Quantitative geomorphic study of river networks and topography in the Northwest Himalaya, India

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Month and year of thesis submission
September 2019

Abstract

Fluvial landscape patterns are excellent markers of the inherent processes governing the evolution of rivers and its landscape. Hence, fluvial patterns are often used as proxies in geomorphic analysis to infer the geological history of a river basin. To this end, this thesis carries out a thorough examination of river or drainage network (DN) pattern and topography geometry in a tectonically active setting of the Northwest Himalaya, India. The main objective of this thesis was to quantify the relationship between river basin geology (including tectonics and lithology) and topography geometry, DN and subsequent modern-day hydrological behavior of a river basin. I used the freely available digital elevation model (DEM) data provided by Shuttle Radar Topography Mission (SRTM) for all my analysis.

In the first part of the thesis, I investigated the sensitivity of the synthetic hydrological response of a river basin to the spatial resolution of the DEM data. I found the river planform (DN)-based hydrological model, which is a function of DN morphometric parameters, to be consistent with DEM resolution. Next part of the thesis probed into the accuracy of different channel initiation functions for extraction

of river network. My results showed that a slope-area initiation function is more efficient than a fixed-area initiation function in river basins with higher slope variability. Further, a slop-area initiation function was found to better capture the variability in drainage density resulting from terrain slope variability. The third part of the thesis addressed the effect of geology (lithology, tectonics, and long-term climate) on the geometry of fluvial topography. I characterized the topography as a fractal surface using its fractal dimension and topographic amplitude. Using basic clustering technique, I demonstrated that these two features together can accurately discriminate different physiographic settings. Further, my results revealed lithology to be a stronger control on topographic geometry even in a tectonically active fluvial setting. Last part of the thesis looked into the impression of tectonic uplift on the topology of DN topology. My results showed a significant effect of tectonic uplift on DN pattern, which also led to defining an indirect control of tectonic uplift on the hydrological response of a river basin. This also underlines the role of geological memory in modern-day process-response relation in a fluvial system. Moreover, discharge is an important governing variable in landscape evolution models and is regulated by climate parameters like precipitation characteristics. My results indicated that discharge is also likely to be very sensitive to change in tectonic uplift. Overall, my thesis highlighted the importance of an integrated multi-faceted study to fully understand the long-term effect of geological processes on fluvial system morphology, its landscape and its modern-day hydrological behavior.

Chapter 2

Sensitivity of GIUH derived hydrological response of a river basin to the spatial resolution of DEM data

Key points

- Sensitivity of morphometry based hydrological model (GIUH) to DEM resolution has been analyzed.
- A new algorithm has been developed for estimation of the morphometric ratios of a drainage network.
- The morphometric ratios are found to be normally distributed, whereas, the GIUH derived hydrograph parameters follow a lognormal distribution.
- Both morphometric ratios and GIUH derived hydrograph parameters are not sensitive towards DEM resolution in a statistical sense.
- Planform-based hydrological model (GIUH) is more consistent with data resolution in comparison to topography-based hydrological models.

Abstract

Drainage network pattern and its associated morphometric ratios, are some of the important plan-form attributes of a drainage basin. Extraction of these attributes for any basin, is usually done by processing of the elevation data of that basin. These plan-form attributes are further used as input data for studying numerous process–response interactions inside the premise of the basin. One of the important uses of the morphometric ratios is the theoretical derivation of the hydrologic response of a basin through GIUH concept. Hence, accuracy of the theoretical basin response to any storm event depends upon the accuracy with which, the morphometric ratios can be estimated. This in turn, is affected by the spatial resolution of the source data, i.e. the elevation model. Intuitively, it seems that, accuracy of the parameters will increase as resolution becomes finer. I estimated the sensitivity of the morphometric ratios and the GIUH derived hydrograph parameters to the resolution of source data using a 30-meter and a 90-meter DEM. The analysis has been carried out on fifty drainage basins in a mountainous catchment. A simple and comprehensive algorithm has been developed for estimation of the morphometric ratios from a stream network. I calculated all the morphometric parameters and the hydrograph parameters for each of these basins extracted from two different DEMs, with different spatial resolutions. Paired t-test and Sign test were used for the comparison. No statistically significant difference was found among any of the parameters calculated from the two DEMs. Along with the comparative study, a first-hand empirical analysis about the frequency distribution of the morphometric and hydrologic response parameters has also been given. Further, a comparison with other hydrological models suggest that planform-based GIUH model is more consistent with resolution variability in comparison to topographic-based hydrological model.

