Quantitative River Profile Analysis to Investigate Exhumation of the Siwalik Foreland Basin, Nepalese Himalaya

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QUANTITATIVE RIVER PROFILE ANALYSIS TO INVESTIGATE EXHUMATION OF THE SIWALIK FORELAND BASIN, NEPALESE HIMALAYA

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Master of Science

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QUANTITATIVE RIVER PROFILE ANALYSIS TO INVESTIGATE EXHUMATION OF THE SIWALIK FORELAND BASIN, NEPALESE HIMALAYA

Date Recommended 4/12/2017

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QUANTITATIVE RIVER PROFILE ANALYSIS TO INVESTIGATE EXHUMATION OF THE SIWALIK FORELAND BASIN, NEPALESE HIMALAYA

Indu Bhattarai May 2017 55 Pages

Directed by: Nahid Gani, Fred Siewers, and Jun Yan

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The Nepalese Himalaya, one of the most active regions within the Himalayan Mountain belt, is characterized by a thick succession of Miocene age Siwalik sedimentary rocks deposited at its foreland basin. To date, much of its tectonic evolution, including exhumation in the Nepalese Siwalik, is poorly understood. This study of a quantitative analysis of the bedrock river parameters should provide crucial information regarding tectonic activities in the area. The study investigated geomorphic parameters of river longitudinal profiles from 54 watersheds within the Siwalik section of the Nepalese Himalaya, for the first time. A total of 140 bedrock rivers from these watersheds were selected using stream power-law function and 30-meter resolution ASTER DEM. The quantitative data from the river longitudinal profiles were integrated with published exhumation ages. Results of this study show, first, a presence of major and minor knickpoints, with a total of 305 knickpoints identified, of which 180 were major knickpoints and the rest were minor knickpoints. Further classifications of knickpoints were based on structures (lineaments extracted from SRTM DEM), lithology, and possible uplift. Second, the Normalized Steepness index ($k_{sn}$) values exhibited a range from 5.3 to 140.6. Third, the concavity index of streams in the study area ranged from as low as -12.1 to as high as 31.1 and the values were consistently higher upstream of the knickpoints. Finally, integration of the river profile data with the published exhumation ages show that the regions with a high $k_{sn}$ value correspond to the regions with higher incision and,
therefore, are likely to have high uplift. The presence of a break in $k_{sn}$ in the eastern section of the study area suggests that the incision is likely accelerated by Main Frontal Thrust (MFT) movements. Erosion of the thrust sheet could have influenced the rapid uplift of the Siwalik due to isostatic processes. Thus, the timing of the source-region exhumation and its rate suggests that MFT-related tectonics, and/or climate processes, likely influenced the landscape evolution of the study area. The results of this study should help in comprehending the neo-tectonic deformation of the Nepalese Himalaya.
CHAPTER 1. INTRODUCTION

This research investigates the exhumation history of the Siwalik Foreland Basin in the Nepalese Himalaya from quantitative river longitudinal profile analysis to understand the tectonic history of the region more effectively. The Himalaya is one of the most significant examples of the ongoing tectonic activity of continent-continent collision between the Indian and the Eurasian Plates (Figure 1A). Some of the world’s major rivers, such as the Ganges, Indus, Brahmaputra, and Mekong carry large volumes of sediment by the processes of erosion, transportation, and deposition. Thus, the Himalaya is considered to be the major source of sediments for the world’s oceans (Milliman and Meade, 1983; Summerfield and Hulton, 1994).

The Himalaya, particularly the Nepalese Himalaya, is also very active seismically (Sabeer and Gornitz, 1983; Chirouze et al., 2011). It is dominated by several mega-thrust faults like the Southern Tibetan detachment system (STDS), Main Central Thrust (MCT), Main Boundary Thrust (MBT), and the Main Frontal Thrust (MFT) (Figure 1B). Previous studies suggest that these mega-thrust faults in central Nepal accommodate ~20 mm/yr of convergence between India and Europe (e.g., Yin, 2006; Wobus et al., 2008). In addition, these faults are dominated by numerous high to low magnitude earthquakes that lead to various geotechnical effects, including surface deformation. Parameswaran et al. (2015) concluded, from an analysis of the recent 2015 Gorkha earthquake in central Nepal, that the mainshock slip was limited to the MCT and MBT. A vertical slip of 1.5 m was observed in the Kathmandu Valley, along with small-to-large slope failures and erosion along the MCT and MBT (Moss et al., 2015).
Although no evidence of surface ruptures was observed in the MFT, several large drainages exposing the MFT scarp were explored near the towns of Amlekhgunj, Purai, and Khayarmara (Moss et al., 2015). Wobus et al. (2005) suggested that the recent surface faulting was concentrated at the MFT, which is considered to be a relatively younger thrust fault than the STDS, MCT, and MBT in the Nepalese Himalaya. These faults deformed various rock units within the Himalaya that include the Tethyan Himalaya, the Higher Himalaya, the Lesser Himalaya and the Siwalik (Bernet et al.,
These rock units are incised by numerous major bedrock rivers (e.g., the Karnali, Koshi, Narayani, and Rapti) and their tributaries, originating from the high elevations of the Nepalese Himalaya and flowing towards the lowlands of the Indo-Gangetic Plain and the Bay of Bengal (Figure 1C).

The present-day Siwalik is an imbricated thrust zone in the foreland basin of the Himalaya, which is the result of uplift of fluvial strath terraces and continuous uplift and erosion of the Himalaya (Cerveny et al., 1988; Chirouze et al., 2011; Landry et al., 2016). During the Neogene time, 4 to 6 km of fluvial sediments were deposited within this basin (Sigdel et al., 2011). The Nepalese Siwalik represents one of the most important natural laboratories for the study of the tectonics, climatic, and erosional history of the Himalaya (Beek et al., 2006). Therefore, several studies have been conducted on the lithostratigraphy, magnetostratigraphy, thermochronology, and river geomorphology to understand the Siwalik exhumation within the Nepalese Himalaya (Mugnier et al., 1999; Beek et al., 2006; Blythe et al., 2007; Chirouze et al., 2011). However, the mode and tempo of the Siwalik exhumation and its drainage network evolution are poorly constrained. As the collision and exhumation were not synchronous laterally from east to west within the Himalaya (Yin, 2006), the lithology and stratigraphy differ as well. The mode and magnitude of deformation also influences the exhumation rates; i.e., the spatial extent and rate of erosion depend on the location and duration of the structural uplifts (Yin, 2006). Similarly, in the Siwalik, the time of exhumation and uplift varies (Beek et al., 2006) from east to west and north to south.

The exhumation rate in the Himalayas has fluctuated through geologic time either by tectonic or climatic factors (Cornivus and Rimal, 2001; Beek et al., 2006; Blythe et al.,
Exhumation ages in the Nepalese Himalaya vary laterally from 0 to >30 Ma (Lave and Avouac, 2001; Najman, 2006; Blythe et al., 2007). A few studies have focused on the exhumation in the western part of the Nepalese Himalaya (Beek et al., 2006; Bernet et al., 2006; Lupker et al., 2012) and a few studies on the eastern part (Chirouze et al., 2011). According to Burbank (1992), the exhumation rate of the western part has increased significantly during the last few Ma. Beek et al. (2006) concluded from zircon fission track and apatite fission track analyses that the exhumation rate within the Surai Khola River section in the eastern part (located in the study area) are 1.4 ± 0.4 km/Ma and 3.5 ± 2.1 km/Ma, respectively.

