# Why do Gangetic rivers aggrade or degrade?

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The rivers draining the Gangetic plains exhibit remarkable geomorphic diversity, and this has consequently characterized the rivers to be dominantly aggradational in the Eastern Gangetic Plains (EGP) and degradational in the Western Gangetic Plains. We suggest that steam power and sediment supply are the two main fluvial parameters which govern the aggradation or degradation in river systems which, in turn, are controlled by inherent catchment parameters such as rainfall and tectonics. The aggradation/degradation behaviour strongly influences major fluvial processes such as channel avulsions and flooding and therefore has wide ranging implications for river management projects in the country.

**Keywords:** Geomorphic diversity, Himalayan rivers, river management, sediment supply, stream power.

THE classical models based on the sediment continuity equation[1–3] postulated aggradation or degradation in river systems in response to (a) increase or decrease in sediment supply either from upstream or lateral sources, and (b) rise or fall in base level without any change in sediment supply. The overall response of aggradation or degradation is manifested in terms of channel geometry and depositional style. In more specific terms, it results in sediment storage of the system. Channel beds aggrade when sediment supply exceeds maximum bed load transport rates and degrade when the reverse is true. As a result, an aggrading river system has a shallow cross section and a less prominent valley, whereas the degrading river has deeper and incised valleys. This paper attempts to explain the major hydrological and geological controls of aggradation or degradation in river systems of the Gangetic plains.

The Gangetic plains are drained by many large rivers from which a significant proportion of total agricultural, industrial and drinking water supplies for a large population of about 250 million people of the country are met. Many of the earlier workers in the Gangetic plains have strongly advocated spatial homogeneity of river systems across the plains and have applied depositional models to compare the rivers in widely separated areas[4–6]. Our earlier work has shown that there is a great deal of geomorphic diversity across the plains manifested as variability of fluvial processes, spatial distribution of different geomorphic units and frequency of geomorphic elements[7]. This has consequently characterized the rivers to be dominantly aggra-

dational in the Eastern Gangetic Plains (EGP) and degradational in the Western Gangetic Plains (WGP) (Figure 1). The Ganga river around Kanpur and the Yamuna river around Kalpi in the WGP are examples of incised reaches. The overall topography in the surrounding region is also of degradational nature. All smaller rivers in the WGP are also incised, and in some areas, a strong development of dissected topography is manifested as badlands. On the other hand, the rivers of north Bihar plains in the EGP exemplify a setting where the large rivers such as Gandak and Kosi as well as smaller rivers such as Burhi Gandak and Baghmati exhibit aggradational morphology. These rivers are characterized by shallow and wide channels.

The Gangetic rivers drain through a distinct rainfall gradient across their east-west extent. In general, the western parts receive less rainfall (from 60 to 140 cm) in comparison to eastern parts (90– >160 cm) both in the hinterland and the alluvial plains[8]. Further, the northern part of plains area receives higher rainfall than the southern part. The amount and distribution of rainfall in space and in time directly control the discharge variability in rivers throughout the year but particularly during the monsoon months.

The discharge variability of the river systems can be assessed through the ratio between the maximum and minimum daily discharges ($Q_{max}/Q_{min}$) based on the available historical record (Figure 2 a). Further, the ratio between the mean annual flood and mean discharges ($Q_{maf}/Q_{mean}$) can be used to gauge the intensity of floods in the Gangetic rivers (Figure 2 a). The most interesting observation which emanates from Figure 2 a is that discharge is quite variable in both large and small rivers. In smaller rivers such as Burhi Gandak, Baghmati and Kamla-Balan, high annual variability
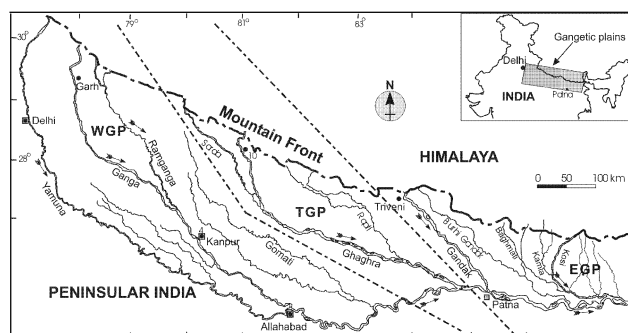


