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Fluvial hydrology and geomorphology of Monsoon-dominated Indian rivers

Hidrologia e geomorfologia fluvial dos rios indianos dominados pelo clima mocônico

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Abstract
The Indian rivers are dominantly monsoon rainfed. As a result, their regime characteristics are dictated by the spatio-temporal variations in the monsoon rainfall. Although the rivers carry out most of the geomorphic work during 4-5 months of the monsoon season, the nature and magnitude of response to variations in the discharge and sediment load varies with the basin size and relief characteristics. Large monsoon floods play a role of great importance on all the rivers. This paper describes the hydrological and geomorphological characteristics of the two major fluvial systems of the Indian region, namely the Himalayan fluvial system and the Peninsular fluvial system. Large number of studies published so far indicate that there are noteworthy differences between the two river systems, with respect to river hydrology, channel morphology, sediment load and behaviour. The nature of alterations in the fluvial system due to increased human interference is also briefly mentioned. This short review demonstrates that there is immense variety of rivers in India. This makes India one of the best places to study rivers and their forms and processes.

Palavras-Chave: Índia, monção, hidrologia fluvia, geomorfologia fluvial

Resumo
As características do regime hidrológico dos rios indianos são controladas por variações espaço-temporais impostas pela precipitação das monções. Ainda que a maior parte do trabalho geomórfico realizado pelos rios seja feito em 4-5 meses durante as monções, a natureza, a magnitude e as respostas na descarga líquida e sólida variam conforme o tamanho e as características do relevo da bacia, sendo que as monções de grande magnitude têm um importante papel em todos os rios.Este trabalho descreve as características hidrológicas e geomorfológicas de dois dos maiores sistemas fluviais da Índia: o sistema fluvial do Himalaia e o da Índia Peninsular. O grande número de estudos aí desenvolvidos indica que existem notáveis diferenças entre os dois sistemas fluviais, com respeito à hidrologia fluvial, morfologia de canal e carga sedimentar. A natureza das alterações introduzidas pelo homem é também comentada. Esta breve revisão demonstra que existe uma imensa variedade de rios na Índia o que a torna um dos melhores lugares no mundo para os estudos de processos e morfologias fluviais.

Key Words: India, monsson, fluvia hydrology, fluvial geomorphology

1. Introduction

The Indian subcontinent is the largest monsoon dominated region in the world. The southwest summer monsoon and associated rainstorms deliver the greatest amounts of moisture. The annual flow pattern of the Indian rivers, therefore, changes in accordance with the monsoon rainfall, and the rivers display all the typical characteristics of seasonal rivers with respect to streamflow, sediment transport and channel morphology. All but a few Indian rivers carry a very high proportion of their annual discharge and sediment load in the 4-5 months of the summer monsoon season. During the remaining part of the year, the rivers carry no flow or very little flow and thus are, by and large, inactive (Kale, 2002).

This paper describes the hydro-geomorphic characteristics of such monsoon-dominated rivers. First, the regime characteristics of the two major fluvial systems of the Indian region are described. Second, the fluvial and flood geomorphology of the two systems are explained. Third, a summary of the studies on the sediment load dynamics is given. Finally, a brief note on the impacts of human interference in the fluvial systems is given.

2. River systems of the Indian region

The Indian region is broadly divided into two major morpho-tectonic units (a) the Peninsular region, and (b) the Extra-Peninsular or the Himalayan region. The Extra-Peninsular region is drained by three mighty rivers and their tributaries, namely, the Ganga, the Brahmaputra and the Indus Rivers. All the three constitute the Himalayan river system. The first two rivers also have tributaries heading in the Peninsular India, but the major drainage is from the Himalayan Ranges (Fig. 1). The Himalayan Rivers are generally perennial, since they also receive flow from the melting of the snow and glaciers of the Himalayan Mountains during the non-monsoon season.

The Peninsula region, on the other hand, is drained by large number of east and west flowing rivers (Fig. 1). The three large Peninsular Rivers (>105 km2) are Godavari, Krishna and Mahanadi (Table 1). The first two originate in the Western Ghat and the last river has its headwaters in the highlands of central India. Two large west-flowing rivers, namely, Narmada and Tapi Rivers, and the Kaveri River of southern India are also considered to be important rivers of the Peninsula (Fig. 1), in spite of their relatively smaller basin area (Table 1). Unlike the Himalayn Rivers, the Peninsular Rivers are entirely monsoon-fed and thus have a highly seasonal flow regime.

