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ORIGINAL PAPER

Active tectonics influences in the Satluj river basin in and around Rampur, Himachal Himalaya, India

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Abstract
The detailed investigation of surface dynamics plays a vital role in the identification of regions experiencing recent tectonic activity. The analytical capabilities of geographic information system (GIS) in association with digital elevation model (DEM) are utilized to extract the morphometric and morphotectonic parameters of Satluj basin around a socio-economically important area (the Rampur zone). The drainage network of Strahler order 5 has been extracted from DEM and further analysed qualitatively and quantitatively in order to delineate areas of active deformation and the influence of neotectonic activities on the basin evolution. Further, the responses of the fluvial drainage patterns and other basinal geomorphic indices against the tectonic disturbances have been assessed. The results of morphometric and morphotectonic parameters affirm the neotectonic activities in the basin which is further verified in the field investigations by the presence of active faults, triangular facets, knick points, sharp truncation of the channel, offset channel etc. In addition, an attempt has been made to associate the landslide occurrences with morphometric features. The results of the morphometric study supported by the data of repeated occurrence of earthquake swarms and landslides in the region suggest high neotectonic activity along an active fault in the basin.

Keywords Morphotectonic · GIS · Satluj Basin · Landslides · Himachal Himalaya

Introduction

The Himalayan orogenic belt represents one of the most active collisional tectonic belts and a zone of exceptional geological complexity on the globe. The complexity results in frequent natural hazards like earthquake, landslide, tectonic upliftment/subsidence and extreme meteorological events during the course of centuries. The belt especially in the northwestern Himalaya under the influence of high strain rate engenders tectonic activities along its major pre-existing faults and lineaments (Lakshmi and Tiwari 2007). The Satluj river basin of Rampur and adjoining areas which comprise a part of northwestern Himalaya, India, illustrate an example of such region where imprints of active tectonics have been nicely preserved and easily accessible and can be studied at outcrop scale in the form of several typical landforms (Mukul and Singh 2016; Singh 2018). The area covers part of Kinnaur, Shimla and Bilaspur districts of Himachal Pradesh and characterized by steep slopes, undulating topography, deep gorges and varying climatic conditions. The study region experiences humid temperate to humid climatic condition and average annual rainfall is > 800 mm (Gupta and Sah 2008a). The rainfall is characteristically confined to the lower elevated region of the basin, whereas the higher elevated regions experience snowfall. Despite such unfavourable geographical characteristics, the area inhabits a privileged position for human settlement and also provides crucial passage to isolated areas of the region from Indian lowlands. The strategically significant Hindustan-Tibet road (National Highway (NH)-05 and NH-305) (Fig. 1)

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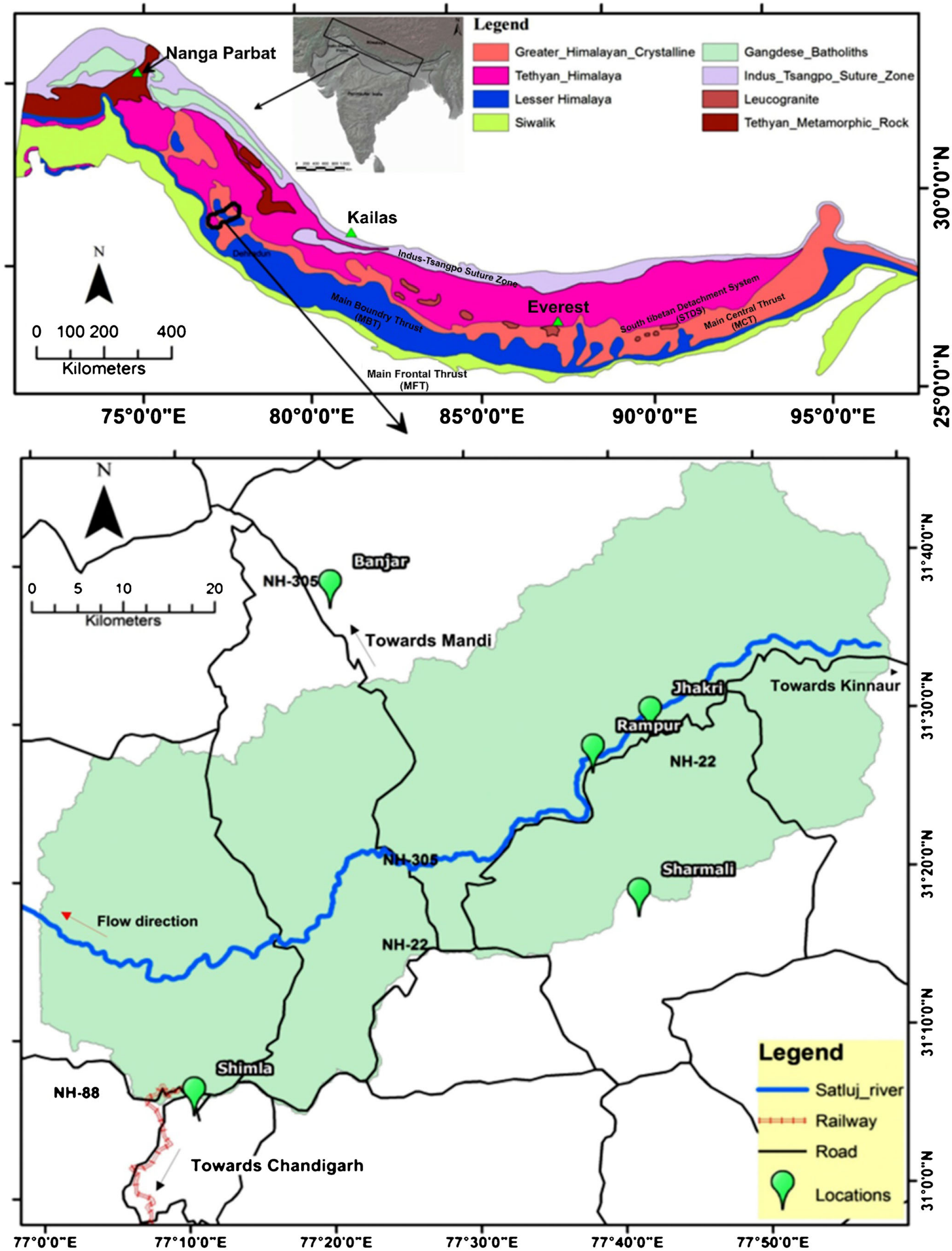