**Figure 1.** Location map of the Western Gangetic Plains (WGP) and the Eastern Gangetic Plains (EGP). The area between the two is marked as Transitional Gangetic Plains (TGP).
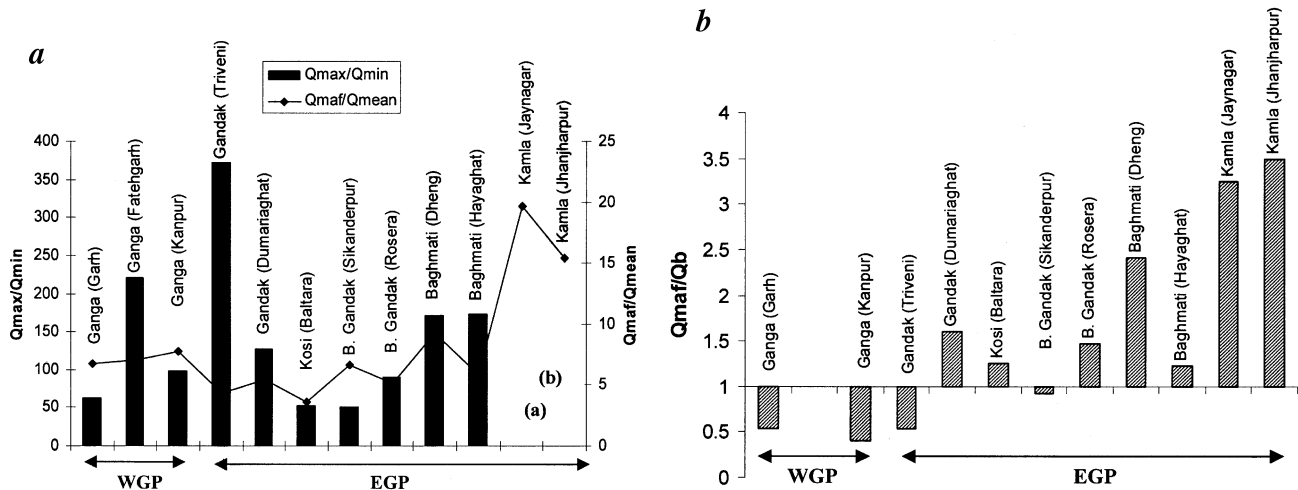
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**Figure 2 $a$, $b$.** $a$, Plot of $Q_{max}/Q_{min}$ and $Q_{maf}/Q_{mean}$ for the rivers of north Bihar to show the variability of discharge and flood intensity respectively; $b$, Plot of $Q_{maf}/Q_b$ for the rivers of the EGP to demonstrate that most rivers flood every alternate year on an average.

of discharge is expected because these are essentially monsoon-fed systems. However, a fairly high variability in large rivers such as the Ganga and Gandak for some stations is a bit surprising given the fact that they are mountain (glacier)-fed[9], perennial systems. This must be related to local channel geometry of the channel or water usage pattern in the surrounding region. Flood intensity variability, as reflected by the ratio of mean annual flood and bank-full discharge ($Q_{maf}/Q_b$), is obviously smaller in small rivers compared to large rivers of the EGP. The fact that mean annual flood in all these rivers is much higher than the bankfull discharge (except for Gandak and Burhi Gandak at upstream stations, see Figure 2 $b$) also indicates that flooding is frequent in all these rivers, at least every second year on an average. Limited data available from the Ganga river in the WGP suggest that $Q_{maf}$ generally does not exceed the bankfull discharge and therefore rivers rarely flood in this region. Flood damage reports[10] also suggest that the area affected by floods in the WGP is almost half ($\sim 20\%$) of that in the EGP ($\sim 39\%$).

The Gangetic rivers erode a large amount of sediments from the upstream Himalayan region, deposit a part of this in the alluvial plains and finally dump a significant amount of sediments in the Bay of Bengal. A recent work on sediment budgeting[11] shows that the Ganga river annually erodes around 794 million tonnes of sediments ( 90% from the Himalaya), brings around 729 million tonnes at Farakka, and finally, 95 million tonnes are dumped in the ocean. Thus, the floodplain of the Ganga river receives around 65 million tonnes of sediments annually. Another estimate of water and sediment flux of the north Bihar rivers[9] using units of mass (kg) transferred per unit time (year) showed that the total sediment flux for the northern Bihar plains is $161 \times 10^9$ kg/year out of which $17 \times 10^9$ kg/year is accommodated by basin subsidence taking a net subsidence of 4 km over 20 million years.