The drainage of Thar Desert (Fig. 1), geomorphologically and hydrologically, does not fall in either of the two fluvial systems. The Luni River is the only large river, with well-integrated drainage system in the Thar Desert (Fig. 1). This river displays all the characteristics of desert rivers - wide, shallow and sandy channel, large variability in discharge and sediment load, and unstable banks.

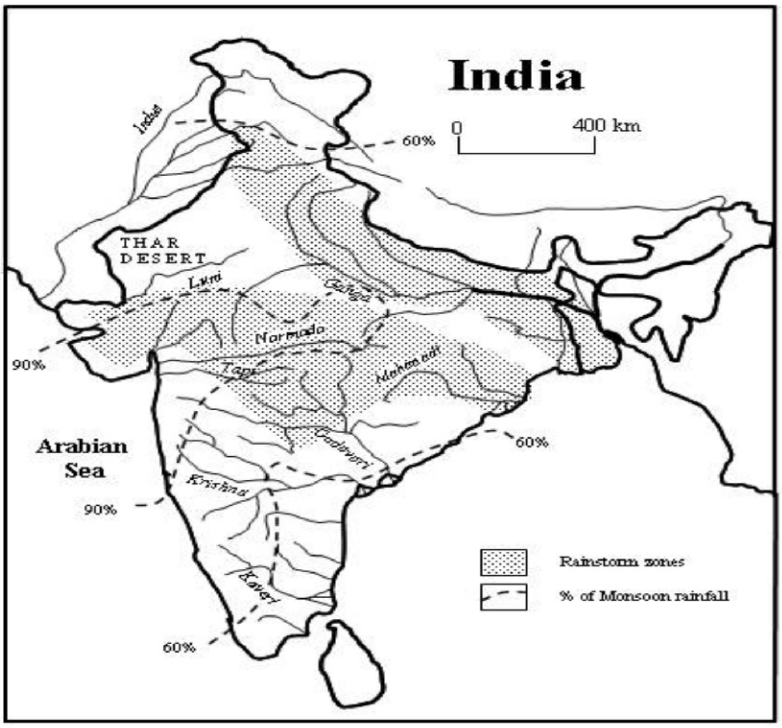

Fig. 1

Figure 1. Map showing the major rivers of India. The map also shows the major rainstorm zones and the percentage of monsoon rainfall. Rainstorm zones after Dhar and Nandargi (1993).

Table 1. Hydrological characteristics of some large Indian Rivers

River	Catchment area in km ^{2}	Peak discharge on record m^3s^{-1}	Sediment yield in $tkm^{2}yr^{-1}$
Indus	468068	32880	1943
Ganga	1050000	72915	1969
Brahmaputra	580000	72748	1891
Godavari	312812	99300	954
Mahanadi	141589	42334	1287
Narmada	98796	69000	906
Krishna	258948	30040	1191
Tapi	65145	41700	935
Kaveri	81155	6205	1214

Source: Sakthivadivel and Raghupathy (1978); Goswami (1998); Central Water Commission, New Delhi.
Sediment yields after Grade and Kothyari (1987)

3. River hydrology

The summer monsoon (June and September/October) contributes more than 80% of the annual rainfall over a greater part of the Indian region (Fig. 1).

Only in the northwestern Himalaya and the southeastern part of the Indian Peninsula the proportion drops to less than 60% (Fig. 1). Since all the rivers are largely monsoon-fed, both the river systems show variations in the patterns of high and low flows and sediment load in association with the variations in monsoon rainfall (Goswami, 1985; M. Singh, 1996; Kale, 2002). Annual hydrographs constructed for some large rivers display a simple unimodal distribution, with their peaks in July-August (Fig. 2). Figure 2 shows that in the case of the Himalayan Rivers the duration as well as the average magnitude of monthly discharges is higher than the Peninsular Rivers. This indicates that the Himalayan Rivers carry enormous volume of water (ca. 1200 km3) and also sediments to the adjoining seas. Another regime characteristic that is evident from the hydrographs is that some rivers experience an order of magnitude increase in their discharge after the onset of monsoons in June/July. Analysis of available discharge data indicates that the Himalayan Rivers carry about 75-85% of their annual discharge during the 4-5 months (June-October) of the monsoon season. This percentage is higher (>90%) for the Peninsular Rivers. It is only in the case of the Kaveri River that the proportion decreases to about two-third because the region also comes under the influence of northeast (winter) monsoon (October to December).

