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Controls on morphological variability and role of stream power distribution pattern, Yamuna River, western India

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ABSTRACT

Understanding the controls on the morphological variability of river systems constitutes one of the fundamental questions in geomorphic investigation. Channel morphology is an important indicator of river processes and is of significance for mapping the hydrology-ecologic connectivity in a river system and for predicting the future trajectory of river health in response to external forcings. This paper documents the spatial morphological variability and its natural and anthropogenic controls for the Yamuna River, a major tributary of the Ganga River, India. The Yamuna River runs through a major urban centre i.e. Delhi National Capital Region. The Yamuna River was divided into eight geomorphically distinct reaches on the basis of the assemblages of geomorphic units and the association of landscape, valley and floodplain settings. The morphological variability was analysed through stream power distribution and sediment load data at various stations. Stream power distribution of the Yamuna River basin is characterised by a non-linear pattern that was used to distinguish (a) high energy 'natural' upstream reaches, (b) 'anthropogenically altered', low energy middle stream reaches, and (c) 'rejuvenated' downstream reaches again with higher stream power. The relationship between stream power and channel morphology in these reaches was integrated with sediment load data to define the maximum flow efficiency (MFE) as the threshold for geomorphic transition. This analysis supports the continuity of river processes and the significance of a holistic, basin-scale approach rather than isolated local scale analysis in river studies.

1. Introduction

Rivers display a variety of patterns and shapes. This variability in morphology illustrates the dynamic nature of the channel and also determines the riverine habitat. The morphological data and understanding of their inherent dynamics provide a basic tool for river rehabilitation planning strategies and for the prediction of river recovery potential (Gore, 1985; Heede and Rinne, 1990; Milner, 1994; Brierley and Fryirs, 2005). Hence, the morphological variability and processes remain the critical areas of enquiry in river science.

One of the earliest studies by Gilbert and Dutton (1880) showed that the shape of the river was influenced by slope and discharge that together constitute the energy regime of the system. Lane (1954) provided a diagrammatic representation of the flow–sediment balance of rivers to explain how channel morphology was shaped by the operation and balance of resistive and driving forces. Morphological appearance forms the basis for river classification distinguishing straight, meandering and braided channels with the subsequent additional class of anabranching channels (Leopold and Wolman, 1957; Nanson and Knighton, 1996). These geomorphic classes were separated on the basis of slope and discharge variability.

Further research has also emphasized the role of sediment supply along with discharge and slope as proxies for resisting and driving forces in morphological variability (Schumm, 1960; Wolman, 1967; Carson, 1984). Subsequently, discharge and slope parameters were integrated in defining the stream power, which was used to characterise the morphological variability at different spatial scales. For example, small-scale bedforms (Simons et al., 1965), spatial variability in bar area and sediment storage (Macnab et al., 2006), occurrence of various channel patterns at reach scale (Ferguson, 1987; Knighton and Nanson, 1993; Van den Berg, 1995) and the major landscape transitions at basin scale from degradation to aggradation stages (Jain et al., 2008) were all related with variation in stream power. In modelling studies, the hypothesis of minimum stream power has been used to explain different channel patterns in river systems (Chang and Hill, 1977; Chang, 1979) and the morphology of meandering streams (Yang, 1971, 1976). One of the major research questions has been the identification of thresholds for morphological variability at a given scale, because threshold identification for geomorphic change could be used to explain the non-linear nature of morphology–flux relationship in fluvial systems (Schumm, 1979, 2005; Phillips, 2006; Jain et al., 2012). Though data from high resolution flume experiments have helped in the identification of geomorphic

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thresholds for morphological variability (Schumm and Khan, 1972), the identification and quantification of thresholds in the field remain a major challenge in geomorphic studies.

Analysis of morphological characteristics of river systems has also progressed with time. Recent research has highlighted the hierarchical nature of morphological attributes at different scales and the interlinkages among processes and landforms at different scales namely catchment, landscape, reach, and site scale (Frissell et al., 1986; Brierley and Fryirs, 2005). Among them, channel bars were referred to as the fundamental geomorphic units of a river with a great ecological significance (Brierley, 1996; Sadler, 2005). Understanding the control of the stream power on morphological variability at different scales in a single river basin is currently lacking. Recognition of such a single dominant controlling parameter will lead to its application in threshold identification for morphological variability at cross over of scales.