Fig. 1 Location map of the studied region in Satluj river basin, Himachal Himalaya, India (modified after O'Brien 2018)

traverses along this densely populated region of the basin which plays a vital role in accelerating and maintaining the socio-economic development and livelihood improvement in this region (Hearn and Shakya 2017). In addition, the areas around Rampur in Satluj basin have been experiencing several large-scale development activities related to hydro-power projects. The two most important hydroelectric projects of Himachal Pradesh are run by Satluj Jal Vidyut Nigam (SJVN) Ltd. are located in this area. One of them is Asia's largest underground Jhakri hydroelectric project of 1500 MW capacity and the other is Rampur hydroelectric project of 343 MW. Some minor projects like 2500-kW Nogli hydel power project are also running around Rampur. The region has been traversed by numerous small- and large-scale neotectonically active thrust faults and shear zones (in older metamorphites) (Pandey et al. 2004), which along with climatic and anthropogenic factors makes the area prone to landslide activities that cause a threat to lives and properties (Gupta and Sah 2008b; Singh et al. 2015b; Singh et al. 2016). The periodic reactivation of the pre-existing discontinuities may be linked with ongoing landslide activities in the area (Mahanta et al. 2016; Kundu et al. 2016) that can hamper the geomorphic setup. Therefore, the present work attempts towards the appraisal of active tectonics and its impact on geomorphic evolution of Satluj river catchment around Rampur area. The study of active tectonics is relatively recent and one of the rapidly growing components of earth sciences due to its wide applicability in solving interdisciplinary problems related to the earth processes (Strahler 1957; Pakhmode et al. 2003; Gangalakunta et al. 2004). Several studies have been conducted to investigate the spatial interrelation between the active tectonics, geomorphic processes and climate (Bartarya et al. 1996; Burbank et al. 1996; Brozovic et al. 1997; Shroder and Bishop 1998; Burbank et al. 2003; Godard et al. 2014; Sharma et al. 2018a; Sharma et al. 2018b). The study of active tectonics is a multi-disciplinary approach incorporating data from different twigs of geology particularly geomorphology, structural geology, tectonics, remote sensing and GIS etc. Hence, the approach has the ability to provide precise information on the assessment of natural disasters such as earthquakes and landslides, delineation of landscape evolution, base information for land use planning development and management programs, and many more on a regional scale (Dubey and Shankar 2019). Further, the ongoing interaction among active tectonics and erosional processes in association with lithology, and climate are mainly responsible for rock upliftment and shaping up of the existing topography in a basin (Azañón et al. 2012).

The shape and geometry of a landform play a very significant role in the study of basin evolution. In addition, the ongoing tectonic activities also influence the drainage pattern in the basin and further responsible for enhanced channel incision, basin asymmetries, channel offsets and complexity of drainage networks (Cox 1994). Thus, the geomorphological features specifically relief and fluvial drainage patterns of an area usually show the imprints of the subsurface geology and structural discontinuities (Keller and Printer, 1996). Such basinal response to active tectonic processes can be significantly decrypted by morphometric and morphotectonic analysis (Keller and Pinter 2002; Chen et al. 2003). The fluvial drainage patterns are considered a sensitive indicator of tectonic activity in a basin as it significantly preserves the imprints of existing tectonic processes and also adjusts itself with different stages of landform evolution (Schumm 1986; Keller and Pinter 1996; Jackson et al. 1998). Therefore, the morphometric analysis gives quantitative information about the relief, channel slope, type and the extent of drainage networks, structural controls, recent diastrophism, and geological and geomorphic accounts of a drainage basin. The 'morphotectonic analysis' uses the structural and morphometric parameters to establish the morphological evolution of a basin (Das and Gupta 2019). Therefore, morphometric and morphotectonic approach expressively helps in basin characterization and also establishes the relation among different basins in terms of geology, geomorphology, structure, tectonic activities, vegetation, soil type and drainage system development (Strahler 1952, 1964; Magesh et al. 2012).