The presence of river networks flowing from the north within the Himalaya to the Indo-Gangetic plain makes the Nepalese Siwalik an ideal place to study the river response to tectonic changes. The influence of river geomorphic parameters (i.e., longitudinal profiles) to erode into bedrock plays a significant role in landscape evolution. Longitudinal profiles of a river usually preserve valuable information about a landscape responding to a changing base level (e.g., Wobus et al., 2006; Gani et al., 2007). For example, a river already adjusted to the landscape shows a concave-up longitudinal profile (Kirby and Whipple, 2001). However, exceptions to the concave-up forms of the profiles can provide valuable tectonic information to measure landscape transience or disequilibrium in a tectonically active landscape like the Siwalik Foreland Basin of the Nepalese Himalaya. This research focuses on a quantitative analysis of river longitudinal profiles of bedrock rivers within the Nepalese Siwalik basin. The objective of the research is to determine the fluvial response to landscape exhumation in order to answer this main research question: What is controlling the exhumation within the study
area? This question was addressed by investigating the variation of the longitudinal profiles and their parameters throughout the study area.

This research is crucial to understanding the landscape evolution of the highest mountain belt in the world, the Himalaya. The research could contribute towards our current knowledge on the interplay among tectonic, climate, and erosion forces within the Himalaya, particularly, the Siwalik basin of the Nepalese Himalaya, a tectonically active and important region. The exhumation history obtained from this study would, therefore, constrain the tectonic uplift and its relation to paleoclimate variation. In addition, this study should also provide the fundamental baseline data for further geodynamic analysis in this region.
CHAPTER 2. REGIONAL TECTONICS AND GEOLOGY

The Himalaya was formed from the collision of the Indian Plate with the Eurasian Plate after the closing of the Tethys Sea (Powell and Conaghan, 1973; Le Fort, 1975; Najman, 2006). Various studies suggested that the age of this collision varies from ~34 to ~65 Ma (Le Fort, 1975; Jaegar et al., 1989; Aitchison et al., 2007). Najman (2006) concluded that this collision occurred between ~50-55 Ma, followed by the formation of a northward-dipping underthrusting (Powell and Conaghan, 1973). Physiographically, the Himalaya is classified into five major divisions (Figure 2.1A) (Le Fort, 1975). These divisions include, from west to east, the Punjab Himalaya (Pakistan), the Kumaun Himalaya (China), the Nepalese Himalaya (Nepal), the Bhutan Himalaya (Bhutan), and the Assam Himalaya (India). The study area is located within the Nepalese Himalaya, which is summarized below:

2.1. The Nepalese Himalaya

The Nepalese Himalaya, which extends 800 km from east to west, is the largest division within the Himalaya (Figure 2.1A). It occupies the central sector of the southwardly convex arc of the Himalaya (Upreti, 1999). The Nepalese Himalaya is divided into four litho-tectonic units. These units include, from north to south, the Tethyan Himalaya, the Higher Himalaya, the Lesser Himalaya, and the Siwalik Himalaya (Figure 2.1B). Each of these litho-tectonic units is separated from the other by the major northward-dipping thrust fault systems that include the STDS, MCT, MBT, and the MFT (Chirouze et al., 2011) (Figure 2.1B and C).
Figure 2.1. Nepalese Himalaya with major litho-tectonic units. Physiographic divisions of the Himalaya (A). Geologic map of the Nepalese Himalaya, showing the litho-tectonic units separated by the major thrust fault systems (MFT-Main Frontal Thrust; MBT-Main Boundary Thrust; MCT-Main Central Thrust; STDS-South Tibetan Detachment System). The study area is shown by the red rectangle (B). The geologic cross-section along the line X-X’ in (B) shows the orientation of the major thrust fault systems (C).
Source: Created by the author (A), and modified by the author from Dahal (2006) (B and C).
2.2. Litho-tectonic Units

The Tethyan Himalaya (Figure 2.1B) consists of the Cambrian- to Eocene-age sedimentary successions and low-grade metamorphic rocks (Dahal, 2006; Chirouze et al., 2011). The Indus-Yarlung suture zone, which consists of ophiolites and flysch deposits, lies north of the Tethyan Himalaya (Szulc et al., 2006). The STDS lies south of the Tethyan Himalaya and separates the Tethyan Himalaya from the Higher Himalaya. This region also consists of fossiliferous sedimentary rocks like shale, sandstone, and limestone (DeCelles et al., 1998; Garzanti, 1999). Zircon fission track analysis conducted by Blythe et al. (2007) suggested that exhumation occurred between ~1.3-0.8 Ma in the central part of the Tethyan Himalaya (near the Annapurna Mountain Range).

The Higher Himalaya (Figure 2.1B), composed of metamorphic rocks ranging in age from Late Proterozoic to Early Cambrian, is the hanging wall of the MCT in the south (Dahal, 2006; Chirouze et al., 2011). Metamorphic grade decreases progressively from north to south within the Higher Himalaya. The common rock types found in this region include kyanite- and sillimanite-bearing gneisses, schists, and marbles (Dahal, 2006). Blythe et al. (2007) suggested that the exhumation in the central part (along the Marsyangdi drainage) of the Higher Himalaya ranges between 1.9 to 0.8 Ma.

The rock types in the Lesser Himalaya (Figure 2.1B) range from unfossiliferous sedimentary rocks to metasedimentary rocks of Proterozoic to Paleozoic age. Some of the common rocks found in this region include shale, sandstone, conglomerate, and dolomite (Dahal, 2006). These rocks are deformed by tight, overturned folds and northward-dipping imbricate faults (Dahal, 2006; Najman, 2006). The Lesser Himalaya is further divided into inner and outer Lesser Himalayan zones based on geochemical variation.
(Ahmed et al., 2000; Najman, 2006). The MCT separates the Lesser Himalaya from the Siwalik in the south. Blythe et al. (2007) suggested that the exhumation in the central part of the Lesser Himalaya occurred between 0.0 to 0.3 Ma.