These annual flow patterns suggest that the Indian rivers are characterized by a tripartite sequence of flows

a) Non-monsoon low or no flows for 7-8 months
B) Common monsoon flows for 4-5 months, and
c) Occasional large-magnitude floods during the monsoon season.

4. Flood hydrology

High-magnitude floods are an integral part of the hydrologic systems of all the monsoon-fed Indian rivers. During the gauge period, peak flood magnitudes ranging between <40,000 and 100,000 m3s-1 have been recorded (Table 1). Such large floods are produced by exceptionally heavy to very heavy rainfall during the monsoon season. Such flood-generating events are associated with (Ramaswamy, 1987; Dhar and Nandargi, 1993):

(a)Active monsoon conditions,
(b) Low pressure systems originating over the Bay of Bengal and the Arabian Sea,
(c) Orographic lifting along mountain barriers, and
(D) Breaks in the monsoon

Cyclonic storms and depressions originating over the Bay of Bengal, the Arabian Sea and the adjoining coastal belt are usually the main cause of intense rainfall over the basins and floods on the rivers. Analysis of the most severe rainstorms over India by Dhar and Nandargi (1993) indicates that the flood-generating rainstorms are confined to two zones. The Ganga Plain and the Punjab Plain fall in the first zone and the north part of the Indian Peninsula constitutes the second zone (Fig. 1).

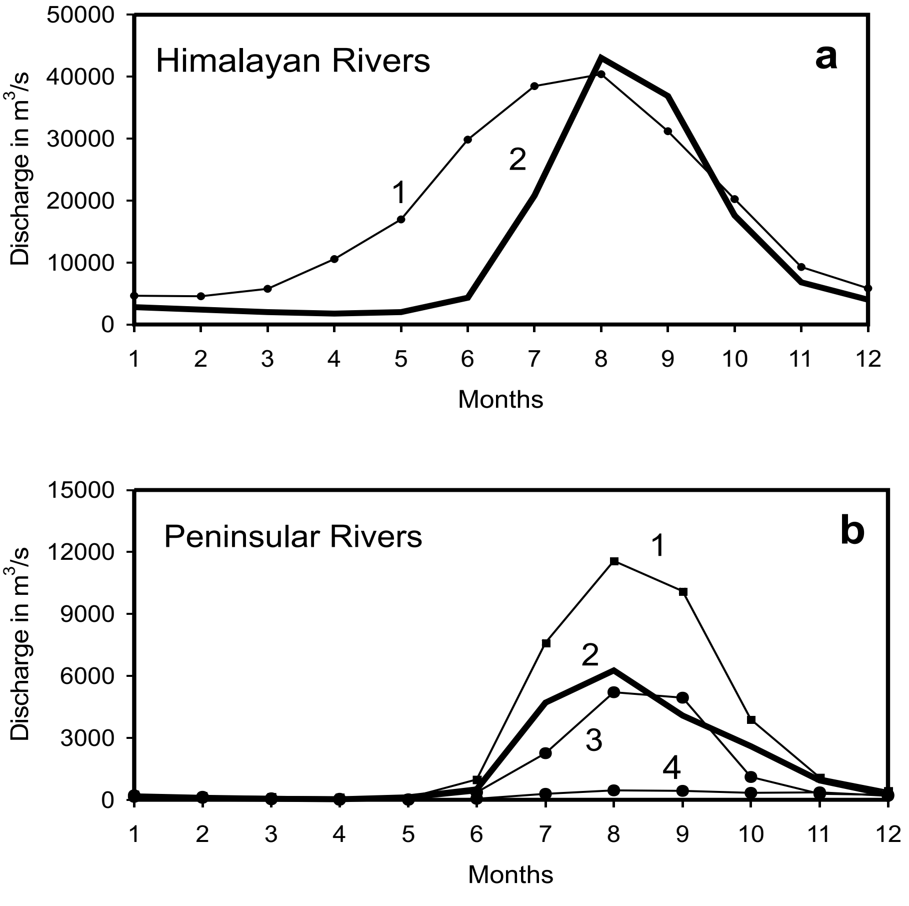

Figure 2- Annual hydrographs (a) Himalayan Rivers 1 = Brahmaputra; 2 = Ganga (b) Indian Penisula Rivers, 1 = Mahanadi, = Tapi, 4= Kaveri.