Nowadays, the DEM (Digital Elevation Model) data along with GIS (geographic information system) technologies are being extensively used to analyse the morphometric parameters of tectonically active regions. The introduction of DEM has revolutionized the process as it has replaced the use of traditional topographic maps, making the analysis more convenient, precise and rapid. Besides, the technique has the capability to provide synoptic observation of large area at the same time (Pareta and Pareta 2011). The quantitative analysis of DEM in GIS environment helps in comparing objectively between varied landforms and calculating the different parameters which can be useful for the identification of specific characteristic of an area, namely 'extent of ongoing tectonic activities' (Keller and Pinter 1996). These parameters are often referred as 'geomorphic indices' and recognized as significant reconnaissance tools (when coupled with field checks) to identify the areas undergoing tectonic deformation (Bull and McFadden 1977; Srivastava and Mitra 1995; Singh and Singh 1997; Nag 1998; Chopra et al. 2005).

Thus, the emphasis of this study is mainly on to decipher the landform evolution, the response of fluvial drainage patterns, and morphometric and morphotectonic features in the response to active tectonics. Further, an attempt has also been made to link the geomorphic characteristics, seismo-tectonic activities and landslide occurrences. Ancillary data, Google Earth imageries and the field observations strengthen the results in the inaccessible remote locations of the region.

Geological and tectonic setting

The Satluj river basin has the rocks of Central Crystalline and Lesser Himalayan Formations exposed between Jutogh-Munsiari Thrust (JMT) and Main Central Thrust (MCT) in the southern and northern margins respectively. It progressed by the time since Early Cenozoic Era when the Indian plate impinged into the then existing Eurasian plate deforming pre-existing Neoproterozoic sedimentary cover and formation of an early 'Tethyan' mountain range. In the course of time as collision sustained, the lower part of Indian plate subducted beneath the Asian plate and deeply buried and metamorphosed slice of crust thrusted upward and formed the Central Crystalline Zone. The Central Crystalline Zone, a 10-km-thick zone, is confined between tectonically active MCT in the southern margin and South Tibetan Detachment plane (STD) at the northern margin (Valdiya 2010). The STD is a set of normal-sense faults and shear zones which has developed as a result of extension and thinning of the crust along the detachment zone. The STD has accelerated the pace of exhumation of the deeply subducted Central Crystalline Zone (Yin, 2006). The central crystalline unit is a predominantly northeast-dipping, highly deformed, amphibolite to migmatitic gneiss sequences. These two thrusts were contemporaneously active while the formation of these rock types during the Early and Middle Miocene (Pandey et al. 2004). In addition, the continued activities along MCT caused rock units of the Lesser Himalaya (from Jutogh-Munsiari Group up to Simla-Damtha Group) to underthrust within rocks of the Higher Himalaya (Valdiya 1980). The geologic units are exposed in the basin as the Kullu-Rampur Window Group (KRWG) (Srikantia and Bhargava 1998). The dominant lithologies of KRWG tectonostratigraphic domain in Satluj basin comprise augen migmatite, biotite gneiss, quartz-mica schist, garnet-bearing quartz-mica schist, muscovite-biotite schist and amphibolite of Palaeoproterozoic and Mesoproterozoic age. These rocks are characterized by low- to medium-grade inverted metamorphism where the regional strike of lithological units is predominantly ENE-WSW with minor local variations in the trend (Singh 1979). The successions of Rampur Formation overlie the Chail Formation with faulted/thrusted contact (Misra and Tewari 1988). The Bandal Granite Complex overlies the Rampur quartzite and exhibits thrusted contact along the Jhakri-Sungri Thrust (JST) which is one of the active thrusts of the area (Pandey et al. 2004). This thrust zone is active from the past 4.5 Myr and younger than the age of MBT (Meigs et al. 1995; Jain et al. 2000; Pandey et al. 2004).

The entire sequence of rock formation exposed in the study area has undergone major deformations due to numerous tectonic pulses resulted from different stages of Himalayan orogeny during the tertiary period (Valdiya 2010). So, the area exhibits a complex system of active thrust zones which probably plays a significant role in the neotectonic activity of the study basin (Bhargava 1980; Valdiya 1980; Meigs et al. 1995; Pandey et al. 2004) leading to the development of regional-scale thrusts, faults and folds (Fig. 2). Such neotectonic activities of the area were also reflected by seismic intensity of MSK VIII or more, as marked by the zone IV and zone V of earthquake hazard zonation map of India (Seeds 2009).

