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Multivariate morphological characteristics and classification of first-order basins in the Siwaliks, Nepal

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ABSTRACT

This study identifies and analyzes a group of interrelated morphometric variables that contribute to the morphology of first-order basins in the Siwaliks and the adjacent part of the Lesser Himalaya in the Far West Nepal. First-order basins were identified and their various morphometric indices (21 variables) such as shape, area, pattern, roughness, height, gradient, angle, and distance were obtained from topographic maps (scale 1:25,000) and a digital elevation model using a geographic information system. The study also identifies the basin types based on morphometric properties and assesses their association with lithology, structure, and uplift rates. A principal component analysis identified seven major components that accounted for 78% of the total variance explained by the original 21 morphometric variables. Variables' loading reveals that the components are the expressions of slope, size, valley/depression, basin shape, relative massiveness, the convergence index, and basin asymmetry. Of these, slope and size components explain 48% of the total variance. The sets of variables represented by each major component for the entire study area were mostly common to all lithostratigraphic units. Some variables such as drainage density, junction angle, and the sediment transport index have associations with more than one group. This implies that complex geomorphic processes are involved in the development of basin morphology. Using the seven major components, five basin types were recognized by cluster analysis. The distributions of these basin types are similar in the Lower and Middle Siwaliks which have similar geological structures. The geometric relationship between the dip and the topography of a homoclinal structure significantly affects the proportion of basin types, as evidenced by the contrasting proportions between the cuesta and hogback and among dip, anti-dip and orthoclinal slopes. Correlation analysis also confirmed the effect of structure (dipping) on the morphometric variables, and indicated the influence of uplift rates on basin slope, stream slope, elevation range, mean elevation, valley angle, the shape index and the convergence index associated with the active thrust.

1. Introduction

First-order basins form a valley head or basin headwaters and an initial channel route for a fluvial system, and they cover a very large part of a mountain basin, i.e., about 60–80% of the cumulative length of the drainage network (Schumm, 1956; Shreve, 1969). For this reason they are a significant geomorphic characteristic of a mountain landscape. Such basins as defined on a given map scale (Horton, 1945; Strahler, 1964) are the smallest unit in a hierarchy of nested basins in a fluvial system (Chorley et al., 1984). Their geomorphic characteristics significantly affect the downstream geomorphologic and hydrologic properties of a higher order basin (Chorley et al., 1984; Gomi et al., 2002). The role of underlying earth materials that interact with the various sub-aerial and subsurface processes on various scales is likely to determine any landform. It is commonly accepted that the evolution of a landscape such as a first-order basin is a result of interaction between geology, structure, tectonics, climate, and surface processes on varying spatial and time scales.

A careful evaluation of the geomorphic features of a landscape that can be measured on a dimensional or non-dimensional scale can provide a wealth of information that can increase our understanding of the influence of abovementioned determinants (e.g. Bull and McFadden, 1977; Miller et al., 1990; Burbank and Anderson, 2001; Champel et al., 2002). Hence, the geometric pattern and the quantifiable properties that can be derived from the drainage topology and the three-dimensional form of a first-order basin can be analyzed to explain the geomorphic properties of such basins.

A large number of dimensional and non-dimensional measures of a basin contribute to the analysis of basin morphology or structure. Using these measures, multivariate techniques can be applied to identify the major feedbacks and co-measures associated with them, and objectively categorize basin types. How these basin types are related to geology, structure, tectonics and, other properties can be an important subject of geomorphic research. Such research will add value to the

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existing geomorphic understanding of drainage basin development in relation to the roles played by the factors noted above.

Although morphometric variables and multivariate analysis have been widely applied in the studies of drainage basin geomorphology and hydrology (Beven and Kirkby, 1979; Quinn et al., 1991), relatively little emphasis has been given to morphologic studies of small head-water basins, as evidenced by several published literature (e.g., Hack and Goodlett, 1960; Parsons, 1980; Gomi et al., 2002; Benda et al., 2005). Especially Gardiner (1978) and Ebisemiju (1985) examined and compared the morphometric characteristics of the first-order basins with those of the higher order small basins using multivariate analysis. Marcus (1980) defined first-order basins and proposed a three fold morphological classification approach for categorizing the basins (a sample of 25) developed on similar lithology. These studies pioneered the scientific approach to the morphology of first-order basins. However, the type and combination of the morphometric variables applied by the earlier studies on smaller basins may not be adequate to characterize first-order basins. Although the potential application of many three dimensional parameters of basins were recognized, it was not realized when computer-supported GIS were not available. Furthermore, most of such studies were carried out in geologically stable regions or areas with uniform lithology (Gardiner, 1978; Marcus, 1980; Ebisimiju, 1985).

The varied morphology of basins in rising folded/faulted mountains such as the geologically complex Siwalik Hills permits us to explore the geomorphic significance of basin morphometric variables of basins from both theoretical and applied perspectives. For the Siwalik basins some studies on morphometric properties (Hurtrez et al., 1999a,b; Delcaillau et al., 2006) or general landform features (Nakata, 1972; Malik and Mohanty, 2007; Devi, 2008) exist, which examined the geomorphic responses to active tectonics. In the light of these studies, a systematic study of morphometry of the first-order basins with a broader spectrum of parameters and a large data set, in relation to lithology, structure and tectonics, could be an important contribution.

The present study attempts to identify and analyze the group of morphometric variables contributing to the morphology of the first-order stream basins in the Siwalik Range and the adjacent part of the Lesser Himalaya in Far West Nepal. The study also identifies basin types based on their morphometric properties, and aims to assess the association of the basin types with lithology, structure, and tectonics.

