obsolete–obsolescent Indus riverains. This
belt represents ‘fulminant malaria…vast cyclical disturbances peculiar to this
region’ manifested in a great, pandemic exaggeration of the normal autumnal
rise in prevalence, at ca 8 year intervals and mostly in years when the SW
monsoon was unusually heavy. An area of at least 25 000 km$^2$ was affected, with
death rates of 40‰ or more [2,64,65]. Spleen rates among the population of this
‘hyperepidemic’ belt were characteristically low, ca 10 per cent before epidemics,
rising to 80–90% in their aftermath, to fall gradually back to the usual low level
over the following 5 or so years. Endemicity, and hence immunity, was low [16].
The vast areas of the eastern and central riverains afflicted with epidemic malaria,
particularly in its fulminant form after an exceptionally heavy SW monsoon, made
Punjab ‘the unhealthiest province in India’ [66].
Table 6. Indus basin delta, Punjab–Sindh. Distribution of Anopheles species identified in the twentieth century [46].

<table>
<thead>
<tr>
<th>Epidemiological type of malaria</th>
<th>Region</th>
<th>Vector</th>
<th>Breeding: site, seasonality</th>
<th>Adult feeding habit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unstable–epidemic, with 'fulminant', autumnal, hyperendemic foci</td>
<td>NW India: Indus foreland basin</td>
<td>A. culicifacies</td>
<td>Chief malaria vector of NW India, largely rural, breeds in winter in sluggish streams, river-bed pools, freshwater sheets, irrigation channels, particularly associated with extensive flooding, hibernates in larval stage, adults common from May 1 to end December</td>
<td>Indifferent: zoophilic–anthropophilic</td>
</tr>
<tr>
<td>Unstable–epidemic</td>
<td>NW India: Indus foreland basin</td>
<td>A. stephensi</td>
<td>Sunlit pools, stream beds, marshes, hardy, long-lived anthropophilic &gt; zoophilic</td>
<td></td>
</tr>
<tr>
<td>Epidemic</td>
<td>Central-submontane</td>
<td>A. fuliginosus</td>
<td>Breeds December–January, found throughout year</td>
<td></td>
</tr>
</tbody>
</table>

The seasonality of malarious fevers in Punjab and their association with riverains and heavy SW monsoons had long been recognized by the Sanitary Commissioner’s department. A review of fever mortality from 1869 to 1876 showed a sudden, steep increase in the monthly death rate from fever—mostly of the kind called ‘malarious’—through October to December, chiefly in areas of poor natural drainage with additional ‘accidental obstruction’ [67, pp. 33–34]. Rainfall was ‘invariably excessive every third year’ and associated with maximum prevalence and fatality from epidemic fever ‘in low-lying tracts where drainage is obstructed’ [67, pp. 33–34]. In east Punjab, ‘vast jhils’ formed in the abandoned channels of the Indus in the wake of a heavy SW monsoon in 1887 and the fever death rate rose: in 1887, to over 25‰ [68, p. 33].

From early in the twentieth century, the chief Anopheles species associated with epidemic malaria in the Punjab were readily identified—A. culicifacies chief among them, infesting the central and eastern riverain tract (table 6).

The highest mortality from malarious fevers was recorded in years of excessive SW monsoon preceded by deficient precipitation in the NE phase. With the expansion of breeding grounds in the waterlogged riverains under the heavy summer rains, the Anopheles population exploded, with consequent increase in transmission of plasmodium. Drought in the preceding winter and spring also contributed, indirectly, to increased transmission by changing the biting habit of the female Anopheles. A. culicifacies, the predominant species in Punjab, was zoophilic and would only turn to man ‘as an alternative to starvation’ [11, pp. 820–821; 69, p. 882]. In rural Punjab, such zoophilic Anopheles would feed preferentially on cattle. The death of cattle in vast numbers from drought obliged Anopheles to feed off humans [70].