Physiography and geomorphology

The Satluj river is the largest and longest river which drains towards the basin which is of antecedent nature. The flow direction of this river is NE-SW in the basin which seems to be structurally controlled (Thiede et al. 2005). The study area is situated in the Lesser and Higher Himalayas having characteristic undulating topography with high and steep mountains flanks. These mountain flanks strike mostly East-West having complex relief patterns. The Satluj river along with its tributaries is the major drainage system in the region which illustrates a complex erosional pattern in the region. The progressive development of surface landforms of the region from the complex erosional patterns might be the result of the presence of lithologies with different strengths, varying dips of bed or foliation planes and complex shear zones. The Satluj river erodes the basin in form of steep valleys and flows through a narrow gorge at Rampur followed by progressive widening of the river course in the downstream region**.** The active and youthfulness of the topography in the study area are revealed by prevailing steep slope, the occurrence of spurs, narrow and steep V-shaped valleys, and triangular facets and include the recent depositional landforms like channel and conglomerate deposits well exposed along engineered slopes. The region possesses mainly clay, sandy and loam black soil of moderate water retaining capacity, which has very high productivity of vegetable and fruit crops. The vegetation is intermittently occurring all along the valley slopes due to exposure of steep rock slopes together with the recurrent occurrence of small-scale landslides (Singh et al. 2018a). The majority of the land in the basin have vegetated by forest cover followed by pasture land and agriculture land. The basin shows high floral diversity since the regions of lower elevation are characterized by Beul, Drake and Kachnar whereas Kail, Devdar, Ban, Moru, etc. are found at relatively higher elevations.

Methodology

The Advanced Spaceborne Thermal Emission and Reflection (ASTER) 1.5 arc second satellite data with a spatial resolution of 30 m has been utilized to extract the Satluj river basin along with stream network and other morphometric features. The extracted basin has been projected on the regional projection