The Siwalik in Nepal (Figure 2.1B), extending east-west, lies between the Lesser Himalaya in the north and the Indo-Gangetic Plain in the south. This unit is bounded by the MBT in the north and the MFT in the south. The Siwalik Foreland basin is an active foreland basin where synorogenic sediments are deposited successively in the outer part of the MFT from the Higher and Lesser Himalayas (Chirouze et al., 2011). The Siwalik Hills, in general, are steeper in the southern slope and gentler in the northern slope, with altitude ranges between 600 to 1500 m (Mugnier et al., 1999). The Siwalik consists of Miocene- and Pliocene-age fluvial sedimentary rocks deposited as a result of Neogene tectonics of the Himalaya (Najman, 2006) that represent the Miocene-Pliocene fill of the Siwalik Foreland basin (DeCelles et al., 1998; Chirouze et al., 2011). Dahal (2006) divided the Siwalik into three subgroups, which include, from older to younger, the lower Siwalik mostly composed of fine-grained sandstone, siltstone and mudstone, and dominated by plant fossils. The sandstone and mudstone ratio is 1:1, where the sandstone is greenish-brown and the mudstone is variegated in color. Then follows the Middle Siwalik, which consists of medium- to coarse-grained sandstones. The ratio of sandstone to mudstone is 2:1, where the mudstone is not variegated in color, and the upper part of the middle Siwalik is coarse- to very coarse-grained pebbly sandstone. Lastly, the Upper Siwalik consists of massive conglomerates with irregularly fossiliferous boulder beds, as well as subordinate beds of siltstone and mudstone. Invertebrate fossils, mostly brachiopods and gastropods, are found in this unit (Dhital, 2015).
2.3. Tectonic Structures in the Nepalese Himalaya

Apart from the four major thrust fault systems (i.e., the STDS, MCT, MBT, and MFT), there are a number of smaller thrust faults and thrust-propagated folds along the east-west extension of the Nepalese Himalaya. The three major thrust faults (MCT, MBT, and MFT) are called collectively the Main Himalayan Thrusts (MHT), as they appear together as a low-angle decollement (basal detachment fault) in the north. This decollement is the major crustal break that separates upper (Eurasian) and lower (Indian plate) continental crusts (Upreti, 1999). The underthrusting of the lower continental crust in the north below the upper crust resulted in crustal thickening beneath Tibet, and there is a southward movement of the upper crust above the decollement towards the south along the MHT. The MFT is the youngest among all MHT, where the MCT is considered the first thrust fault to deform the Indian crust (Figure 2.1C) (Upreti, 1999).

The Main Dun Thrust lies in the north of the Siwalik, where the Dun Valley developed due to thrust-propagating large symmetric folds, and is filled with recent sediments (Mugnier et al., 1999; Upreti, 1999). Neogene to quaternary Siwalik sedimentary rocks are overlying the MBT where it has been offset by north-south-trending transverse faults (Appel et al., 1991). According to Mugnier et al. (2004), the thrusting along the MFT occurred between 1.8 and 2.4 Ma. The lesser Himalaya consists of the metasedimentary rocks with overriding crystalline nappes and klippes, while the eastern part of the lesser Himalaya consists of a single thrust sheet. The central part of the Lesser Himalaya is covered largely by Kathmandu Nappe that extends in a narrow arm to join the large eastern thrust sheet. The Higher Himalayan rocks are separated by the MCT in the south from the Lesser Himalaya.
2.4. Study area

The study area is situated within the Siwalik in the western part of the Nepalese Himalaya (Figures 2.2A). This region is overlapped with conglomerate to sandy facies towards the south (Mugnier et al., 1999; Cornivus and Rimal, 2001). The study area is characterized by the Upper Siwalik, the Middle Siwalik, and the Lower Siwalik Figure 2.2B). The Upper Siwalik is segregated into two formations, which include the Dhan Khola and the Dobatta formation (Mugnier et al., 1999).

Figure 2.2. Geologic map of the study area and its stratigraphy. Location of Figure 2.2B shown in red box (A). Lithology of the Upper, Middle, and Lower Siwalik units. These units consist of sedimentary rocks and are divided further into different formations. Various tectonic features also are shown, such as the attitude of beds, chevron folds, and any unconformity (B). Source: Modified by the author from Dhital (2015).
The Dhan Khola Formation is about ~1100 m thick and consists of conglomerate that is not fully consolidated with sediments. No fossils are found in this region. The Dobatta Formation is ~750 m thick and is composed of light-colored to brown mudstones with coarse-grained sandstones and vertebrate fossils. The Upper Siwalik in this section was deposited between ~3.5-0.5 Ma years ago. The Middle Siwalik consists of the Surai Khola Formation and the Chor Khola Formation. The Surai Khola Formation is ~1310 m thick and consists of medium- to coarse-grained salt and pepper sandstones and siltstones. Coal, plants and animal fossils are present in this formation. The Chor Khola Formation is ~1235 m thick and consists of fine- to medium-grained mica-rich
sandstones, grey mudstones, and some limestones (Muginer et al., 1999). Mugnier et al. (1999) found the depositional age of the Middle Siwalik ranges to be between ~8-10 Ma and ~3.5 Ma. The Lower Siwalik consists of fine-grained sandstones and mudstones that contain paleosols and plant fossils. It has a thickness of ~585 m and is known as the Bankas Formation. The depositional age of the Lower Siwalik ranges is between ~10 and 8-10 Ma. The fold and thrust belt of the Siwalik outer belt consists of a laterally propagating fault-bend associated with the MFT and its hanging wall synclines. The inner belt is composed of a series of laterally relayed and transported thrust sheets (Figure 2.3) (Mugnier et al., 1999; Beek et al., 2006).

2.5. River Network

The Nepalese Himalaya is characterized by a number of major rivers like the Koshi, Narayani, Surai Khola, and Karnali flowing from the north to south. These rivers are fed from many different tributaries that pass through the Siwalik range (Beek et al., 2006). Due to the uplift and lateral propagation of active fault-related folds along the MFT, lateral drainage diversion is observed within the Siwalik (Beek et al., 2006).

Bedrock rivers within the study area are north to south-flowing and lie at the south of the Dun Valley (Figure 2.4), flowing across the east-west trending MFT. These river systems derive their sediments from the Himalayan foothills, and large proportions of these sediments are re-deposited in the plains or the foreland basin (Jain and Sinha, 2003). The Higher Himalaya also acts as the source of the sediments in the foreland basin (Lave and Avouac, 2000). The geomorphic responses of these rivers to tectonic processes are crucial in delineating landscape evolution, as the study area is located in the seismically active region.
2.6. Exhumation History

In a tectonically active orogenic belt, the typical rate of erosion ranges from 0.5 to 5 mm/yr (Rahl et al., 2007). The variable uplift rates within the Siwalik in the Nepalese Himalaya have gained considerable attention to understand its long-term erosion history. A limited number of studies have focused on determining the recent exhumation rates within the Siwalik using detrital thermochronology (Burbank et al., 2003; Beek et al., 2006; Blythe et al., 2006). Beek et al. (2006) performed fission track analyses in the Karnali, Tinau, and Surai Khola river sections of the western Siwalik in the Nepalese Himalaya (Figure 2.5), which show similar cooling ages in the Karnali (15.8 ± 1.8 Ma) and Tinau Khola sections (15.9 ± 0.9 Ma). In the Surai Khola section (located within the study area), the cooling age varies between 3.4 Ma -11.6 Ma (Beek et al., 2006). An exhumation age within the Surai Khola section was also calculated based on magnetostratigraphic and biostratigraphic ages (Appel et al., 1991; Mugnier et al., 1999;
Szulc et al., 2006). Lave and Avouac (2001) used river terrace dating and elevation measurements for estimating river incision rate for the Nepalese Himalaya, where they found that the incision rate varied based on the location, but were steady throughout the Holocene. In the Siwalik region, the river incision rate is very rapid at 10-15 mm/yr (Lave and Avouac, 2000). Kirby and Whipple (2001) analyzed river longitudinal profiles, based on the rock uplift rate obtained from Lave and Avouac (2001), by interpolation of high resolution DEM. They found that the dependence of incision rate and erosion is consistent in the Siwalik.

