Geomorphology 227 (2014) 73–86

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Connectivity structure of the Kosi megafan and role of rail-road transport network

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ARTICLE INFO

Article history:
Received 21 June 2013
Received in revised form 12 April 2014
Accepted 25 April 2014
Available online 9 May 2014

Keywords:
(Dis)connectivity
Transport network
Effective catchment area
Sediment flux
Waterlogging
Kosi megafan

ABSTRACT

Movement of biophysical fluxes and resultant processes are governed by among other things, the (dis)connectivity structure of a landform. Hence, the quantification of connectivity structure of a landform is important in order to analyze water and sediment fluxes over a surface. Two dimensional connectivity structure through analysis of lateral and longitudinal connectivity for water and sediment flux has been quantitatively defined for the well-known Kosi megafan in north India. The avulsive behavior of the Kosi River has resulted in various paleochannels over the megafan, and they guide the flux transfer over the surface and also control the local topography of the megafan. As (dis)connectivity structure of landform is governed by its physical characteristics and also affected by anthropogenic disturbances, both these factors have been considered to quantitatively analyze the connectivity structure of the Kosi megafan for sediment and water fluxes. Megafan surface characteristics have been defined through local slope variability, land use-land cover map and flow length. These surface parameters have been used to map ‘buffers’ in the area. The distribution pattern of ‘buffers’ on the megafan surface has been used to define the ‘natural’ (dis)connectivity structure. Further, the megafan surface has also been affected by progressive development of the rail-road transport network, which is mostly east-west aligned and intersects the south flowing paleochannels. These rail-road network acts as an anthropogenic ‘barrier’ for water and sediment fluxes across the megafan surface. A detailed mapping of rail and road network in different years (1955, 1983 and 2010) has been used to characterize anthropogenic disturbance on the connectivity structure. The spatio-temporal variation in connectivity structure is attributed to density of the transport network. Finally, natural and anthropogenic disturbances on connectivity structure have also been integrated to quantitatively define the present day connectivity structure of the Kosi megafan for water as well as for sediment flux. Further, the (dis)connectivity structure has been used to explain the spatial variability of waterlogging over the megafan surface, which is presently a serious hazard in the region.

1. Introduction

Connectivity structure is one of the fundamental aspects of geomorphic processes in a fluvial landscape. Connectivity structure of a geomorphic surface characterizes the nature and pattern of connectivity in a single or in all dimensions namely longitudinal, lateral and vertical dimensions (Brierley et al., 2006; Jain and Tandon, 2010). The nature of connectivity defines the degree of linkages between parts of landscape/landform and governs its response as a geomorphic unit against any external disturbances. Connectivity has been defined in different ways in various disciplines including geomorphology (Harvey, 2002; Hooke, 2003; Brierley et al., 2006; Fryirs, 2013), hydrology (Pringle, 2003; Bracken and Croke, 2007), ecology (Lindenmayer and Fischer, 2006) and graph theory (Foulds, 1992). The study of the connectivity structure in fluvial system is important because it governs channel processes, movement of the biophysical fluxes in the river basin i.e. sediment, water and nutrient fluxes in river system, river sensitivity and its response to external controls, and the pattern of natural hazards in a river basin over a range of spatial and temporal scales (Jain and Tandon, 2010; Jain et al., 2012; Fryirs, 2013; Sinha et al., 2013).

Brierley et al. (2006) provided a conceptual framework of geomorphic connectivity in a river basin at different spatio-temporal scales and defined connectivity in three dimensions namely longitudinal, lateral and vertical connectivity. Understanding of connectivity in all three dimensions is important to have a holistic, process-based understanding of river basins (Brierley et al., 2006; Jain et al., 2012). The nature of connectivity in any dimension is governed by physical connection (structural connectivity) and/or material transfer between two

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http://dx.doi.org/10.1016/j.geomorph.2014.04.031

compartments (functional connectivity) (Jain and Tandon, 2010; Wainwright et al., 2010). Different combinations of these parameters lead to different types of connectivity structures such as connected, partially connected and disconnected systems (Jain and Tandon, 2010).

In general, most of the geomorphological studies use the concept of connectivity in relation to flux transfer, as it defines form and process relationships. In the case of flux transfer, connectivity is controlled by different types of barriers, buffers and blankets in a river basin, which in turn may be natural or anthropogenically controlled (Fryirs et al., 2007a). Identification and quantification of the impacts of buffers, barriers and blankets help to assess and quantify the connectivity structure of the landforms. Mapping of the landform characteristics as buffers and barriers may be used for estimation of 'effective catchment area', which signifies the part of the catchment area that has the potential to directly contribute sediment or water flux to the channel and therefore represents connectivity structure in different sub-basins (Fryirs et al., 2007b).

The connectivity structure of a river basin is also strongly influenced by the anthropogenic factors, and the transport network is one such important anthropogenically driven barrier. Recent studies have highlighted the role of the transport network on the connectivity structure as barrier (Jones et al., 2000) and buffer (Blanton and Marcus, 2009) at regional (Jones et al., 2000) and local scale (Croke et al., 2005). The transport network may significantly impact watershed by altering sediment and water fluxes (Montgomery, 1994; Wemple et al., 1996; Forman and Deblinger, 2000; Wemple et al., 2001; Croke et al., 2005). Spatial variability in river processes and flux movement also leads to variability in channel habitats, morphological parameters, floodplain evolution, biodiversity and riparian ecosystem processes in a river landscape (Sherrill et al., 2008). Hence, there is a need to understand the impact of 'anthropogenic' disturbance on the connectivity structure and to integrate this with 'natural' drivers to define the complete structure of the geomorphic connectivity.