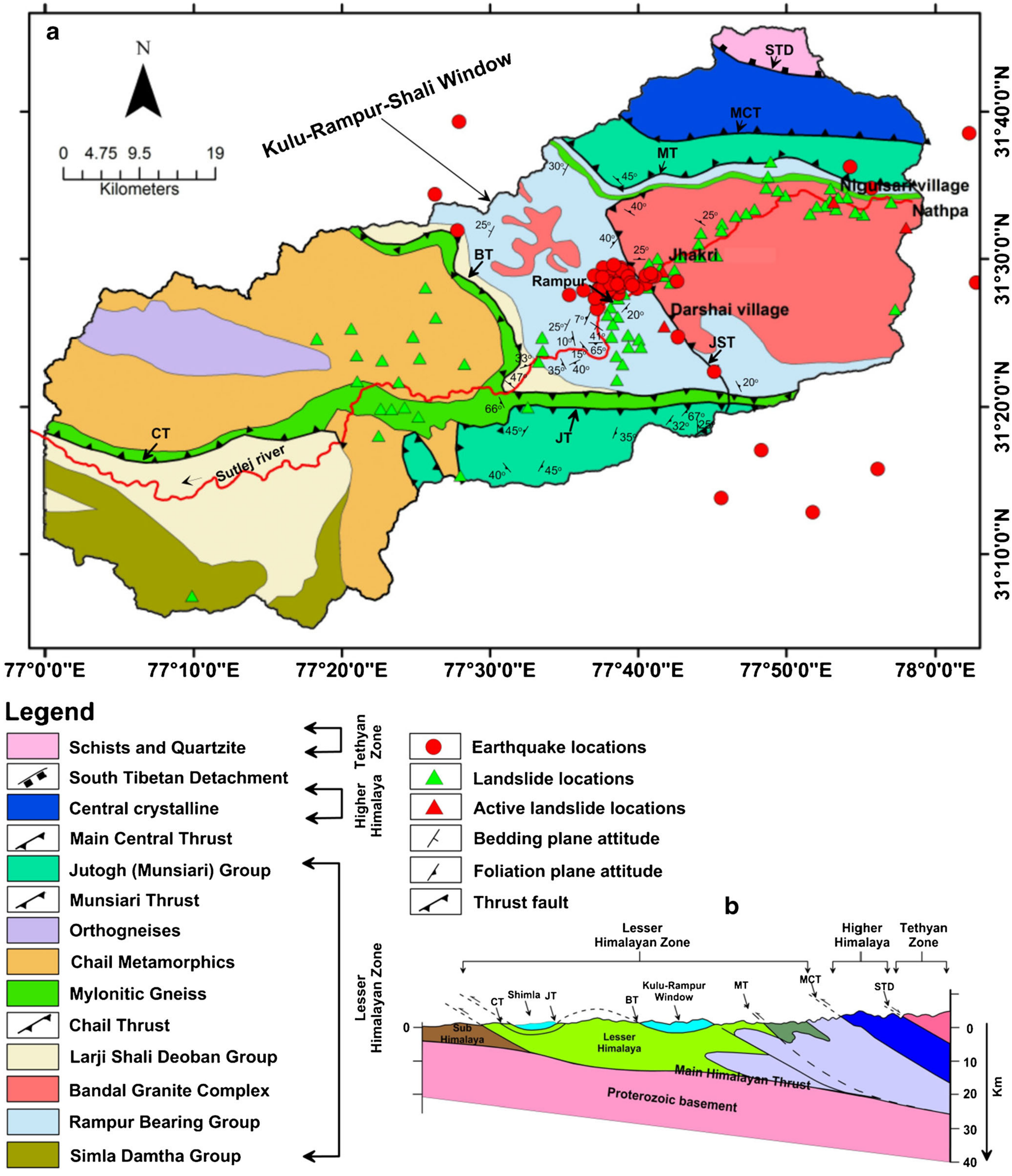


Fig. 2 **a** Geological sketch of the study area in Satluj river basin, Himachal Himalaya, India where STD, South Tibetan Detachment; MCT, Main Central Thrust; MT, Munsiari Thrust; JT, Jutogh Thrust; JST, Jhakri-Sungri Thrust; BT, Banjar Thrust; CT, Chail Thrust (modified after Pandey et al. 2003) (The data of epicentral locations of local earthquakes have been taken from Singh et al. 2018b (Table 3), whereas landslides data have been taken from Kumar et al. 2018; Kahlon et al. 2014 and this study). **b** Schematic representation of structural cross section of the study area (modified after Robert et al. 2011)

WGS 1984 and UTM Zone 43N in GIS environment (ArcGIS 10.2.2). The Arc Hydro tool in GIS environment along with Global Mapper and Surfer has been used to calculate geometric properties of the basin such as area and perimeter of the basin and length and number of streams. Similarly, other morphometrical parameters comprising stream's order, bifurcation ratio, drainage density, form factor, circulatory ratio and elongation ratio have been calculated and analysed from a statistical point of view using formulas given by Horton (1945), Miller (1953), Schumm (1956) and Strahler (1964).

In addition to these, the longitudinal profile of the river along with different morphotectonic indices such as stream length gradient (SL) index, asymmetry factor (AF), hypsometric integral (HI), transverse topographic symmetry (*T*), valley floor height width ratio (Vf), and basin shape (Bs) have been computed and analysed for the study. The Vf and *T* factors have been calculated at every 500-m interval in Global Mapper version 13.2 software. The different morphotectonic indices have been discussed in the next section.

Drainage basin morphometric indices

Stream order This constitutes the preliminary stage in drainage basin analysis. In this study, the stream segments of the basin have been ranked according to the law proposed by Horton (1945). The Horton system of stream ordering is based on the simple assumption that when two streams of same order join the resulting stream segment increases in stream order by 1. If a higher and lower order stream join, then the stream of higher order is maintained (lower flows into higher).

Stream number The stream number (Nu) refers to the sum of stream channels in each order. The Nu denotes the number of streams of a certain stream order (Su). The Nu has been calculated according to the law proposed by Horton (1945). He suggested that the stream number of each order bears an inverse geometric sequence relationship with the stream order (Mukherjee 2011). Besides the logarithmic plot of stream number with stream order bears a linear relation.

Stream length The stream length (Lu) is one of the most significant morphometric parameters which reveal surface runoff behaviour of a basin. The total stream length of different orders (from the mouth to drainage divide) has been analysed using the law proposed by Horton (1945). He suggested that the total stream length is maximum for first-order stream segment and decreases with the increase in stream segment order.

Bifurcation ratio The bifurcation ratio (Rb) is used to express the ratio of stream segments of a given order 'Nu' to that of the next higher order '(Nu + 1)'. It is considered an index for relief and dissertation. The higher bifurcation ratio indicates rugged topography with a tectonic control on the drainage of the area, whereas the lower bifurcation ratio suggests mature topography and less structural disturbances and less distorted drainage pattern (Strahler 1964). Furthermore, the low bifurcation ratio values signify high drainage density and indicate where the geology is reasonably homogeneous.

Drainage density The term 'drainage density' has been proposed by Horton (1945) and defined as the total length of stream segments (Lu) per unit area (*A*) of the basin. The ratio significantly depicts the degree of closeness of stream spacing (Horton 1932). The drainage density is mainly influenced by the climatic conditions, surface roughness and runoff in a basin. The regions with rather permeable subsurface materials and thick vegetation cover are depicted by low drainage density as the runoff is reduced, whereas, a region experiencing high rainfall, less permeable subsurface material and low vegetation experiences high surface runoff and therefore will have more drainage density.

Form factor The 'form factor', initially proposed by Horton (1932), is a ratio of basin area (*A*) to the square of the basin length. The form factor (Rf) is a quantitative expression of drainage basin circumference where a higher value of Rf indicates the circular shape of the basin and the value nearby 1.0 indicates a region of low relief (Strahler 1964).

Circulatory ratio It is a dimensionless expression which defines a ratio of basin area to the area of a circle having the same circumference as that of the basin (Miller 1953). The ratio illustrates the degree of circularity of a basin where the values vary from 0 (linear basin) to 1 (circular basin). The lower values of circulatory ratio show elongated nature and permeable and structural control of the drainage basin. Further, the lower value also signifies high relief and steep slope of the drainage basin.