Figure 2.5. Published thermochronologic and geomorphic works in Nepal. Various exhumation studies conducted in the Nepalese Himalaya used zircon and apatite fission track and apatite (U-Th)/He thermochronology from detrital sedimentary rocks (red box), and river profile analysis (green box), The study area is shown by the dark blue box. Notice the major rivers are shown in light blue lines. Source: The background geologic map was modified from Dahal (2006).
CHAPTER 3. METHODS AND TECHNIQUES

Several data sources were used in this study. These data included: lineament data, extracted from the Shuttle Radar Topography Mission (SRTM) Digital elevation Models (DEMs), for the identification of any unmapped lineaments in the study area; river longitudinal profile data, extracted from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) DEMs, for the extraction of the regional tectonic information; several geomorphic parameters, such as knickpoint, concavity, and steepness index, extracted from the river profile data, for the determination of exhumation information; modern precipitation data, acquired from the Humanitarian Data Exchange (Zearley, 2015), for the analysis of the precipitation effect on any change on the geomorphic parameters; and, finally, published exhumation ages for the interpretation and comparison of the geomorphic parameters in the context of regional exhumation and uplift.

3.1. Lineament Analysis

In order to understand the tectonics of a region, it is important to understand the lineament distributions involving patterns, orientation, and types (Masoud and Koike, 2006). The identification of lineaments obtained from remotely sensed images has been shown to be useful for the interpretation of tectonic deformation in a particular region (Caran et al., 1981). According to Masoud and Koike (2006), lineaments are linear features on the Earth’s surface that represents a crustal structure or structural zone of weakness. Lineaments obtained from the remote sensing data are based on distinct geomorphologic features such as linear segment of a channel segments of a channel, drainage deflection, radar shadow-illumination, linear ridges and valleys, displacement of ridge lines, scarp
faces, etc. (Prabu and Rajagopalan, 2013). In this study, lineament extraction was performed from the 90 m resolution SRTM DEM using ArcGIS (Figure 3.1A). A hillshade function using variable sun angles was used to obtain the hillshade images of the study area. This function stimulates artificial light arriving from the point source of illumination from a different altitude and azimuth (Masoud and Koike, 2006).

Figure 3.1. Image analysis for lineament extraction. Map of the study area generated from the SRTM DEM, which was used to generate hillshade images (A). An example of a hillshade image that was generated from the SRTM DEM using 45° sun angle (B). Lineaments, extracted from this hillshade image, are shown in yellow lines (C). Notice the location of the hillshade image is shown in A. Source: Created by the author.
Figure 3.2. Lineaments on different hillshade angles in DEMs. Examples of lineament (yellow lines) distribution in the study area that were extracted using 45° (A), 135° (B), and 160° (C) hillshade images.

Source: Created by the author.
The hillshade images were generated using 45°, 90°, 135°, 160°, and 180° sun angles (Figure 3.2) to allow viewing the topography of the study area from different angles. Each lineament was traced from these hillshade images based on a distinct feature as mentioned in the previous paragraph. The lineaments then were compared between hillshade images in order to avoid any DEM-related artifacts (Figures 3.1 and 3.2). Various geometric properties of the extracted lineaments were measured, which included the length, strike and frequency. The lineaments then were draped over the knickpoint distribution in the study area.

3.2. ASTER-derived DEM:

The 30 m resolution ASTER DEM, obtained from the U.S Geological Survey Earth Explorer (USGS, 2017), was used for the extraction of river networks and river longitudinal profiles. These DEMs were created from remote sensing data that contain anomalies and holes because of extreme relief, water bodies, and cloud cover (Wobus et al., 2006), which were further processed for the geomorphic analysis in ArcGIS. The DEM was first projected to the Universal Transverse Mercator (UTM) coordinate system. The projected DEM then was analyzed using various functions in ArcGIS hydrology tools. These functions include extraction of fill, flow direction, flow accumulation, watershed, and stream order. Fill function was used to remove data gaps in the DEM due to the presence of sinks or peaks. Application of this fill function allowed deriving the continuous DEM for further analysis. Flow direction function was performed on the filled DEM to create a raster image with flow direction from each cell to its steepest downslope neighbor. The flow direction and fill functions facilitated the flow accumulation function to create a raster image to accumulated flow. The filled DEM and flow accumulation
raster image were used later to extract river longitudinal profiles using codes in the MATLAB software and the Profiler Tools extension in ArcGIS. The watershed, drainage area, river network and Strahler stream order also were extracted from the filled DEM and flow accumulation image for long profile analysis (Figure 3.3).

Figure 3.3: Concept map for research methodology. Workflow of the methods applied in this study. Source: Created by the author.

Geomorphic parameters like knickpoints, normalized steepness index ($k_{sa}$), and concavity index ($\theta$) were extracted from the longitudinal profile. For this, the artificial spikes were removed and a smoothing value of 250 m was set. The spikes were removed because the smoothing value may cause concavity to fluctuate and give an unbiased concavity value. The smoothing of the DEM was set to avoid the scattering of the slope-area plots from the longitudinal profiles. The contour interval of 12.192 (default) was
also set for an even distribution of the data in log S- log A space to avoid bias in the regression analysis (Wobus et al., 2006).

3.3. Longitudinal River Profile Analysis

Geomorphic systems, specially the river systems, show significant response to recent tectonic activities (Kale et al., 1996; DiBiase, 2011; Olivetti et al., 2012; Aiken and Brierley, 2013). The evolution of tectonic deformation is usually recorded by longitudinal profiles in a river system of a particular region (Chen and Willet, 2016). The interaction between fluvial incision, variable lithology, and base-level change can result in the alteration of these profiles (Montgomery and Brandon., 2002). The shape of the long profiles, including their parameters like steepness and concavity indices and knickpoint location, can mark the evolutionary processes of landscape development (Kirby and Whipple, 2001; Wobus et al., 2006; Lee and Tshai, 2010), such as an equilibrium or transient state of a landscape. If the river longitudinal profile shows a concave-upward shape, the river is considered to be in an equilibrium state or steady-state condition where the erosion is equal to uplift. On the other hand, a convex profile suggests that the uplift is higher than the erosion (Ambili and Narayana, 2014).