Chapter 2 has been published in its current form in Computers and Geosciences with co-author V. Jain, article doi: https://doi.org/10.1016/j.cageo.2017.10.001.

Chapter 3

Assessment of drainage network extraction algorithms in the Northwest Himalaya

Key points

- Assessment of two process-based drainage network extraction algorithms was carried out.
- Slope was included in channel initiation function to extract drainage network from DEM.
- A python-based function was used to implement the slope-area thresholding method.
- Slope-area thresholding method was found to be more efficient than only area thresholding method in regions/basins with high slope variability.
- Drainage density of a river basin was better approximated with slope-area thresholding method.

Abstract

Smaller (lower order) channels or headwater channels play pivotal role in watershed modelling of any river basin, as they cover approximately 70-80% of the total channel length of the river network besides providing over 50% of the flux (water, sediment and nutrient) to higher order channels in the river basin. Automated channel network extraction for watershed (river basin) modelling is generally carried out by applying a fix threshold on upstream contributing area (fix-area threshold, A_t) derived from a digital elevation model (DEM). However, the area thresholding algorithm produces channel network with abnormal drainage density (DD), especial]0.0lly for lower order streams, either by underestimating or overestimating the frequency of smaller channels. The main aim of my work is to assess the improvement in drainage network (DN) extraction from relatively coarser but globally available and widely used DEM data. It was achieved through modelling of headwater or smaller channels by incorporating topographic slope in the thresholding variable (slope-area method, $f(A, S)_t$) by using SRTM data in the Ramganga River basin, Northwest (NW) Himalaya. Four small sub-basins were selected for the current work. These sub-basins have variable rock types and slope conditions. Comparisons were done w.r.t the channels digitized from Google Earth images. My results showed a higher variability in threshold values for the area algorithm across all the sub-basins compared to the slope-area algorithm. Slope-area algorithm was also found to be more efficient in mapping the smaller channels in sub-basins with high slope

variability. Further, I observed an overestimation or underestimation of DD with the area thresholding method, whereas the slope-area based threshold generated a DN with close to natural DD for the respective sub-basins. The current work highlighted the need for incorporating slope-area thresholding-based DN in resource planning and management activity.

3.1. Introduction

Drainage network (DN) is a conduit that links the upstream catchment processes (hillslope activities) with the downstream channels and floodplains (Yadav and Hatfield, 2018). Topology of DN decides the structural and functional connectivity inside a fluvial landscape. Additionally, any signal generated at the base level (tectonic uplift or base level lowering) in the form of potential energy propagates throughout a fluvial system through the DN. The propagation speed also depends on the physical attributes of DN. Hence, DN has been widely used in Earth Sciences community to study the effect of geological and climate control on landscape evolution (e.g. Zernitz, 1932; Horton, 1945; Strahler, 1957; Shreve, 1966; Abrahams, 1984, Costa-Cabral and Burges, 1997; Castelltort et al., 2012). Further, physical and topological attributes of DN have also been applied for estimating the modern-day fluxes across the landscape (e.g. Snyder, 1938; Nash, 1960; Kirkby, 1976; Rodriguez-Iturbe and Valdes, 1979; Gupta et al., 1980; Veitzer and Gupta, 2001; Lee et al., 2006; Li et al., 2010; Rigon et al., 2016).

DN topology constitutes an arrangement of channel links, which can be divided into exterior (source channels) and interior links. Exterior links are those having no tributaries. These exterior links (also known as first order streams) are part of the headwater channels, which constitutes a large part of the total channel length within a fluvial system and have major hydrological and ecological significance (Henkle et al, 2011; Wohl, 2017).

Chapter 4

Process inference from fractal characteristics in the tectonically active Northwest Himalaya

Key points

- Lithology has a predominant control in sustaining topographic relief in the Northwest Himalaya.
- Fractal-based measures were found to be useful in classifying the different geomorphic provinces of the study area.
- My results emphasized that it is imperative to analyze the combined effect of the governing agents on topographic characteristics when inferring the landscape evolution history.