Hydrological and sediment transport characteristics are two main fluvial parameters affecting the aggradation–degradation behaviour of the river systems. I choose unit stream power, defined as ($gQ.s/w$), where $g$ is the specific weight of water, $Q$ the discharge, $s$ the slope and $w$ the channel width, to represent the sum total of hydrological parameters. It must be emphasized that a right combination of these three parameters would give rise to the requisite stream power to erode the river bed and produce incised channels. Figure 3 $a$ plots unit stream power using bankfull discharge as well as the average annual discharge for different rivers in the EGP and WGP. It is striking to note that the stream power of the rivers of the western Gangetic plains rivers is significantly higher ($40–43$ w/m$^2$) than that of the eastern Gangetic plains rivers ($6–20$ w/m$^2$). Data on sediment yield of different rivers of the EGP and WGP (Figure 3 $b$) also indicate that the sediment supply from the upstream Himalayan catchment is variable from west (UP plains) to east (Bihar plains). The WGP rivers such as the Ganga (at Haridwar) and Yamuna (Allahabad) are characterized by low sediment yield of $150–350$ t/km$^2$/yr, while the EGP rivers such as the Kosi (at Barakshetra) and Gandak (at Triveni) rivers are characterized by much higher sediment yield of $1500–2000$ t/km$^2$/yr. Even the smaller rivers show a similar trend, for example, the Ramganga river in the WGP has much less sediment yield ($\sim 300$ t/km$^2$/yr) in comparison to the Baghmati ($\sim 2700$ t/km$^2$/yr) and Kamla-Balan ($\sim 4600$ t/km$^2$/yr) rivers in the EGP. High sediment yields of the mountain-fed rivers in the EGP are quite understandable due to the exceptionally high topographic relief in their source areas and high rainfall in their catchments. The foothills- and plains-fed rivers of Bihar plains show even higher sediment yields and this indicates that the sediments are remobilized vigorously by the smaller rivers[9]. Lower sediment yields of the rivers draining the UP plains is clearly a function of, apart from the distance from
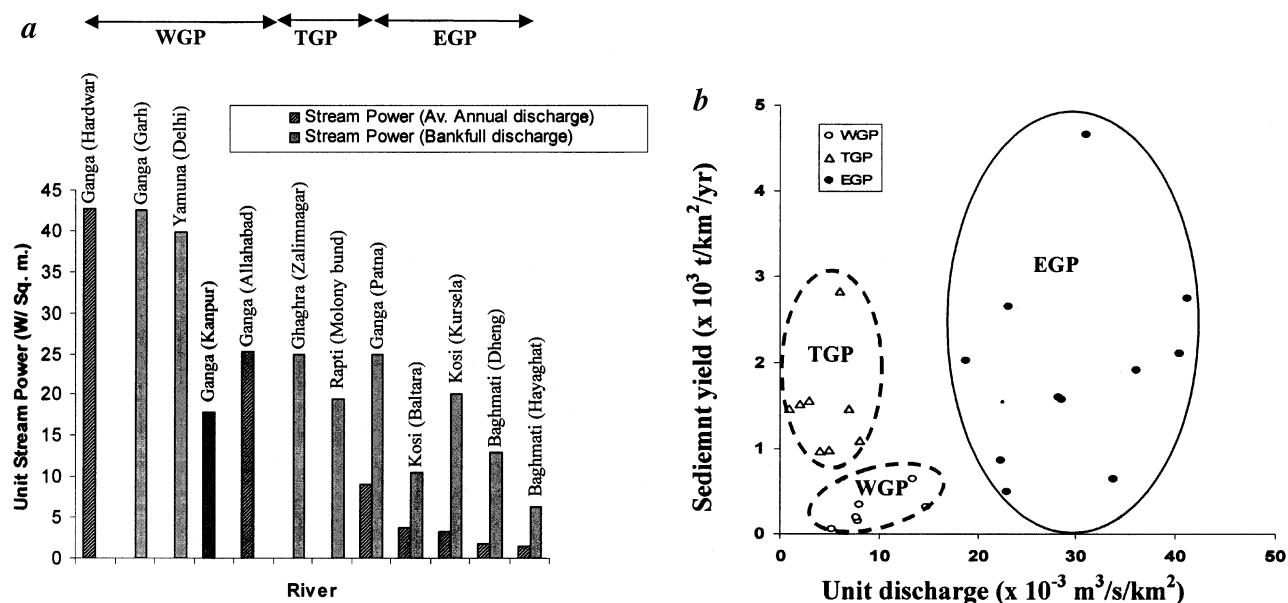
**Figure 3 *a, b*.** Comparison of (*a*) Unit stream power and (*b*) sediment yield of the rivers of the WGP and EGP. Unit stream power has been computed using both average annual discharge and bankfull discharge.