Since river longitudinal profiles preserve valuable information of landscape evolution, certain anomalies and abrupt changes in river gradients within the profiles indicate tectonic activities within a region. The presence of the anomalies like knickpoints and knickzones is caused by local landscape deformation (Ambili and Narayana, 2014). According to Bishop et al. (2005), a knickpoint is a steep reach in a river profile that can be caused by localized bed incision, rock uplift, or shear stress applied to resistant lithology. Thus, profile parameters such as knickpoints, concavity, and steepness
indices are important for understanding tectonic activities. In this study, the longitudinal profiles were extracted based on the stream power law function (Lu and Shang, 2015). According to Hack (1957), this power law function is the relationship between the local channel slope from the fluvial channels and contributing drainage area, which is expressed by the following equation:

\[ S = k_s A^{-\theta} \]  

(Eq. 1)

Where \( S \) indicates local channel slope, \( A \) is the upstream drainage area, and \( k_s \) and \( \theta \) are channel steepness and concavity indices, respectively. Equation 1 is applicable for the drainage area above a critical threshold, \( A_{cr} \), which shows the transition of a river from a debris-flow regime to the fluvial process (Wobus et al., 2006). The different segments in a longitudinal profile exhibit the variation in \( k_s \) and \( \theta \), which were analyzed and studied to extract tectonic information. As \( k_s \) varies widely with a slight variation of \( \theta \), \( k_s \) is normalized to \( k_{sn} \) using a reference concavity \( \theta_{ref} \) to compare steepness values within a basin using the following equation (e.g., Wobus et al., 2006):

\[ S = k_{sn} A^{-\theta_{ref}} \]  

(Eq. 2)

Where \( S \) indicates local channel slope, \( A \) is the upstream drainage area and \( k_{sn} \) and \( \theta_{ref} \) are normalized steepness index and reference concavity indices, respectively. Individual segments of slope-area data were then fitted using reference concavity for the determination of \( k_{sn} \). The benefit of using \( k_{sn} \) is that it is proven to be useful for comparing with uplift (e.g., Wobus et al., 2006).
3.4. Knickpoint Extraction and Identification

Knickpoints are the reaches of anomalously steep gradients that are capable of recording tectonic information (Mitchell, 2006). Knickpoints can be formed by changes in base level due to incision, rock uplift, climate changes, or variation in rock strengths (Bishop et al., 2005; Ambili and Narayana, 2014). Knickpoints are usually classified into major knickpoints (reliefs of ≥200 m) and minor knickpoints (relief of ≤200 m). The presence of major a knickpoint in long profile indicates that river incision may be controlled by changes in the base level. The presence of minor knickpoints indicates lithologic variability and/or smaller pulses of incision (Wobus et al., 2006). Major knickpoints migrate through headward erosion, incising into relict topography (Crosby and Whipple, 2006). In erosive landscapes, knickpoints could be considered as the migrating boundary between downstream regions that are adjusting to new forcing and upstream regions in order to retain its original or preexisting characteristics (Wobus et al., 2006; Whipple et al., 2007).

Major and minor knickpoints were identified on river longitudinal profiles using MATLAB codes and were plotted in ArcGIS to study their spatial distribution. Major and minor knickpoints were classified based on the relief (knickpoints with ≥200 m relief as major and with ≤200 m relief as minor). The knickpoints were then integrated over the lithology, $k_{sn}$, and lineaments for further analysis. Then, lithology controlled knickpoints and lineaments/structure-controlled knickpoints were identified. The density of observed knickpoints from each stream was calculated using kernel density for further analysis.
3.5. Normalized Steepness Index ($k_{sn}$) and Concavity ($\theta$) Index Classification

Longitudinal profiles of the bedrock rivers usually exhibit a concave-up shape when steady-state conditions are achieved (i.e., uplift rate is equal to erosion rate) (Sobel and Strecker; 2003; Wobus et al., 2006). The concavity of the river longitudinal profile depends on various factors such as tectonics, climate, and base level change (Zaprowski et al., 2005). According to Ambili and Narayana (2014), river profiles in tectonically active regions exhibit a higher concavity index, whereas equilibrium river profiles exhibit a lower concavity index. In order to extract the normalized steepness and concavity indices, linear regression from the slope and drainage area of the river profile segments was performed. As, $k_s$ and $\theta$ are auto corrected, steepness index values are normalized ($k_{sn}$) by reference concavity value ($\theta_{ref} = 0.45$), where the reference theoretical range is (0.3-0.6) (Synder et al., 2000; Kirby and Whipple, 2001; Olivetti et al., 2012). The normalized steepness index and concavity index map were generated by calculating the values of $k_{sn}$ for each segment of the river above the minimum input drainage area. The $k_{sn}$ values for 142 rivers of the study area were classified into 10 classes that range from 5.3 to 140.6.
CHAPTER 4. RESULTS

4.1. Lineaments

A total of 128 lineaments were extracted from the study area (Figure 4.1A). Various hillshade images at different angles (45°, 90°, 135°, 160°, and 180°) were compared in order to finalize the existence of each of the lineaments and to avoid any image artifacts. The longest lineament observed is about 8 km (~8498 m) and the shortest is about 0.5 km (~569 m) (Figure 4.1 B). The majority of the lineament trends east-west and are similar to the strike of the MFT (Figure 4.1C). Thus, these lineaments are interpreted to be faults and/joints associated with the MFT. A few of the lineaments show north-south trends that were also interpreted as faults, fractures, or joints (Figure 4.1C). Further analysis of these lineaments with knickpoint location was performed in section 4.3.

4.2. Longitudinal River Profiles

About 140 bedrock rivers from 54 watersheds were extracted and analyzed (Figure 4.2). Most of these major rivers flow from the southern Rapti basin (Dun Valley) in the north towards the south into the Indo-Gangetic Plain. The rivers extracted from the DEM lie between 82°00' E longitude to the west and 82°60' E longitude to the east. In each watershed, the tributaries were represented by numbers range from 1 to 11. The drainage area of the watersheds ranges from 1,000,000 m² to 27,000000 m², and most of the rivers reveal first order streams. Stream orders from 1 to 4 were observed within these drainage areas (Figure 4.2).
Figure 4.1. Lineaments extracted from the study area. Spatial distribution of lineaments identified within the study area (A). Bar graph showing the length vs. frequency of the lineaments (B). Lineaments with less than 4 km of length have higher frequency than those with lengths of >4 km. Rose diagram showing the general north-south and east-west orientation of the lineaments (C).

Source: Created by the author.

The lengths of the river profile range from 2.5 km to 18 km, measured from the head to the mouth of the river. Longitudinal river profiles show the plots of drainage areas as a function of downstream distance (Figures 4.3 and 4.4). A log of drainage area versus a log of channel slope plots give the power law regressions of each river profile, which, in turn, indicate concavity index ($\Theta$) and normalized steepness index ($k_{sn}$). Most
of the streams exhibit a concave shape in their longitudinal profiles that consist of at least one knickpoint with a varying normalized steepness index \((k_{sn})\) and concavity index \((\Theta)\) upstream and downstream of that knickpoint. Some of these long profiles exhibit convex profiles that are separated by distinct knickpoints (Figures 4.3 and 4.4). The smooth configuration of each longitudinal profile reflects an equilibrium profile, while the convex profile represents reaches that are at a transient state (Wobus et al., 2006).

![Figure 4.2](image)

**Figure 4.2.** Watershed and stream order of the extracted river profiles. Map generated from ASTER DEM showing 54 watersheds with tributaries. Stream order in each watershed and the location of knickpoints are shown. Source: Created by the author.