Consequently, rivers such as Godavari, Narmada, Mahanadi, Tapi, Ganga etc. are subjected to large-magnitude floods from time to time.

Although heavy rainfall is usually the main cause of large floods on Indian rivers, breaching of landslide/debris flow and glacial dams are also known to produce massive floods on the Himalayan Rivers (Wohl and Cenderelli, 1998). Such breach floods have been reported from many Himalayan Rivers such as Indus, Shyok, Sutlej, Bhagirathi, Alaknanda, Teesta, Subansiri, Malipa Gad, Kali and many others (Kale, 2003). In the last century, some disastrous floods were produced by the failure or breaching of man-made dams and embankments, following intense and prolonged rainfall in the catchment. More than a dozen instances of such dam-failure floods are known from the Indian region.

Large year-to-year variability in the flood magnitudes is a special characteristic of the flood regime of the Indian rivers. The Himalayan Rivers, in general, show high average flood discharges, and relatively low variability in annual peak discharges. In comparison, the Peninsular Rivers display large range in the peak flood discharges (Fig. 3). Flash flood magnitude index (FFMI) computed for some large rivers indicates that the values range between 0.1 and 0.3. This along with high average discharges (3000 50,000 m3s-1) indicates that large-magnitude discharges occur relatively frequently on the Indian rivers (Kale, 2003).

Since the annual flow pattern and the distribution and magnitude of large floods varies in accordance with the monsoon rainfall, long-term changes in the monsoon precipitation, El Niño/La Niña events, and variations in the Southern Oscillation Index (SOI) have a strong bearing on the fluvial and flood hydrology of Indian rivers (Bhalme and Jadhav, 1984; Ropelewski and Halpert, 1987; Kripalani and Kulkarni, 1996). Analyses have shown epochal variability in the all India monsoon rainfall series with periods 1880-1900 and 1931-1960 being above-average (wet) and period 1901-1930 and 1961-1990 being below-average (Kripalani and Kulkarni, 1997). Studies by Kale (1998; 1999a) demonstrate that the flood series of some large Indian rivers is strongly linked to these long-period variations in the monsoon rainfall.

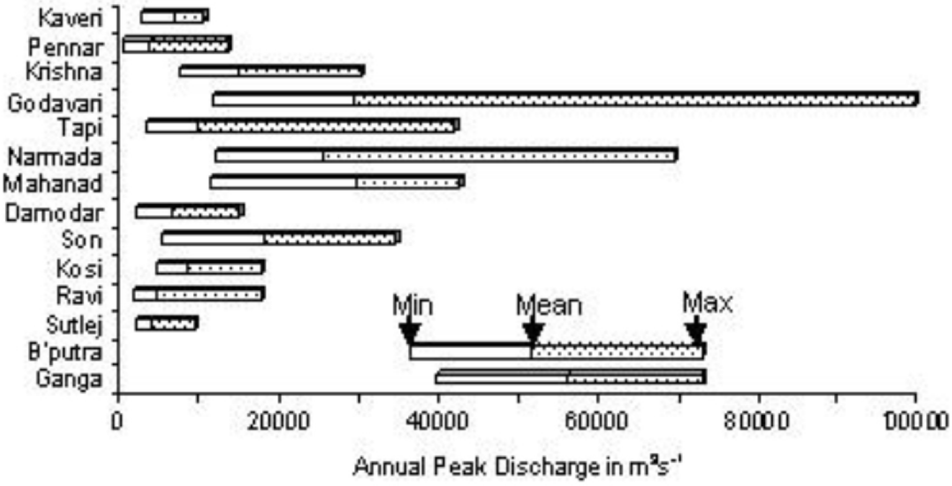

Figure 3. Range of annual peak discharges recorded during the gauge period on Indian rivers.

Century-scale variations in flood frequency and magnitude and a noteworthy clustering of large floods during the historical period (ca. 2 ka) have also been indicated by investigations of slack-water flood deposits. Palaeoflood records from some rivers of central and western India (Kale et al., 1994; Ely et al., 1996; Kale, et al., 2000; Kale, et al., 2003) indicate a period of significantly reduced frequency of large floods during the late Medieval and the Little Ice Age. The studies also suggest that no floods comparable in magnitude to the post-1950 large floods have occurred in the last several hundred years (Kale, 1999b).