Elongation ratio The 'elongation ratio' can be defined as the ratio between the diameter of the circle of the same area as possessed by drainage basin and the maximum basin length (*L*) (Schumm 1956). The elongation ratio (Re) values generally vary between 0.6 and 1.0 depending upon geologic and climatic factors. The lower values signify high relief with steep slope topography in the basin (Singh and Singh 1997). Further, the values in proximity to 1.0 depict lower topography with a gentle slope in the basin (Strahler 1964).

Morphotectonic indices

Stream length gradient index The stream length gradient (SL) index was initially proposed by Hack (1973) in order to deduce the interaction between tectonic and climate along with the longitudinal profile of the streams as it varies with the discrepancy in channel slope (Burbank and Anderson 2001). The index has been widely utilized by various researchers (Etchebehere et al. 2004, 2006; Missura 2005; Monteiro 2010; Troiani and Seta 2008). The index can be expressed as Eq. (1).

$$SL = (\Delta H/\Delta L) \times L \tag{1}$$

where

SLStream length index

Δ Change in elevation of the streams

Δ Change in length of the channel

*L*Total length of the channel

The study of abrupt variation in the slope gradient (Δ /Δ) coupled with SL index gives significant information about ongoing tectonic upliftment of the area (Seeber and Gornitz 1983).

Asymmetry factor The asymmetry factor (Af) is used to calculate the regional tilt of a basin in the response of active tectonism. The Af can be expressed by using Eq. (2) after Keller and Pinter (2002).

$$AF = (A_R/A_T) \times 100 \tag{2}$$

where

AFAsymmetry factor

A_RArea of the basin to the right (facing downstream)

A_TThe total area of the drainage basin

The value of AF above or below 50 suggests basin tilting, either in the response of active tectonics or due to lithological/structural control. In the tectonically active region, the activities in faults cause downward displacement of the valley floor and, therefore, production of the steep slope. Such displacement of valley floor results in basin tilting and further causes lateral migration of river from basin midline (Mahmood and Gloaguen 2012). In order to determine tectonic tilt in the northern or southern slope of the basin and avoid the possible intermingling of the result, the AF was further enhanced to the previous after Perez-Pena et al. (2010) as Eq. (3).

$$AF = \left| 50 - \frac{(A_R \times 100)}{A_T} \right| \tag{3}$$

Hypsometric integral The hypsometric integral (HI) illustrates the distribution of relief in an area and is very advantageous in deciphering the role of tectonic and lithological factors influencing the geomorphic development of basin at different stages (Strahler 1957; Gardner et al. 1990; Moglen and Bras 1995). The integral represents the volume of a basin which is not been affected by erosion. The integral is independent of basin area and can also be expressed as the area lying below the hypsometric curve. Therefore, the HI can be expressed by using Eq. (4) (Pike and Wilson 1971; Mayer 1990).

$$HI = \int_{\text{minele}}^{\text{Max ele}} \left(\frac{a}{A}\right) \times \left(\frac{\Delta h}{H}\right) \tag{4}$$

where

HIHypsometric integral

*H*Highest elevation of the watershed

*A*Total area of the watershed

*a*The area of the watershed above a given elevation h

a/*A*Relative area

h/*H*Relative height

The region experiencing higher and recent neotectonic activities exhibits higher values of HI. Low values of HI depict least neotectonic activities in the region and also suggest that the region exhibits comparatively older landscapes that have experienced higher erosional activities (El-Hamdouni et al. 2008). The HI is supported by a hypsometric curve which depicts a plot between the relative height (h/H) against the relative area (a/A). The shape of the curve is very informative as the convex-upward curve indicates relatively young watershed, concave-upward curve depicts relatively old watersheds, and the S-shaped curve demonstrates moderately eroded watersheds (Strahler 1957; Delcaillau et al. 1998; Keller and Pinter 2002).

Transverse topographic symmetry The transverse topographic symmetry evaluates the tectonic tilt of basin. The transverse topographic symmetry (*T*) can be expressed by using Eq. (5).

$$T = Da/Dd \tag{5}$$

where

*T*Transverse topographic symmetry

D_aDistance from the midline of the drainage basin to the midline of the active meander belt.

D_dDistance from the basin midline to basin divide.

The value of '*T*' generally varies in between 0 and 1 where '*T*' = 0 characterizes perfectly symmetrical basin and '*T*' = 1 signifies a perfectly asymmetrical basin (Hare and Gardner 1985).