About twelve longitudinal profiles are devoid of any knickpoints, and are concave-up profiles (Figure 4.5). These rivers likely have already adjusted or are in an equilibrium state. The drainage areas of these rivers are small. The knickpoints that are found in >1,000,000 m² of drainage area are considered to be debris flow or slope-failure related (Wobus et al., 2006). Thus, no knickpoints from these small drainage-area watersheds were taken into consideration for any further analysis.
Figure 4.3. River longitudinal profiles with slope area data. Longitudinal river profiles of the tributaries 1b, 4a, 1d, 28d, 28d, and 46a (e.g. 1b: 1 - watershed; b - tributary) (A). Each of these profiles shows the locations of major and minor knickpoints. Notice that the knickpoints in each profile are categorized by possible geologic controls. Log-log plots of the gradient and drainage area for each profile are also shown. Normalized steepness index and concavity index of each segment of the profile are provided as well. The location of each profile is shown in Figure 2.4. 
Source: Created by the author.
Figure 4.4. Additional river longitudinal profiles with slope area data. Longitudinal river profiles of the tributaries 6e, 5a, 38a, 39a, and 48a (e.g. 1b: 1- watershed; b- tributary) (A). Each of these profiles shows the locations of major and minor knickpoints. Notice that the knickpoints in each profile are categorized by possible geologic controls. Log-log plots of the gradient and drainage area for each profile are also shown. Normalized steepness index and concavity index of each segment of the profile are provided as well. The location of each profile is shown in Figure 2.4. Source: Created by the author.
4.3. Knickpoint Identification and Analysis

A total of 305 knickpoints were identified within the long profiles. Within these knickpoints, a total of 180 were classified as major knickpoints and the remaining 125 were classified as minor knickpoints (Figure 4.6). Most of the major knickpoints are located at the elevation of $\geq 320$ m and minor knickpoints are located between an elevation of 160 m and 320 m (Figure 4.7). The maximum number of knickpoints were observed in the drainage area of less than 2,000,000 m$^2$ (Figure 4.8). More than one knickpoint was observed in higher order streams and were overlapped (the knickpoints in the profiles that fall within the confluence of these profiles with the main river). Thus, 74 overlapping knickpoints that fall within this category were not considered for further analysis.
Figure 4.6. Location of major and minor knickpoints. Red circles indicate major knickpoints and blue circles indicate minor knickpoints. Source: Created by the author.

Figure 4.7. Scatter plot of elevation vs. number of knickpoints. Red circles indicate major knickpoints and blue circles indicate minor knickpoints. Source: Created by the author.
In order to identify active tectonic influence unequivocally, the knickpoints were separated based on the lithology, lineaments, and tectonics present in the study area. The 200 m elevation threshold was used while identifying these controlling factors of the knickpoints. The lithology-controlled knickpoints’ count was about 74, where major knickpoints count up to 45 and the number of minor lithology-controlled knickpoints is 29. A total of eight knickpoints were found at the contact between the upper Siwalik (Dobatta Formation) and the middle Siwalik (Surai Khola Formation). Similarly, 24 knickpoints are seen at the border of the Surai Khola and Chor Khola formations (both are middle Siwalik). A total of 19 knickpoints are observed at the border of the middle Siwalik and the lower Siwalik (Chor Khola and Bankas formations). Thirteen knickpoints

Figure 4.8. Scatter plot of drainage area versus knickpoints. Red circles indicate major knickpoints and blue circles indicate minor knickpoints.
Source: Created by the author.
were observed at the contact between lower Siwalik (Bankas Formation) and the Terai region (Figure 4.9A).

Figure 4.9. Map of knickpoints controlled by lithology, structure, and tectonics. Lithology-controlled knickpoints (A); Structure-controlled (e.g., faults and joints) knickpoints (B); and tectonic knickpoints (C). Source: Created by the author.
About 128 lineaments were observed throughout the study area. These lineaments are likely geological structures such as faults, joints, and/or geomorphological features like cliffs, terraces, and linear valleys. About 152 knickpoints were identified as structurally-controlled. Out of these, 111 are structure-controlled major knickpoints and 41 are minor knickpoints (Figure 4.9B). The remaining 50 major knickpoints and 42 minor knickpoints are likely influenced by tectonics (Figures 4.9C and 4.10).

Figure 4.10. Bar graph for knickpoints and their geologic controls. The Y-axis shows the frequency of knickpoints and the X-axis shows their possible geologic controls. The red bar indicates the number of major knickpoints and the blue indicates minor knickpoints. Source: Created by the author.

4.4. Steepness Index \((k_{sn})\) Patterns

A normalized steepness index \((k_{sn})\) was used for the analysis of longitudinal profiles in the study area. Multiple segments of longitudinal profiles represent spatial and temporal variations in incision rate, thus rock uplift (Wobus et al., 2006). Several studies concluded that \(k_{sn}\) can be associated with rock uplift, lithology, precipitation, and/or
climatic variables (Kirby and Whipple, 2001; Duvall et al., 2004; Hu et al., 2010; Ambili and Narayana, 2014). The change in lithologic resistance to erosion also influences the $k_{sn}$ (Cyr et al., 2014). According to Duvall et al. (2004), rock uplift is directly proportional to $k_{sn}$ and is higher where there is an increase in $k_{sn}$. Additionally, a higher magnitude of incision is directly related to a high $k_{sn}$, whereas a lower incision is related to a low $k_{sn}$ (Kirby and Whipple, 2001; Gani et al., 2007; Neupane, 2011). With the uniform lithology and other climatic factors, high and low $k_{sn}$ could be related to tectonic activities (Ambili and Narayana, 2014).

The presence of knickpoints has contributed to the distinct difference of the $k_{sn}$ value. The $k_{sn}$ values are different above and below knickpoints (Figure 4.11A). Locally, there are variable $k_{sn}$ values within same lithology. In the middle Siwalik, the value is higher than the other regions. This means that the lithology does not have much role in influencing the variation in $k_{sn}$. The $k_{sn}$ map was also compared with the precipitation map (Figure 4.11B). Nepal’s annual precipitation ranges from 500 mm to >5000 mm. The high topography, slope direction and altitude, and distance from the ocean and the the Bay of Bengal are the main factors associated with rainfall variation within the Nepalese Himalaya, which receives its maximum precipitation during the monsoon season (June to September). During the monsoon, sediment load in the streams may govern the capacity of river to accelerate erosion rates (Hu et al., 2010). The Terai and inter-montane valley receive rainfall of about 100 mm to 2500 mm, while the hills (Siwalik and higher mountains) receive precipitation ranging 1700 to 3000 mm, depending on their location (Khadka, 2013).
Figure 4.11. Maps of $k_{sn}$ distribution, annual precipitation, and slope. The $k_{sn}$ classification map shows the variation in $k_{sn}$ within the study area (A). The annual precipitation ranges between 2500mm and 1435mm (B). The slope map is obtained from ASTER DEM and shows the relief of the study area (C).

Source: Created by the author (A and C), and modified from Zearley (2015) (B).
The annual precipitation in the study area ranges from 1435 to 2500 mm. The slope of the study area ranges from 0° to 68.9° (Figure 4.11C). The slope is higher in the southern part of the study area. Since the Nepalese Himalaya receives orographic rainfall (rain that is caused by the lifting of moist air over the mountain), the southern slope is likely to be eroded more. The precipitation overlay map ((Figure 4.11B) shows the eastern part with high precipitation where the $k_{sn}$ and slopes are higher (Figure 4.11). On the other hand, the middle section of study area with relatively low precipitation shows minor variation in the $k_{sn}$.