Abstract

Topography evolves under the coupled effect of exogenic and endogenic governing agents, and their scale-invariant dynamics/processes. This results in a self-affine fractal topography which is widely characterized by its fractal dimension. Past studies have focused on the effects of different governing agents on fractal characteristics of topography with only a few examining their combined effect. This study examines the association between litho-tectonic and climatic settings, and the fractal characteristics of topography in the tectonically active Northwest Himalaya. I used roughness-length method to calculate the fractal parameters (fractal dimension, *D*; ordinate intercept, *q-param* along with the scaling range) of the regional topography. The Lesser Himalaya and the Higher Himalaya were found to be characterized by low *D* and high *q-param*, while the foreland alluvial plains are characterized by high *D* and low *q-param*. The tectonically active Sub Himalaya was also found to have high *D* and low *q-param*, highlighting the predominant effect of lithology in sustaining topographic relief (both its amplitude and texture). I also examined the effect of climate on the fractal parameters. I found regionally variable relation between fractal parameters and climate, modulated primarily by lithology along with vegetation. These results showed that the geological-geomorphological settings and associated processes of an area can be well inferred using fractal characteristics of topography. Moreover, my analysis established a semi-quantitative process-form association between fractal properties of topography and the governing agents (tectonics, lithology and climate) and also highlighted the complex interactions between their dynamics in overall landscape evolution.

Chapter 5

Tectonic imprint on drainage network topology in a neotectonically active area

Key points

- RT model was used to quantify the difference between the drainage networks in hangingwall and footwall of a tectonically active thrust in the Northwest Himalaya through a χ^2-based measure.
- Tectonic imprint on the drainage network topology is scale dependent and moderate size drainage networks better preserve the signature of tectonic disturbance in terms of surface uplift.
- Inclusion of slope in channel initiation function (AS^2) produced better representation of drainage network magnitude in an area having large slope variability.
- GIUH model was used to analytically derive synthetic hydrological response of sub-basins around different thrusts in the Northwest Himalaya.
- The GIUH parameters, q_p and t_p, were found to be significantly different for different thrusts, and indicates the presence of a nonlinear geological memory, modulated by lithology.

Abstract

Drainage networks are an integral component of Earth's landscape. Their topology, among other attributes, is widely used to interpret various controls or processes that shape them. However, their response to surface deformation in a tectonically active area remains poorly examined and understood. Tectonics impose constraints on landscape evolution. Subsequently, DNs can respond by adjusting their topological arrangement in a manner which do not obey the typical random growth theory proposed by Shreve's Random Topology (RT) model. The goal of this study is to quantitatively measure the deviation of present day DN patterns from expected random DN patterns under tectonic constraint. I used a well-established tectonically active out of sequence thrust in the Northwest Himalaya in my analysis, which has been accommodating a significant portion of the Indo-Eurasian convergence. DN patterns were extracted through slope-area thresholding method using a python-based algorithm. This method provided better representation of DN magnitude in the area having large slope variability and it also helped to identify the sensitivity of DN on topographic slope. RT model was applied for DNs in hangingwall and footwall region of the active thrust to characterize their pattern frequency. I adopted a statistical divergence measure (χ^2) to quantitatively express the corresponding deviations of DN patterns on hangingwall and footwall from the expected random patterns suggested by RT model. DN patterns in hangingwall were found to be

significantly different from expected random pattern due to tectonic forcing. Further, it was observed that tectonic imprint on DN is scale dependent and this imprint is better reflected in moderate size drainage basins. DN pattern further regulates the hydrological response of a river basin. Thus, I have also analyzed the effect of tectonic uplift on modern-day flux in a river basin in term of a synthetic hydrological response model, GIUH. My results from the GIUH analysis indicates the presence of geological memory in fluvial system.

5.1. Introduction

5.1.1. Tectonic process and Drainage network pattern

Tectonic process is responsible for the large-scale reshaping of the Earth's topography. Though being endogenous, its response gets exposed on Earth's surface in the form of topographic upheaval or depression at different spatial scales (Cotton, 1950; Rubio and Simón, 2007; Lavé and Avouac, 2000; Kirby et al., 2008). Geomorphologists have been using these exposed surface responses, both qualitatively and quantitatively, for interpreting the tectonic history of a fluvial landscape.

A narrative of the temporal evolution of surface topography of fluvial landscape can also be traced through the characteristics of drainage network (DN), since DN acts as a skeleton or basic framework for a river basin (Meisels et al., 1995). DN responds and evolves in response to topographic changes by adjusting its basin perimeter shape, long profile shape, channel geometry or network topology (Burbank and Anderson, 20012; Molnar, 2013). Several indices and measures related to changes in drainage basin shape (Cannon, 1976; Cox, 1994; Ramírez-Herrera, 1998; Cox et al., 2001; Delcaillau et al., 2006), long profile morphology (Hack, 1973; Whipple and Tucker, 1999; Kirby and Whipple, 2001; Wobus et al., 2006; Pritchard et al., 2009; Perron and Royden, 2013; Demoulin et al., 2017; Sonam and Jain, 2018), channel geometry (Bishop, 1995;