Large monsoon floods are important geomorphic events in terms of erosion and sediment transport. Extraordinary floods are characterized by dramatic increase in the channel boundary shear stress and power per unit area. Peak discharges are associated with unit stream power values ranging between 300 and >1000 W m-2 (Kale, 1998; Kale, 2003). Several workers have noted the dominant influence of large-magnitude floods on the channel forms and processes of the Himalayan and the Peninsular River systems (Colman, 1969; Starkel, 1972; Dhir et al., 1982; Goswami, 1985; Sarma 1986; Sarma and Basumallick, 1986; Gupta, 1988; Kale et al., 1994; Gupta et al., 1999; Goswami, et al., 1999; Kale and Hire, 2004). Flood-induced changes include (a) widening of channel, (b) erosion of bars and banks, (c) scouring of floodplains, (d) movement and deposition of coarse gravel (e) changes in channel sinuosity, (f) avulsion and changes in the river courses, and (g) formation of a channel-in-channel physiography.

5. Fluvial geomorphology of Indian rivers

With respect to fluvial geomorphology, the two major fluvial systems of the Indian region, namely the Himalyan and the Peninsular systems, display distinct characteristics on account of significant differences in their hydro-climatic and morpho-tectonic setup. Some of the outstanding aspects are discussed below.

5.1 The Himalayan river system

Most Himalayan large rivers originate and flow through deep valleys, cut across Himalayan Ranges, before debouching onto the Ganga-Brahmaputra Plains. Deep gorges, incised meanders and multiple river terraces are the main features displayed by the rivers and their tributaries in the Himalayan Ranges, characterized by rapid uplift and high incision rates. Studies of cosmogenic exposure using radionuclides (10Be and 26Al) from the upper Indus River by Burbank et al. (1996) indicate rapid river bed erosion rates of 1.9 to 12.0 mmyr-1 over the last ca. 6 to 70 ka. Sharma et al. (1998), however, estimated lower average rate of erosion between 2.0 and 0.30 mmyr-1 for the same river. On the basis of drillhole measurements and cosmogenic radionuclides, Hancock et al. (1998) also found much lower modern and recent (last 2 ka) rates of bedrock erosion in the same river in Pakistan.

In the Himalaya Mountains, slope failure is a dominant geomorphic process (Shroder, 1998). Therefore, landslides and debris flows, following earthquakes or intense monsoon rainfall, are very common. Often river courses are blocked, and breaching of these natural dams generates enormous floods downstream (Coxon et al., 1996; Wohl and Cenderelli, 1998). The capacity and competence of such floods to transport sediments exceeds the common monsoon high flows by several orders of magnitude (Shroder, 1998).

The behaviour of the rivers dramatically changes as soon as they emerge from the Himalayan Ranges onto the Indus-Ganga-Brahmaputra (IGB) Plains. They form a belt of coalescing fans at the Himalayan foothills. Large rivers, such as Ganga, Yamuna, Kosi, Gandak, etc. have developed large alluvial fans, known as megafans, characterized by multiple channel patterns and unstable channels (I. Singh, 1996). Downstream, the rivers retain their dynamic characters and respond to large changes in discharge and sediment load by shifting their courses or by dramatically changing their morphology and bedforms. Numerous examples of abandoned channels, ox-bow lakes and meander scars have been identified throughout the IGB plains on the basis of map and remote sensing studies (Coleman, 1969; Gole and Chitale, 1966; Chitale, 1977; Goswami; 1985; Sarma and Basumallick, 1986; Tangri, 1992; Jorgensen, et al., 1994; Sinha and Friend, 1994; I. Singh, 1996; Sinha, 1996; Goswami et al., 1999). These studies also have brought out frequent channel migrations, continual changes in the bankline, channel width, sinuosity and size of channel bars (Bajpai and Gokhale, 1986; Tangri, 1992; I. Singh, 1996; Sinha, 1996). Several courses of the Kosi River have been identified, that suggest episodic lateral shifting of the river by about 113 km in 228 years (Gole and Chitale, 1966; Wells and Dorr, 1987). Similarly, the Brahmaputra River has shifted its course by 10 km westward in the last 150 years (Coleman, 1969). Geomorphic evidence of avulsion and changes in the channel position of the Indus River, near Hyderabad in Pakistan, have also been identified (Jorgensen, et al., 1994; Goswami, 1998; Goswami et al., 1999). The frequent and sometimes sudden channel migrations have been attributed to tectonic movements, catastrophic floods, extreme sediment loads imposed from upstream and human interference in the fluvial systems (Coleman, 1969; Wells and Dorr, 1987).