Figure 4.12. Concavity index map of the river longitudinal profiles. The values range from -12.1 to 31.1.
Source: Created by the author.
4.5. Concavity Index (Θ)

The concavity index (Θ) of the tributaries in the study area varies from as low as -12.1 to as high as 31.1. It is classified into two classes: -12.1-0.5 and 0.6-31.1 (Figure 4.12). According to Wobus et al. (2006), concavity varies in the range of 0.35 to 0.65 in a tectonically active region. The Upper Siwalik has mostly low concavity values and the Lower Siwalik has high values. According to Kirby and Whipple (2001), low concavities are found in those regions where the rock uplift rate is increasing downstream, and high concavities where the rock uplift is decreasing downstream. The low concavity values in the study area might indicate that the uplift is increasing downstream (Figure 4.12).
CHAPTER 5. DISCUSSION

The analysis of longitudinal river profiles provides valuable information on landscape evolution. Longitudinal profiles are considered to be the most sensitive to regional tectonic activity compared to other geomorphic indicators (Burbank and Anderson, 2011). The bedrock river profiles are characterized by the channel shape, steepness, concavity, and knickpoints (that can be related to tectonics, structure, lithology, or tributary confluence). The geometry of the river profile can be used as a proxy for the identification of the spatial patterns of rock uplift (Kirby and Whipple, 2001).

The application of this methodology is restricted without its interaction with other processes like erosion or denudation rates and time for a complete understanding of the exhumation in that particular region. Therefore, in this study, quantitative longitudinal river profile analysis was used within the Siwalik section of the Nepalese Himalaya. In order to understand landscape exhumation, the longitudinal profile morphology is discussed in terms of the parameters extracted in this research (such as knickpoints, $k_{sn}$, and concavity), and integrated with various data like precipitation, lineaments, and published exhumation data.

The presence of knickpoints in the longitudinal profile represents the landscape transience (Ambili and Narayana, 2014). In this study, the majority of the longitudinal profiles are characterized by two segments separated by one major knickpoint and some minor knickpoints (Figures 4.3 and 4.4). The profile segments separated by knickpoints have different $k_{sn}$ values upstream and downstream of the knickpoints (e.g., tributaries 1f, 1d; see Figures 4.3 and 4.11A), and likely represent different incision phases (Gani et al.,
Major knickpoints are mostly located at higher elevations than the minor knickpoints (Figure 4.7). The presence of knickpoints at a nearly constant elevation suggests that the longitudinal profiles are transient due to changing boundary conditions (Wobus et al., 2006). About 92 major knickpoints were identified that are not controlled by structure or lithology (Figures 4.9C and 4.10). These major knickpoints were classified as tectonically influenced or as knickpoints that resulted from regional rock uplift (Crosby and Whipple, 2006; Foster and Kelsey, 2012). These tectonic-influenced major knickpoints migrate upstream as headward erosion (Crosby and Whipple, 2006). The minor knickpoints could be a result that represents lithologic variation or low incision. These minor knickpoints can also be associated with the change in sediment flux related to landscape adjustment (Holland and Pickup, 1976).

The $k_{sn}$ values range from 5.3 to 140.6 (Figure 4.11A), where average $k_{sn}$ values on the eastern side of the study area are higher than those in the west. As $k_{sn}$ is directly proportional to uplift rate (Wobus et al., 2006), here the $k_{sn}$ values are compared with the uplift zones deduced from the tectonic-influenced knickpoints (Figure 5.1). The plot of density of these tectonic-influenced knickpoints displays a hotspot within the study area (Figure 5.1). A high $k_{sn}$ value might be related to high uplift. The major knickpoints from the east to the mid-section of the Siwalik follow the trend, and then there is a break in the knickpoints trend. This could be related to the MFT but not to local structure or uplifts. Further, not all the knickpoints related uplift zones necessarily correlate with high $k_{sn}$. The high $k_{sn}$ may also be due to the erosion caused by the climatic factors such as monsoon precipitation.
Figure 5.1. Comparison of high and low $k_{sn}$ values with the local uplift. Major (red plus symbol) and minor (blue plus symbol) tectonic knickpoints overlain by the density map (A). Low $k_{sn}$ with uplift zones indicated by minor knickpoints where there is subtle incision (B). The knickpoint could also be influenced by the MFT (C) (Low $k_{sn}$ with uplift zones represented by minor knickpoints due to the presence of MFT). High $k_{sn}$ with uplift zones represented by major knickpoint and minor knickpoints likely related to the MFT (D). Source: Created by the author.

The concavity index values range from -12.1 to 31.1. These anomalously high and low concavities might be due to the direction of flow relative to the gradient in the uplift (Figure 4.12). In the Siwalik, tributaries approaching anticlines or MFT-related fault systems from the north show negative concavities. These negative values might indicate rapid increase in slope as uplift rates increase downstream (Kirby and Whipple, 2001). According to Wobus et al. (2006), downstream transition between different steepness values is bridged by the zone of high and low concavity. Since the length of most of the tributaries in this study is short, the $k_{sn}$ would be more useful for the evaluation of regional tectonics than concavity indices (Wobus et.al, 2006).
The results of the long profile parameters were correlated with the published seismic and exhumation data within the study area. Large-scale thrust fault-related deformation and complex collisional tectonics have made the Nepalese Himalaya a very active seismic zone (Pandey and Molnar, 1988; Bilham et al., 2001; Sanker et al., 2011). The Nepalese Himalaya has had large magnitude (≥ 6.0) earthquakes over the last 100 years (Sanker et al., 2011) (Figure 5.2A). The 8.4-magnitude Bihar-Nepal earthquake occurred in 1934 and impacted areas up to 200 ± km from its epicenter at the MFT (Pandey and Molnar, 1988). The most recent earthquake in central Nepal occurred in 2015, with a magnitude of 7.8 (Figure 5.2A) (Parameswaran et al., 2015). The MCT and MBT were impacted by this earthquake with some slope failures and erosion. Visible surface ruptures were not observed at the MFT, except a few large drainages uncovered the MFT scrap in Central Nepal (Moss et al., 2015).

The study area has not experienced any earthquake larger than magnitude 6. The map (Figures 5.2B) shows the record of magnitude ≤ 6.5 earthquakes that occurred between 1803 and 1962 C.E. (Sanker et al., 2011). Structures like folds and regional faults are the results of transfer of the strain due to repetition of large earthquakes over time (Lave and Avouac, 2000). The 2015 earthquake may not have had a direct impact on the MFT-related structures, as no evidence of surface rupture is seen in the MFT in the study area (Moss et al., 2015; Parameswaran et al., 2015). Although there is no correlation with the earthquake events recorded in the study area, the intensity of the seismic wave of the above-mentioned historical earthquakes can propagate within the study area and likely activate or reactivate some of the mapped lineament system. In other words, the study area devoid of any seismic events can be a seismic locked zone,
where seismic energy might continuously be building slowly with the movement of the MFT (Lave and Avouac, 2000).