The melancholy record continued in the twentieth century. Localized epidemics of malaria were recorded in districts marked by riverains and visited by heavy rainfall and floods. A. culicifacies was regularly identified as the agent [65, pp. 12–14; 71, p. 11; 72, p. 19; 73, p. 1].
Within the regions of the Indus basin characterized by epidemic malaria, there were exceptions to the general rule of low endemicity, pockets where spleen rates were persistently high, and immunity in adults relatively rare. These pockets were ‘more associated with old defective [irrigation] systems, where leakage and waterlogging are a feature’—perennial seepage and pooling in terrain and climate geared to episodic, seasonal waterlogging [64]. Whether the large-scale canal systems for perennial irrigation introduced by the British Government of India were responsible for an aggravation of malaria, if so, how much, and how to rectify it, were questions repeatedly debated by Government throughout the nineteenth and early twentieth century [74]. The western Jumna Canal, the first large-scale system in British India, was a strict realignment-cum-reconstruction by British Indian military engineers in the early nineteenth century of an old Moghul irrigation channel meandering through low-gradient plains just to the west of Delhi. Defective drainage along the lower reaches of the canal and the ‘liability of the inhabitants to miasmatic fever’ were the subject of an extensive enquiry in 1847: the three-man committee travelled 1400 miles in a few months, visited more than 300 villages and clinically examined more than 12,000 villagers of all ages. From the findings, Surgeon-Major Dempster devised the spleen rate (which served as index of malarial infection until replaced by blood sampling for parasitaemia early in the twentieth century). The committee concluded that in tracts of stiff, retentive soils, swamps bordered on the canal, from seepage and/or the canal embankments’ obstruction to natural drainage. The district of Karnal was especially remarkable for insalubrity [75].

From the 1850s to 1885, various drainage schemes were implemented, culminating in realignment in 1885, with little change in the annual mortality from fever in the low-lying districts [76, pp. 250–252]. In dry years, the death rate from malarious fever in Punjab fell, except in Karnal district. With an abnormally heavy SW monsoon, it was the worst in the Province—endemicity complicated by fulminant epidemic [65,77,78]. Intensive epidemiological studies of the Karnal district in the 1930s by the Malaria Survey of India showed why: the swamps were favoured breeding places of the chief malaria vectors of the Punjab, *A. culicifacies*, *A. stephensi* and *A. fuliginosus* [77,78].

The great canal systems pioneered in the late nineteenth and early twentieth centuries to reclaim and colonize the uplands of the western Indus basin had a better record, largely because the natural drainage was by no means defective [12]. But where perennial canals, their distributaries and the embankments of roads and railways cut across obsolete and obsolescent riverains of the central and eastern basin, perennial swamps arose and, with them, malarious fever settled into endemicity [76, pp. 254–255].

4. Sindh: the lower Indus

South of the foreland basin, the Indus narrowed in a relatively steep-sided channel to emerge near Sukker, to spread over alluvial plains with a fall of a mere 55 m in 402 km into a huge delta. Most of its old channels east of the main stream were abandoned by the main stream of the Indus in its shifts to the west: ‘the whole surface is furrowed and cross-furrowed by the beds of ancient river channels which have left their meanders’, shrinking to a string of *dhands* or salt lakes. On
the eastern boundary, one old channel, the eastern Nara, meandered southwards [79]. The climate was, and remains, harsh—the epitome of monsoon instability. In field surveys of the 1920s and 1930s, rainfall was described as ‘scanty and precarious’, average annual precipitation ranging from 73 mm at Sukker, at the apex of the southern, inland Indus delta, to 179 mm towards its base, with wild interannual variation; summer temperatures of at least 45°C and a seasonal mean humidity of 41 per cent. Sindh was the driest and hottest of British India’s provinces [18, 48, 79, 80].