the source areas, difference in rainfall in their catchments and fluvial processes operating in the plains. Not just that sediment production is low in their catchments, there is obviously no remobilization of sediments due to incised nature of the river channels.

Further, tectonic activities of the hinterland of the river systems directly affect the erosion rates and sediment production. A higher uplift rate would eventually mean availability of a larger amount of sediments in the catchment which would ultimately be brought down by the rivers into the plains. On the other hand, tectonically stable catchments would contribute significantly less quantities of sediment to the river systems. The Gangetic rivers draining from the Himalayan catchments plains are obviously affected by the Himalayan tectonics related to the sub-surface transverse faults and longitudinal faults in the Himalaya. Similar to the rainfall distribution, we also observe spatial variation in the uplift rate along an east-west transect. The eastern parts are characterized by higher uplift rate (15–20 mm/yr) along MFT in Nepal[12–14], based on the analysis of deformation of terraces along Baghmati river system. On the other hand, the present models on Himalayan seismotectonics predict westward decrease in uplift rate along HFT and a rate of ~7 mm/yr has been computed around Dehradun[11,14]. Similarly, the crustal shortening rates in the hinterland of EGP have been computed to be much higher (~20 mm/yr)[12–14] than in the WGP (~12 mm/yr)[12,15]. This explains the higher sediment yield of the rivers draining the EGP in comparison to those in the WGP.

It follows therefore that the combined influence of stream power and sediment supply would result into aggradation or degradation. Figure 4 is a process-response system constructed to depict the major controls of aggradation and

degradation in the EGP and WGP. The feedbacks of the individual parameters have been indicated by positive (+) and negative (–) signs. For example, a positive feedback from 'sediment supply' and a negative feedback from 'stream power' would result into aggradation, and vice versa (Figure 4). The rivers in the EGP are dominantly aggradational due to low stream power and high sediment supply which in turn is attributed to higher rainfall and higher tectonic uplift. This has resulted in shallow and wide channels with unstable banks in most rivers in the EGP (Figure 4). In contrast, the rivers in the WGP have an order of magnitude higher stream power and have a much lower sediment yield, and this has resulted in degradation of their channel bed and development of incised channels with stable banks (Figure 4). It is also important to note the negative feedback of 'sediment supply' to 'channel slope'. With continued aggradation due to higher sediment supply, channel slope would tend to decrease, thereby decreasing stream power. It would seem therefore that sediment supply is the most fundamental parameter controlling the aggradation/degradation phenomenon.