On the IGB Plains the channel pattern is determined by the amount of sediment load imposed from the upstream and by the resistance provided by the bank materials (Kale, 2002). Many large rivers, such as Ganga, Brahmaputra, Kosi, Gandak, Ghaghara etc., display braided channel patterns in spite of the fine-grained sediment and very gentle channel slopes (Jorgensen et al., 1994; I. Singh, 1996; Shukla et al., 1999). Other rivers of the plains, such as Gomati, Bhurihi Gandak, Burhi Dihing etc. exhibit highly meandering channel pattern. Large rivers originating in the Himalaya Mountains are braided since they have high ratio of upland area to plains, and have been classified as 'mountain-fed rivers' by Sinha and Friend (1994). For example, the Kosi River has a ratio of more than five and shows a multi-channel pattern. In comparison the 'plains-fed rivers' originate in the plains and have low to zero ratio of upland area to plains (Sihna and Friend, 1994). Such channels reveal highly sinuous channel planforms.

Channel avulsion is one of the dominant fluvial processes observed on the Ganga Plain (Gole and Chitale, 1966; Galgali, 1986; Gohain and Prakash, 1990; Richards et al., 1993; Jorgensen, et al., 1994; Sinha, 1996). The avulsion and subsequent changes in the path of the river channel have been attributed to neotectonic movements, large sediment flux and floods (Wells and Dorr, 1987; Mohindra et al., 1992; Mohindra and Prakash, 1994; I. Singh, 1996; Sinha, 1996).

Due to peculiar relief, rainfall and sediment load characteristics many Himalayan Rivers display some very special and unusual characteristics and features. Some of them are given below:

a) The Brahmaptura River is one of the largest, outsized braided rivers in the world, which is at some places 10-17 km wide and has widened its channel by 2-3 km in 10 years (Goswami, 1985).

b) The Kosi River is one of the most unstable rivers in the world. It has shifted its course by more than 110 km in approximately 230 years (Gole and Chitale, 1966).

c) The Kosi River and other Himalayan Rivers have developed exceptionally large alluvial fans (Gole and Chitale, 1966) in spite of the fact that the rivers are perennial and carry only sand-sized material.

d) The Ganga and Brahmaputra Rivers reveal braided channel pattern on large-scale with large islands (braids) in spite of the fine sandy bedload and very gentle slopes (Goswami, 1985; I. Singh, 1996).

e) Other distinctive features of the Himalayan Rivers are the co-existence of braided and meandering channel patterns, frequent avulsion and shifting of channels, and dramatic changes in channel dimension during floods.

5.2 Peninsular river system

The Peninsular Rivers, in comparison, are more stable, because of low channel gradients and more resistant channel boundaries even in alluvium (Gupta, 1988; Kale, 1990; Gupta, et al., 1999). Most rivers flow alternatively in bedrock and alluvium, and display noteworthy changes in their morphology between sections (Gupta et al., 1999). Since the channels are incised, they have adequate channel capacity and even high flows are insufficient to fill the entire channel (Gupta, 1995). Overbank flows are almost unknown, except in the deltaic regions.

The alluvial channels in the Peninsular India exhibit a channel-in-channel physiography with a small low-flow channel, patches of floodplain, and point bars enclosed within high alluvial banks (Gupta, et al., 1999; Deodhar and Kale, 1999). The channels are filled only a few times in a century, and so the fluvial activity is confined within the banks.

Because of resistant channel boundaries the incised channels of the Peninsular Rivers respond to the increase in monsoon discharge by decreasing their width-depth ratio and increasing their flood power (Gupta 1995; Kale et al., 1994; Deodhar and Kale, 1999; Kale, 2003). Hydraulic geometry equations derived for some large rivers such as Narmada, Tapi, Godavari, Krishna and Bhima (Kale et al., 1994; Deodhar and Kale, 1999) show that the rate of change in depth (f exponent) with discharge is much higher than the rate of change in width (b exponent).

Several of the Peninsular Rivers of India flow in bedrock channels and display spectacular evidences of high-energy flood processes and responses. Two main types of bedrock channels are commonly observed (Baker and Kale, 1998)

Wide, shallow channels, characterized by low channel gradient, absence of sediments, scabland morphology and erosion bedforms, and

Narrow, deep, incised channels, bounded by high rocky cliffs, inner channels, deep pools, rapids, narrow scabland areas and large boulder berms characterise such channels.