Figure 5.2. Siesmotectonic map of the Nepalese Himalayas. Earthquakes that occurred in Nepal since 1800 C.E. until now (A). Seismic map of the study area with <6.5 magnitude earthquake location (B).
Source: Modified from Sanker et al. (2011) (A) and the Wall Street Journal (2015) (A), and created by the author (B).
A few exhumation studies were conducted within the Siwalik of the Nepalese Himalaya (Figures 2.5 and 5.3) (Beek et al., 2006; Najman, 2006; Chirouze et al., 2011; Lupker et al., 2012). The exhumation rate of the Muksar Khola (0.8 mm/yr) in the eastern Siwalik is slower than that in the western Siwalik (1.1 mm/yr) (Lupker et al., 2012). This could be related to the position of the MCT further south in the eastern Nepal than the west, which results in less erosional exhumation of the Higher Himalayan rocks (Figure 5.3A) (Beek et al., 2006; Chirouze et al., 2011). But in the western Siwalik, exhumation ages indicate that the sediments were fed by the drainage system originating from the Higher Himalaya (Bernet et al., 2006; Beek et al., 2006; Szulc et al., 2006), which means a high exhumation rate from the Higher Himalaya. This high rate likely indicates that the rate of uplift is higher in the western Siwalik than in the eastern Siwalik.

The rock uplift and surface uplift have a complex relationship in a mountain setting and depend on the erosional exhumation (Sobel and Strecker, 2003). The uplift caused by the MFT may have created the orographic barrier for monsoonal precipitation (Figure 5.3B). The monsoonal precipitation may have a high input on the rapid exhumation rate of ~1.8 km/Ma in this region (Beek et al., 2006). Various studies have been done in the Surai Khola River section within the study area to understand exhumation (Appel et al., 1991; Mugnier et al., 1999; Cornivus and Rimal, 2001). According to Beek et al. (2006), the Upper Siwalik and the Middle Siwalik (Jungli and Shivgarhi formations) exhibit different exhumation ages: 3.4- 7.1 Ma, 6-8.8 Ma, and 5.3 to 11.6 Ma. The quantitative data show that the Upper Siwalik and the Lower Siwalik have low uplift rates, as they show a low $k_{\text{ex}}$ in both sections. Yet the middle Siwalik has a high uplift rate. The work done by Lave and Avouac (2000), about 200 km east of the study area, suggests that the
rock uplift rate is 1.5 cm/yr. Any change in the relief of the region with a high $k_{sn}$ value can result in a change of erosion or exhumation rates (Montgomery and Brandon, 2002). Since the exhumation rate of this section corresponds with the shortening of the MFT at 20 mm/Myr (Beek et al., 2006), the high $k_{sn}$ suggests that it has the capacity for higher river incision (Figure 5.3C). As the exhumation, and thus uplift, rate is higher, the Upper and Middle Siwalik (Jungli Formation) are exhumed at a higher rate than that of the Shivgarhi Formation, which is mostly controlled by the MFT and related structures (Figure 5.3C). Erosion of the thrust sheet could have influenced the rapid uplift of this section around 6 Ma to 8 Ma. Thus, the high $k_{sn}$ obtained from this study correlates with the high exhumation in the western Siwalik, and suggests that MFT-related tectonics and climate processes influenced the orogeny and were active at different times and scales.

The incising rivers in this study have provided the relationship between variable uplift, topography, and/or climate related erosion. The higher $k_{sn}$ values from the river long profiles correspond to higher incision in the study area above the MFT. The eastern part within the study area shows a higher variation in $k_{sn}$ values than in the western part. The presence of a distinct break of tectonic knickpoints between high and low $k_{sn}$ values on the east side might be related to MFT-related tectonic deformation and/or induced by higher precipitation. The high $k_{sn}$ suggests that it has the capacity of higher river incision. Erosion of the thrust sheet could have influenced the rapid uplift of this section.
Figure 5.3. Exhumation rates and $k_{sn}$ index with climate. Published exhumation rate and age along the Siwalik of the Nepalese Himalaya (A). Study area with annual precipitation and $k_{sn}$ overlay (B). Study area with $k_{sn}$ and knickpoint density (C).
Source: Modified from Dahal (2006) (A), modified from Zearley (2015) (B), and created by the author (C).
CHAPTER 6. CONCLUSION

This research revealed the exhumation of the Siwalik in the Nepalese Himalaya by integrating geomorphological parameters of the river longitudinal profiles with the spatial distribution of lineaments, lithologic variation, precipitation variability, earthquake distribution, and published exhumation ages. Perhaps, in the study area, this is the first research of its kind to investigate active tectonics from the integration of exhumation and river profiles. In this research, 30 m resolution ASTER DEM was used for analyzing the profile parameters such as knickpoints, normalized steepness index $k_{sn}$, and concavity index $\Theta$. These parameters were used to better understand the tectonic controls within the study area. In addition, 90 m resolution SRTM DEM was used for mapping lineaments.

The river profile parameters like knickpoints, $k_{sn}$, and $\Theta$ were identified and these values were used to deduce the tectonic controls over the study area. The knickpoints in different order rivers are found to be situated in equivalent elevations. The major knickpoints (a total of 180) are mostly located at the higher elevations and within the larger drainage areas compared to the minor knickpoints (a total of 125). Tectonically controlled knickpoints, isolated from lithology and structure-controlled knickpoints, indicate several phases of incision within the study area. A further comparison of these knickpoints with $k_{sn}$ and $\Theta$ found that the tectonically controlled knickpoints are likely influenced by MFT-related tectonics. The $k_{sn}$ values range from 5.3 to 140.6 to identify high and low exhumation areas. The concavity index of the tributaries range from as low as -12.1 to as high as 31. Since information about the paleodrainage pattern or network, and about the source material being eroded, is necessary for the interpretation of the
depositional record in terms of exhumation (Sobel and Sketcher, 2003), these data are compared with the exhumation rate of the study area. High $k_{\text{sp}}$ values indicate that this section of the Siwalik has a high uplift rate and corresponds with high incision. Both tectonic and climatic processes could possibly be responsible for the uplift and exhumation in the study area.

The results of this study conclude that the exhumation could possibly be controlled by the active tectonic deformation of the MFT, and/or by local climatic variation. The MFT-related uplift and lateral propagation of active fault-related folds along the MFT causes an increase in the localized uplift and exhumation within the study area. Since the Siwalik is the orographic barrier for the monsoonal precipitation in Nepal, the windward side is likely exhumed faster than the rain shadow region on the northern side of the Siwalik.

Further modelling and analysis are necessary to understand the constraints of these quantitative data, obtained from digital elevation models, more completely. Validation of tectonic-controlled knickpoints could be confirmed further by conducting field-based observations and modeling. This research on exhumation history should contribute to a more detailed understanding of existing knowledge about the interplay among tectonic uplift, climate, and erosion within the Himalaya, the highest mountain belt in the world. Additionally, this study can provide a platform for further geodynamic analysis of the region.
REFERENCES