Throughout most of its moribund delta, the bed of the main Indus stream is higher than the surrounding country. The subsoil water rises at the time of every inundation, assisted, in the traditional, rich, rice-growing tracts of the delta closest to the main stream, by flooding from seasonal, inundation canals. Sindh was visited periodically by unstable epidemics, as in 1897, 1906, 1916–1917 and 1929, with a high death rate generally through the population, most likely from a coincidence of unusual rainfall and flooding [81–83]. Stable, hyperendemic pockets were recognized, chiefly in the rice-growing tract of Larkana on the west bank of the lower Indus, distinguished by a moderate death rate and high immunity. Elsewhere, ‘the amount of endemic malaria according as local conditions were favourable or unfavourable for the breeding of malaria-carrying mosquitoes…Thus villages situated on the banks of “dead” rivers (e.g. the Sind Dhoro, a former bed of the Indus) were invariably highly malarious’ [80, 81].

In 1932, the Lloyd Barrage at Sukker with its canal system, the penultimate great irrigation enterprise of the British Indian Government, began operation. In 1927, before the Barrage’s construction, Government had launched the Sind Malaria Inquiry. In an exemplary series of field surveys, from May 1928 to May 1935, Gordon Covell and Subedar J. D. Baily surveyed selected areas in all talukas (district subdivisions) that came under the command of the scheme, before and after its coming into operation, together with certain tracts outside, for comparison. Establishing the incidence and prevalence of malaria as above, prior to the scheme’s operation, they revisited each area after it opened in 1932, to assess its effects. They concluded that, in many places, the incidence of malaria had increased: in the areas most affected by the epidemic of 1929, the spleen rate had fallen below its level immediately after the epidemic—the usual finding, as earlier, in Punjab—but was still much higher than in the 10 year period between epidemics observed before the barrage was opened.

The higher incidence, and prevalence, of endemic malaria was to be attributed to ‘conditions favouring malaria transmission produced by the operation of the Barrage Scheme’—familiar from long experience in northern India: a rise in subsoil water level; actual or threatened waterlogging; seepage from some new canals; the ‘cutting-off of sections of old canals, thus forming prolific Anopheles breeding grounds; a 40 mile lake had formed above the Barrage, and the subsoil water level had risen along it; rice cultivation had expanded in the areas outside the scheme, under irrigation with water from the lake and remodelled canals—a wretched catalogue of the adverse effects of irrigation and especially over-irrigation by inundation in the presence of defective drainage, largely determined by geomorphology, and a highly unstable climate, so familiar from the NE Indus basin [80, 84].
Recommendations for rectifying a root cause of intensified malaria transmission by the provision of efficient drainage would not be implemented—or could not, given the simple impediment of low gradient. The options for treatment, strongly recommended by Covell [84], were wretchedly inadequate.

It was fitting that, in 1952, the year Macdonald published his theory of equilibrium, an India-wide programme for the eradication of malaria by eliminating vector populations with dichlorodiphenyltrichloroethane (DDT) was under way, with considerable initial success. The interruption of the programme in the late 1950s has led to a revival of malaria, albeit not with its former ferocity. Our understanding of transmission and transmissibility, while vastly more sophisticated in recent years, with the introduction of complex probabilistic analysis and stochastic modelling, is still far from complete.

5. Conclusions

The use of historical records in reconstructing the recent past of the Earth, its geomorphological processes and the variations of its climates is often frustrated by the limitations of elderly data. For the Indian subcontinent, it is a different matter. Through the later nineteenth century, to the mid-twentieth century, officers of the British Government of India—engineers, surveyors, geologists, meteorologists, zoologists, botanists, physicians—explored the subcontinent’s landscape, its mountains, rivers, flora, fauna, its populations, the history of their habitations, their occupations and their diseases, with inexhaustible curiosity, great skill in observation and methods of surface recording and a remarkable command of the language of analysis, verbal and mathematical.

The great Indo-Gangetic river systems of northern India, the site of continuous habitation over many millennia, were a constant focus of scientific enquiry by the Imperial Government. From its records, unsurpassed in their consistency and accuracy over the better part of a century, an extraordinary river history can be reconstructed—extraordinary in its events, given the dynamic nature of fluvial processes forming these great deltas and the variability of the monsoon weather system to which they were subject, and in the conditions of their environment, which favoured vector-borne disease, principally malaria. With such a history to hand, present-day problems of rivers and their environment may be better understood.

References

Indian rivers, monsoon and malaria