Estimates indicate that narrow bedrock reaches are associated with high levels of power expenditure in the range of 102 to 103 Wm-2 (Baker and Kale, 1998; Kale, 2003). Under such circumstances, high rates of bedrock erosion are expected. Kale and Joshi (2004) have provided evidence of the formation of several potholes (0.2-1.0 m in diameter) in about 60 years, within man-made channels and pits carved in bedrock basalt in the channel of the Indrayani River, in the Deccan Trap region.

Although most bedrock channels exhibit single-thread channel pattern, some river reaches display multi-channel patterns in bedrock (Kale and Shingade, 1987; Kale et al., 1996). Kale et al. (1996) have attributed the occurrence of the multi-thread pattern in the Narmada River to block or domal uplift, and intense erosion by extreme floods along linear weaknesses in the bedrock. According to them, the pattern provides a mechanism for channel widening in conjunction with incision, which according to some workers, is the most effective means of energy dissipation in a disturbed channel (Kale et al., 1996).

6. Sediment load and storage

On the global scale, the greatest fluvial suspended sediment discharges are observed in the Indian subcontinent (Milliman and Meade, 1983; Meade, 1996). In general, the sediment yields in case of the Himalayan Rivers are substantially higher than the Indian Peninsular Rivers (Table 1). Sediment yield varies from >2500 t km-1yr-1 in the Himalayan region to <1000 t km-1yr-1 in parts of the Indian Peninsula (Garde and Kothyari, 1986). Due to the high relief, high intensity rainfall, as well as steep and unstable slopes, the Ganga-Brahmaputra River system produces substantially higher loads and yields than all other mountainous rivers of the world (Milliman and Syvitski, 1992).

Annual siltation rates derived from data available for selected large reservoirs in India indicate that the annual rate of silting ranges between 2.6 and 18.2 ha m/100 km2 (Thatte et al., 1986b; Varshney et al., 1986). Available studies also show that about 65 to 70% of the suspended sediment is stored in the channel or on the floodplains and does not reach the sea (Goswami, 1985; Chakrapani and Subramanian, 1990).

Owing to the availability of data, many workers have studied the dynamics of suspended sediment transport in monsoonal rivers, such as Godavari (Bikshamaiah and Subramanian, 1980), Ganga (Abbas and Subramanian, 1984; Singh and Dubey, 1988; M. Singh, 1996), Brahmaputra (Goswami, 1985), Krishna (Ramesh and Subramanian, 1988), Mahanadi (Chakrapani and Subramanian, 1990), Kosi, Gandak and Baghmati (Sinha and Friend, 1994).

The suspended sediment concentration and the discharge are, by and large, not strongly correlated. Accordingly to Kale et al. (1986), Gole and McManus (1988) and Kale and Hire (2004), the suspended sediment concentration is usually high immediately after the onset of monsoon and decreases thereafter. This is mainly due to the increase in soil moisture and the vegetation cover as the monsoon season progresses. Therefore, irrespective of the magnitude, the initial monsoon runoff carries large amounts of sediment. This fact suggests that the timing of high flows, with respect to dry periods is more important in the transportation of suspended load.

Compared to suspended load, there is very little information on the rate of bedload movement from Indian rivers. Only a few studies have been carried out in India. Thatte et al. (1986a) estimated the rate of bedload movement for the Narmada River by entrapping bedload in pits and by using marked pebbles. The seven-year study shows that the bedload range as percentage of suspended load is 1% to 27% for gravel and sand respectively, and that pebbles (2.5 to 6.0 cm) move only 28-55 m in one season. The rate of bedload movement (12.3 t d-1m-1) was found to be only about 1/10th of the rate estimated by using Einstein's and Toffleti's theoretical equations. In the Deccan Trap region, field experiments reveal that during peak monsoon floods, coarse gravel (12-20 cm) is carried a maximum of 10 to 60 m downstream (Deodhar and Kale, 1999). Measurement of bedload in small streams in central Himalaya indicates that bedload constitutes a large part (61%) of the total sediment load (Rawat et al., 1992). In tectonically disturbed areas Rawat and Rai (1997) found that streams carry 24 times more bedload than less disturbed lands.

In general, the Himalayan Rivers are sediment surplus and the Peninsular are sediment deficit. Enormous deposition of sediments by Himalayan Rivers within the river channels and on the floodplains, therefore, is common. As a result, the rivers are highly unstable and are characterized by large alluvial fans, frequent avulsion, bar formation and braiding, and frequent changes in channel position and planform.