2. Geological and geomorphologic setting of the study area

The study area (28°53′58″–29°07′52″N and 80°24′17″–80°38′31″E) extends over an area of 427 km^2 in Far West of Nepal (Fig. 1). Approximately 87% of the study area is underlain by the Siwaliks, the youngest parallel mountain chain in the Himalayan orogen (Gansser, 1964). The Siwalik Ranges form the most tectonically active Himalayan belts because of the ongoing collision between the Indian and Eurasian plates which has resulted in active deformation, dislocation and uplift of rocks along this belt, giving rise to a complex geologic structure and a broad range of differential geomorphic activities (Nakata, 1989; Lavé and Avouac, 2001). The remaining adjacent part in the north is underlain by the metamorphic and metasedimentary rocks of the Lesser Himalaya of the pre-Siwalik age. The complex and varied geology of the study area could be reflected in various multivariate indices of the morphology of a first-order basin pertaining to shape, area–length, pattern, roughness, frequency, height, gradient, angle (distance) and various derivatives.

2.1. Lithology

Based on lithological characteristics DMG (2007) broadly subdivides the Siwalik sediments into three major units: the Lower Siwaliks (LS), Middle Siwaliks (MS), and Upper Siwaliks (US).

The LS consists of an interbedding of mudstone and fine sandstone. The mudstone is variegated in color with a wide occurrence of green and purple shales. The sandstone beds are thin to thickly bedded, fine to coarse grained, and greenish grey to grey in color. The proportion of mudstone is greater than that of sandstone in aggregate. Thickness of mudstone layer ranges from 0.25 to 3 m, while that of the sandstone ranges from 0.3 to 5 m. The LS is delineated from alluvial deposits of the Terai plain by the Main Frontal Thrust (MFT) in the south. The rocks are well exposed in the Kolmuda, Baddi Machheli, Sim, Chhap, Dhimada, and Lamjile areas. A fining upward cycle can be observed within this formation.

The MS is comprised of a higher proportion of sandstone in a sequence of interbedded sandstone-mudstone. The proportion and coarseness of the sandstone increase towards the upper formation of the MS. The lower member is comprised of fine to coarse grained sandstone interbedded with mudstone. The thickness of the variegated mudstone layer ranges from 0.5 to 10 m. The sandstone is medium to coarse grained and micaceous in nature, with a thickness from 1 to 70 m. Close to its upper member, the sandstone displays a salt-and-pepper texture that contains pebbles of quartz, quartzite, and feldspar. Pebbly sandstone interbedded with mudstones can be seen in the upper member of the MS. Medium to coarse grained sandstone is also present in the unit. The sandstone beds range in thickness from 1 to 30 m, while the mudstone ranges from 0.5 to 4 m (Gorkhali, 2001).

The US consists mainly of conglomerate beds and an interbedding of mudstone, sandstone and conglomerate. In the lower part, the conglomerates are pebbly and gravelly, and are well sorted and compact. The clasts are rounded to well-rounded and are composed mainly of sandstone, mudstone, and quartzite. In the upper part, gravel- to boulder-sized clasts are present that are ill sorted and weakly cemented.

The middle section along the N–S traverse of the study area presents a stratigraphic unconformity. This section is occupied by Quaternary sediments (Q) which overlie the LS and MS between the Jogbuda Thrust and the Rangoon Khola Thrust, and the LS up to the Main Boundary Thrust (MBT). The Quaternary sediments consist of coarse boulders, river terraces and alluvium. The size of the Quaternary boulders reported by Kayastha (1979) ranges from 1 to 3 m. The sphericity of the boulders sphericity indicates that they have been brought from a great distance or they might be reworked sediments of an intraformational conglomerate of the Sangram Formation (Kayastha, 1979). Such Quaternary sediments can be found on the ridge lines and summits, indicating an inversion of topography probably during the middle to late Quaternary. At some river sections and lower slopes, the underlying LS and MS rockbeds can be seen.

To the north of the Siwaliks lie the Lesser Himalayan rocks (metasedimentary and metamorphic types) of the Precambrian to Lower Cretaceous (DMG, 2007). These rocks are grouped under the Sangram Formation: Sg (greenish grey to grey carbonaceous shale and grey quartzite), the Ramkot Formation: Rm (pink sandstone with ripple marks and purple grey shale, with mud cracks), and the Dubbidanda Formation: Dbd (grey to green chloritic phyllite, gritty phyllite, and white grey quartzites with amphibolites).

2.2. Structure

Several series of thrusts that extend from east to west and a system of faults, folds, fractures, and joints complicate the geology of the study area (Fig. 2). The Main Frontal Thrust, which dips about 25°–30° NE or NNE, delimits the Siwaliks to the south. It is the most active frontal fault where the LS are thrust over the alluvium in the piedmont zone (Nakata, 1989). The MBT, which is relatively less tectonically active than the MFT, delimits the Siwaliks to the north. It consists of medium grade metasediments. Along this zone, the Lesser Himalaya is thrust onto the Siwalik units. Between the MBT and MFT, the study area is traversed by two thrusts trending NW–SE: the Jogbuda Thrust (reverse fault) and the Rangoon Khola Thrust. These thrusts dip 25°–30° NE to NNE, and along these zones, the LS override the MS or US rock in different sections. The Jogbuda Thrust is ruptured by the Malla Bhir Fault