Valley floor height and width ratio The valley floor height and width ratio (Vf) is defined as the ratio of the width of valley's floor to its average altitude (Bull and McFadden 1977; Bull 1978) and estimated by Eq. (6).

$$Vf = 2V_{fw}/(E_{ld} - E_{sc}) + (E_{rd} - E_{sc}) \tag{6}$$

where

VfThe valley floor width to altitude ratio

V_{fw}The width of the valley floor

E_{ld}, E_{rd}The elevations of the left and right valley divides, respectively

E_{sc}The elevation of the valley floor

The value of Vf depends upon the basin size, stream discharge and lithological attributes of the basin. The valley incision is generally related to basin upliftment and tectonic activities. The lower values of Vf (< 1) indicate V-shaped valley with higher rates of uplift and incision, whereas the higher values (> 1) reveal a wide U-shaped valley with lower rates of the incision. It is determined at a prescribed distance towards upstream from the mountain front (Silva et al. 2003).

Basin shape The younger drainage basins tend to be elongated in shape normal to the topographic slope in tectonically active areas and tend to be more circular in shape within tectonically stable regions (Bull and McFadden 1977). The basin shape index is expressed by using the relationship after Cannon (1976), and Ramirez-Herrera (1998) as Eq. (7).

$$Bs = Bl/Bw \qquad (7)$$

where

BlThe length of the basin measured from the headwaters to the mouth

BwThe width of the basin measured at its widest point

The higher values of Bs (> 1) are commonly associated with elongated basins with relatively higher tectonic activity while low values of Bs (< 1) indicate a more circular-shaped basin with low or no tectonic activity.

Field validation

In addition to the analysis, field investigations have been carried out at several locations to validate the geomorphic developments related to active tectonics in the Satluj river basin in and around Rampur, Himachal Himalaya, India. Various stream channel responses to neotectonic such as channel straightening, sudden deflection of channels, sharp bending and channel divides have been investigated in the basin. The stream flowing along active lineament exhibits channel straightening and across active faults depicts sharp truncation. Besides these, other geomorphic features like knick points and triangular facets have been identified at outcrop level. The triangular facets and knick points are very important neotectonic markers as they represent recent activity in the basin and formed by the activity of faults which traverse across the river channel. The tectonic triangular facets are mainly formed due to predominant tectonic and erosional processes and base-level fall. They are very common in the region of active extension and erosion of fault-bounded mountain ranges (Guido 2013). Similarly, knick points are formed by tectonic upliftment in the basin or due to the base-level fall.

Results and discussion

In the present work, the Satluj river basin in and around Rampur exhibits highly variable topographic elevation ranging from 600 to 5656 m above the mean sea level (Fig. 3). The regions of higher elevation are mainly confined in the upstream side of the basin (NE part of the basin). The perimeter of the Satluj basin under consideration is found as 348.76 km and the total area as 3661.3 km^2. The drainage map suggests that the basin is of 5th order. Further, the basin is predominated by trellis, rectangular and sub-dendritic (in lower reaches) drainage patterns that indicate structural control in the basin (Fig. 4). The drainage map has been further analysed for different geomorphic indices which have been discussed below.