7. Anthropogenic activities vis-à-vis river hydrology and sediment load

Dramatic increase in population in the last few decades and associated large-scale changes in the land use and vegetation cover in the catchment areas and widespread developmental activities in the floodplains and deltaic regions have adversely affected the fluvial environment. Studies by Rawat and Rawat (1994), Rawat and Rai (1997), Garde and Kothyari (1987), Singh and Dubey (2000), Forehlich and Starkel (1993), Deodhar and Kale (1999) and others have shown strong influence of anthropogenic activities on runoff, discharge and sedimentation rates.

Engineering structures along (embankments) and across (dams and weirs) the rivers and diversion of river flow have been responsible for noteworthy changes in the hydrological characteristics of floods, sediment supply and morphological characteristics of the channels during the last few decades (Galgali, 1986; Jorgensen, et al., 1994; Basu et al., 1996; Deodhar and Kale, 1999). Construction of numerous dams have been responsible for changes in the channel cross sections due to erosion and aggradation, increased variability of streamflow, diminished sediment supply and reduced magnitude of large floods (Kale, 2002). The impact of man-made structures on the sediment flux has been unambiguously indicated by the sedimentation studies of a large number of small and large reservoirs in various parts of the Indian region (Garde and Kothyari, 1986; Varshney et al, 1986; Grade and Kothyari, 1987). There is little doubt that most of the Indian rivers today, especially in the Peninsular region, are altered fluvial systems. The environmental and geomorphic consequences of such alterations are not fully understood due to paucity of requisite data.

8. Conclusion

The summer southwest monsoon overwhelmingly dominates the rainfall supply of the river basins of the Indian subcontinent, producing ca. 80 to 90% of the total annual rainfall. As a result, the annual flow pattern of these rivers is intimately tied to the pattern of variation in summer monsoon rainfall. Commonly, cyclonic systems embedded within the monsoon system produce heavy rainfall over the basins and floods on the rivers. Because the streamflow pattern of these rivers changes in accordance with the monsoon rainfall, almost all the geomorphic work by the rivers is carried out during the 4-5 months of the monsoon season. Large floods, which occur at an interval of few years to decades, play a role of great importance in both the Indian river systems, since they have the ability to alter the channel and floodplain morphology in a significant way.

On account of the differences in the morpho-tectonic setup, the Himalayan Rivers are different in many respects from those of the Indian Peninsula. The Himalyan Rivers are highly dynamic in nature because they experience extreme variability in discharge and sediment load and dramatic downstream changes in the channel gradient. Earthquake- and rainfall-induced landslides and debris flows have a great impact on these rivers from time to time, especially in the Himalayan Ranges. The rivers draining the Ganga-Brahmaputra Plains are characterized by frequent changes in shape, size, position and planform (Kale, 2002, 2003). In comparison, the adjustments in Peninsular Rivers are less frequent and of a much smaller magnitude (Kale, 2002). Exceptionally large floods are generally confined to the river channels and therefore, all the geomorphic work is also confined within high banks.

The Indian rivers display several riverine forms and features that are potentially of great interest to fluvial geomorphologists. Some of the noteworthy subject areas are listed below.

a) Response of rivers flowing across tectonically active high mountains, with frequent earthquakes, intense rainfall, landslides and rapid decline in channel gradient.

b) Process of braiding and bar formation in outsized rivers (such as Brahmaptura) characterized by enormous sediment load (sand) and massive floods.

c) Formation of megafans by large, perennial rivers (such as Kosi) that have very high basin relief, high ratio of upland area to plains, and huge floods and sediment load.

d) Mechanisms and causes of frequent avulsion in alluvial rivers and unidirectional shifting of river channels.

e) Behaviour of rivers flowing alternatively in bedrock and alluvium.

f)Geomorphic impacts of extraordinary floods on high-gradient and/or sediment-surplus (Himalaya) and low-gradient and/or sediment-deficit (Peninsular) streams.

g) Bedrock erosion and incision under monsoonal flow conditions.

In recent years the Indian fluvial systems are experiencing large-scale (at times rapid) changes in their flow regime conditions, sediment load and behaviour due to increased human interference. It would be interesting to monitor, evaluate and understand the nature of channel adjustments over different time scales. Predicting the geomorphic and environmental consequences of such altered rivers is exceedingly important for one of the most densely populated regions of the world.

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