Apart from manifestations in channel geometry, two major fluvial processes which are directly affected by aggradation/degradation phenomenon are channel dynamics and overbank flooding. Incised rivers in a degradational setting such as in the western Gangetic plains are confined and stable and show no significant channel movements. Except some localized channel movements in Ghaghra, Rapti and Sarda in the UP plains, no large scale channel movements are reported from this area. These rivers are also not prone to flooding due to deep and incised valleys which seldom allow the water to overtop the banks. On the other hand, in areas of high sediment supply and aggrada-
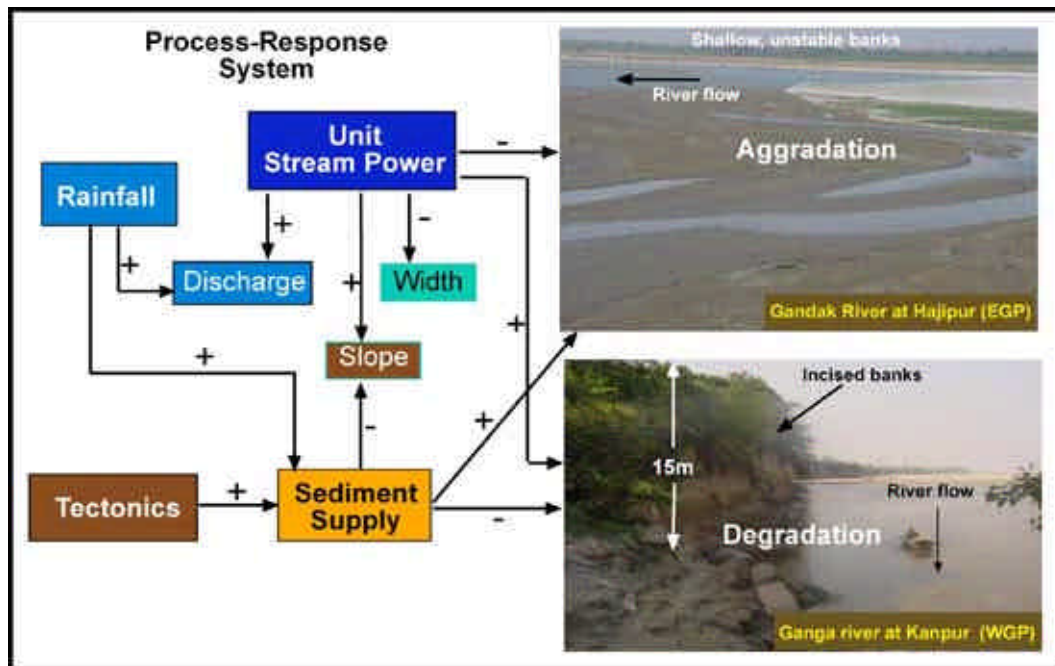
**Figure 4.** A process-response system depicting the controls of aggradation and degradation in the Gangetic river systems. Positive (+) and negative (–) signs indicate the feedbacks.

tional setting, channels are prone to avulsions due to sedimentological readjustments often triggered by neotectonic movements. The filling of sediments at channel mouth up to a level higher than the normal water level allows only the monsoonal flow through the abandoned channel. Most of the large and small rivers in north Bihar plains in the EGP are known for rapid and frequent channel shifting. The Kosi river has migrated for about 150 km to the west in the last 250 years and several studies have documented this migration[16–20]. Besides the Kosi river, the Gandak river has shifted over its megafan from west to east over a distance of about 80 km in a period of 5000 years[21]. The smaller rivers in the EGP such as the Burhi Gandak, Baghmati and Kamla-Balan have also migrated significantly[22,23]. In one of the most comprehensive reconstruction of fluvial dynamics in this region, decadal scale avulsions have been reported in the Baghmati river over the last 250 years and the term 'hyperavulsive' has been used to describe such rivers[24,25]. Major controlling factors for such avulsions are local sedimentological adjustments due to aggradation and neotectonics. Most rivers of the EGP are also known for disastrous flooding almost every year[26–28] and the hydrological data bear testimony to this (Figure 2 b). The dynamic behaviour of river channels and frequent avulsions often divert the flow into a newly formed channel with low bankfull capacity causing extensive flooding.

It is concluded that the stream power and sediment supply are the dominant hydrological controls of aggradation or degradation, and they in turn are influenced by rainfall and tectonic characteristics of the catchment. This explains the geomorphic diversity of the Gangetic rivers in the western and eastern plains which are dominated by degradational and aggradational regime respectively. Apart from its manifestations in channel geometry, the agggradational/degradational behaviour of the river systems strongly influences the fluvial processes such as channel dynamics and flooding. The results of this paper have far-reaching implications for long-term river management in our country, and the ambitious projects such as river interlinking must address these issues. The interbasinal water transfer envisaged in the river interlinking project would certainly alter the delicate balance between the stream power and sediment supply and would thereby influence the fluvial processes operating in different river basins.

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