This work aims to characterise the geomorphic characteristics of the Yamuna River system in western India (Fig. 1) in a hierarchical order and to develop an understanding of the geomorphic controls at different scales. High-resolution reach-scale mapping of channel morphology is used as the basis to identify the threshold for morphological variability through an integration of sediment load data with stream-power distribution patterns.

2. Study area

The Yamuna River is the largest tributary of the Ganga River in northern India. Originating from the Yamunotri glacier in the Higher Himalayas at an elevation of about 6330 m a.m.s.l. (Rao, 1975), it meets the Ganga River at Allahabad after travelling a total length of 1370 km. It drains a total basin area of 345,848 km^2 and is characterised by 96.1×10^9 m^3 of annual discharge and 107×10^6 tons of total load per year at Allahabad (Jha et al., 1988). The Yamuna is characterised by two hinterlands namely, the Himalayan orogen in the north and the cratonic highlands in the south. Around 3% of the Yamuna basin falls in the mountainous terrain, ~50% in foothills and plateau region, and ~47% in plains and valley region (CPCB report, 2006). The Yamuna is mainly a rainfed river receiving most of the water from rainfall and groundwater and very little (9%) from glacial/snow melt (Bookhagen and Burbank, 2010).

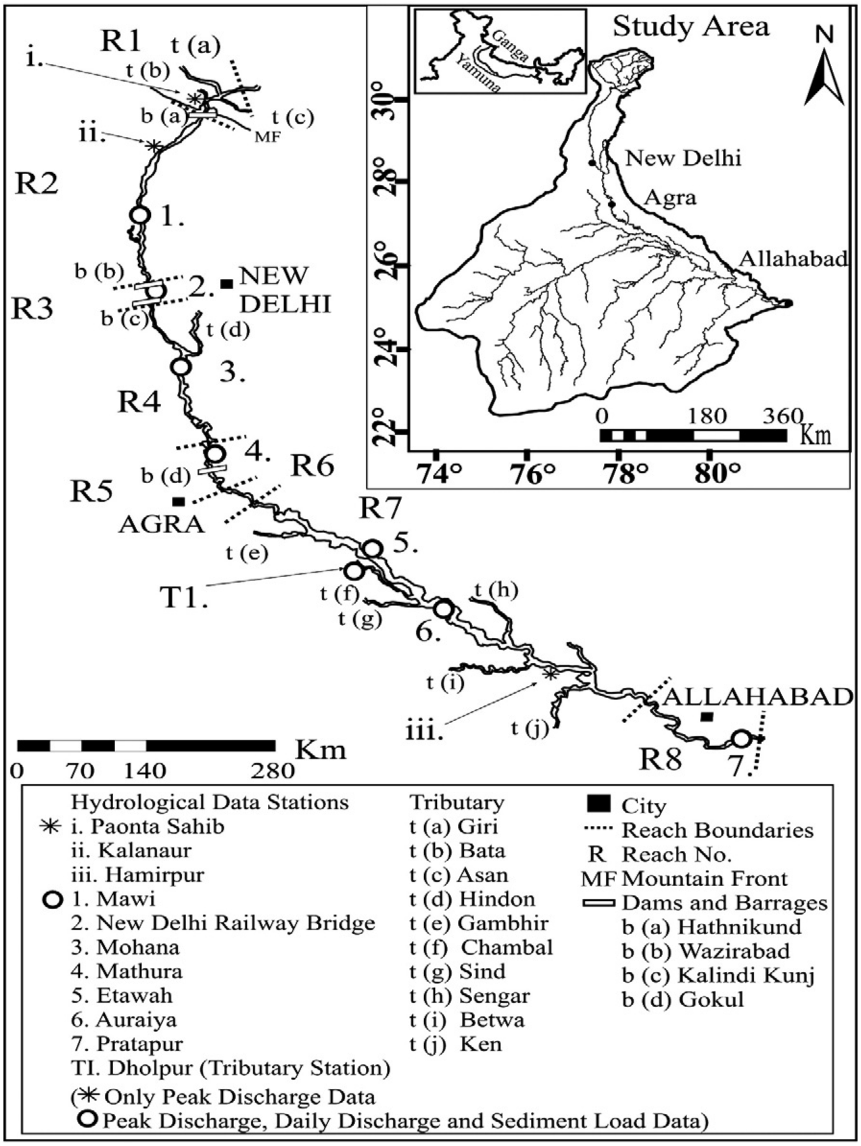

Fig. 1. The Yamuna River basin and its channel with the location of hydrological stations, tributaries and anthropogenic structures. The Yamuna River has been divided into eight reaches on the basis of geomorphic data.