This paper presents the two-dimensional dis(connectivity) structure of the Kosi megafan, India, including the lateral and longitudinal dimensions of geomorphic connectivity. The 'natural' two-dimensional connectivity structure of the Kosi megafan was quantitatively defined and the 'anthropogenic' impacts on the connectivity structure due to railroad transport network were also estimated. The role of the rail and road transport network on connectivity structure of the Kosi megafan has been analyzed and quantified through detailed mapping of 'buffers' and 'barriers' over the megafan surface. The 'buffers' have been defined as low slope regions on the megafan surface, from where sediments of different caliber cannot be transported. Whereas, the 'barriers' have been formed by a dense network of transport embankments, which intersect the flow lines on the megafan surface, and control both the water and sediment fluxes. Further, distribution of the 'buffers' provides the 'natural' connectivity structure of the megafan while that of the 'barriers' represents 'anthropogenic' disturbance on the connectivity structure. Finally, the control of the geomorphic connectivity on waterlogging problem on the Kosi megafan has also been discussed.

2. Study area

The Kosi megafan, one of the world's largest fans, has a surface area of 11,223 km^2. The principal drainage of the Kosi megafan, the Kosi River, is well known for its dynamic behavior (Gole and Chitale, 1966; Wells and Dorr, 1987; Gohain and Parkash, 1990; Agarwal and Bhoj, 1992; Singh et al., 1993; Sinha and Jain, 1998; Kale, 2008; Sinha, 2009; Chakraborty et al., 2010). The Kosi River is presently embanked on the both sides and flows along the western margin of the fan (Fig. 1). Embankments on both sides of the main channel were built between 1954 and 1963 with a total length of 246 km and a barrage was commissioned in 1963 at Birpur in Nepal. Several breaches have occurred along both eastern and western embankments over the last several decades resulting in major avulsions and flooding of the megafan surface. The most recent breach at Kusaha in Nepal, 12 km upstream of the Kosi barrage, occurred on 18th August, 2008 inundating large areas in Nepal and North Bihar plains and affecting more than 3 million people.

The Kosi megafan is predominantly characterized by various south flowing paleochannels that represent the former courses of the Kosi River (Fig. 1). Most of these paleochannels get activated during the monsoon season and influence the distribution of water and sediment flux over the megafan. These paleochannels on the conical fan surface also govern the local topographical variation over the megafan surface. In a recent work, Sinha et al. (2013) analyzed the connectivity structure of the megafan surface to predict the avulsion pathway of the August 2008 event and demonstrated that the connectivity structure can serve as a predictive tool for postulating future avulsion pathways. The megafan surface has also been severely affected by a fast-developing, dense network of road and rail embankments, which run mostly in an E-W direction, transverse to the flow direction of the rivers. In most places, these embankments act as barriers and disconnect the flow of the channels.

Various parts of the Kosi megafan are characterized by severe drainage congestion and waterlogging, which has increased markedly in the last 50 years, particularly between 1955 and 2005 (Pandey et al., 2012). Apart from converting large fertile tracts into a wasteland and thereby affecting the livelihood of a large population, waterlogging severely affects the soil and groundwater systems through increased salinity (Pandey et al., 2012).

3. Data used and methodology

Various datasets were used in this study entailing the LANDSAT Thematic mapper (TM data) for the post-monsoon period (2010), having a spatial resolution of 30 m, digital elevation model (DEM) data of SRTM (Shuttle Radar Topographic Mission) of 2002 with a resolution of 3 arc-seconds (90 m), Linear Imaging Self Scanning sensors (LISS III) data for the post- and pre-monsoon periods (2010) and Cartosat-I data of resolution 2.5 m for 2009, acquired by Indian Remote Sensing Satellite (IRS) providing the spatial resolution of 23.5 m, and Survey of India (SOI) toposheets of 1955 and 1983 on a 1:50,000 scale. LANDSAT and SRTM DEM data of February 2002 were downloaded from Global Land Cover Facility (GLCF) (http://glcf.umd.edu/data/landsat/) and CGIAR-CSI (http://www.cgiar-csi.org) websites respectively. Geomorphic mapping through digital data was verified in the field.

3.1. Mapping of natural connectivity setup of the megafan

The megafan surface was considered as a connected surface for movement of the water flux, as water will flow even during the gentle slope condition. Hydrological disconnectivity will occur only in the presence of large natural sink, which was not observed on the megafan surface. The natural connectivity structure for the sediment flux was analyzed through two different approaches. The first approach for sediment connectivity involved the computation of the 'effective catchment area' on the basis of topography (after Fryirs et al., 2007b). The model assumed that sediment movement would occur when the surface slope exceeded a threshold value, whereas slope values lower than the threshold would indicate disconnection (Fryirs et al., 2007b). Threshold slope values for the effective catchment area were estimated on the basis of a slope frequency histogram (Fig. 2). The values of the slope threshold represent different conditions of hydrological forcing and hence highlight the temporal (seasonal) variability of the connectivity structure. For example, the average slope will be lower during floods because sediments will move from everywhere during this period. Connected surface area was defined as the 'effective catchment area'. 'Effective catchment area' was estimated for different slope thresholds, and these values were used to define the pattern of the sediment connectivity over the megafan.

Secondly, the connectivity structure of the Kosi megafan was assessed by spatial sediment connectivity on the basis of surface roughness, slope and contributing area (after Borselli et al., 2008). The