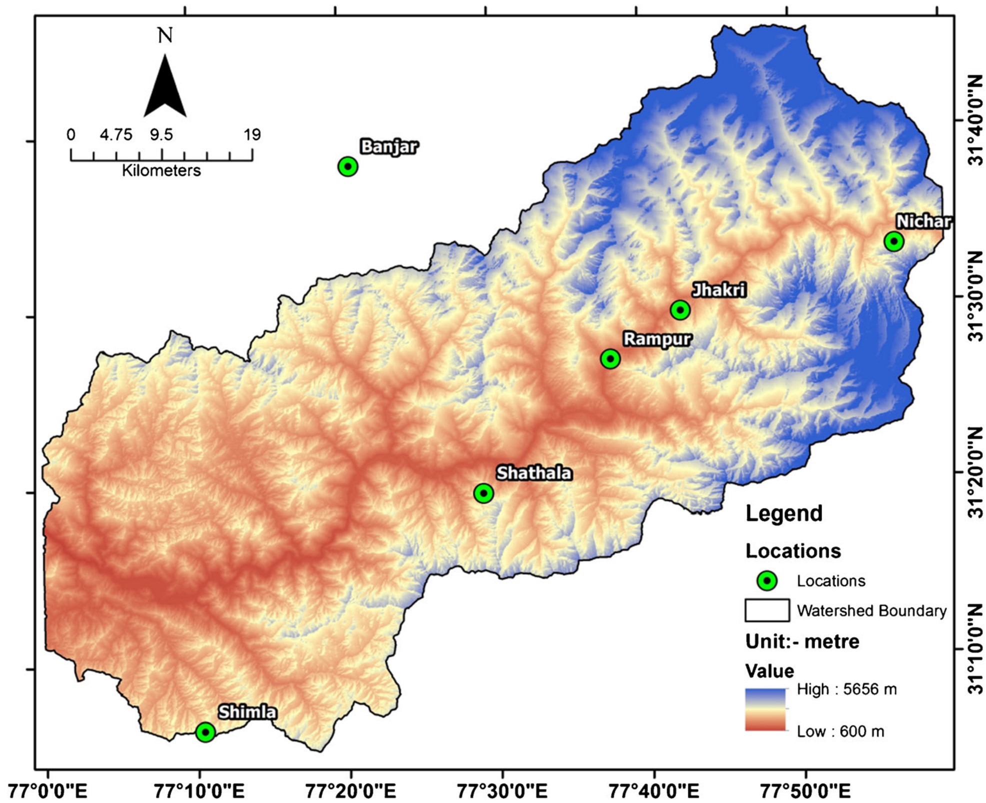
Morphometric characteristics

The higher stream order (5th order) suggests greater discharge and higher velocity of the stream which further points to enhanced erosional rates (Costa 1987). In the present study, the first-order stream exhibits the maximum frequency which suggests that the basin is prone to sudden downstream flash flood after heavy rain (Chitra et al. 2011). Further, the occurrence of numerous streams in the basin significantly depicts the ongoing erosional activities and immature topography. The plot between the stream number and stream order suggests that the stream number decreases in geometric progression with an increase in stream order (Strahler 1964) (Fig. 5a). The bifurcation ratio of the basin ranges from 3 (between 4th and 5th orders) to 6.3 (between 3rd and 4th orders). The observation suggests that the geological structures have control over the drainage pattern development (Jagannathan et al. 1996). The highest value of the bifurcation ratio suggests that the 3rd- and 4th-order streams have developed over a steep slope. The mean bifurcation ratio of the Satluj basin has been calculated as 4.49. The result of mean bifurcation ratio indicates a predominance of structural heterogeneity encompassing fold, faults and tectonic joints (Pankaj and Kumar 2009). The analysed value of weighted mean bifurcation ratio has been observed as 4.44 which is almost close to mean bifurcation ratio of the basin (Table 1). The value of the weighted mean bifurcation ratio indicates the neotectonic activity in the study area.

The observations of the calculated stream length of the basin suggest that the total length of the stream is maximum in the first order and decreases as the stream order increases (Table 2). The plot of stream length versus stream order depicts an almost linear pattern which indicates the presence of lithologies of relatively homogeneous erodibility in the basin (Fig. 5b). The total stream length of the basin has been found as 1480.99. The values of mean stream length depict remarkable variation from the expected trend as proposed by Horton (1945) (Table 2). These variations may be attributed to change in slope and topography within the basin.

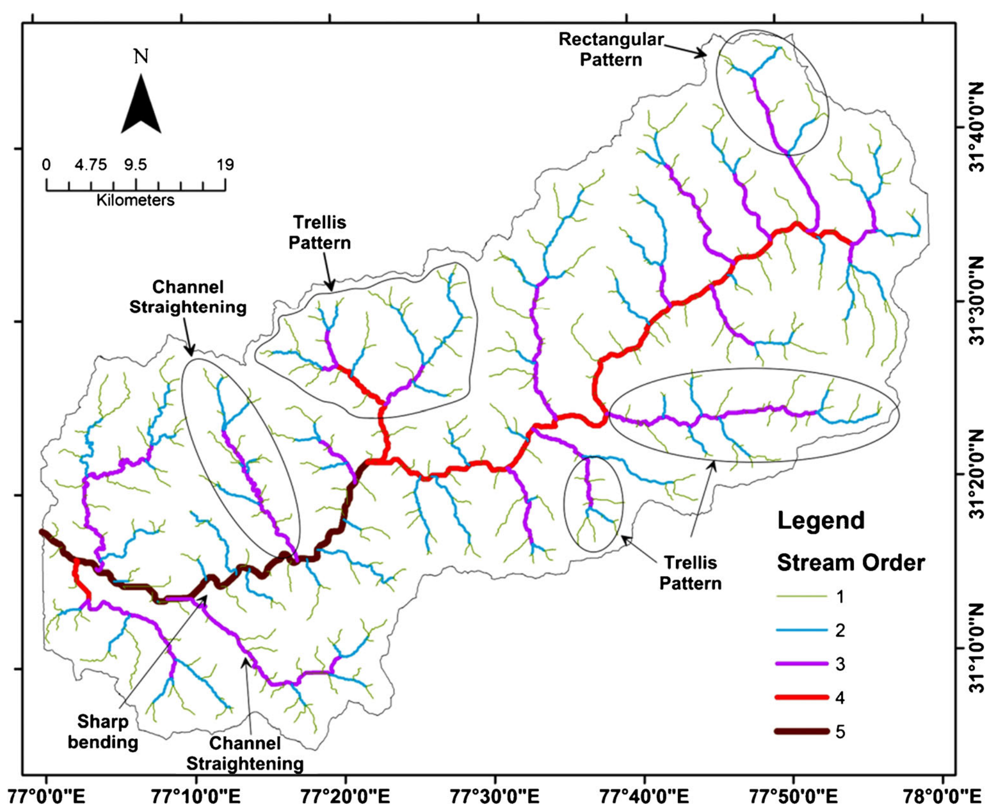
The drainage density (Dd) of the basin catchment has been found to range from 0 to 3.1 km/km^2 (average 0.40 km/km^2) suggesting overall low drainage density. The low drainage density can be a result of permeable subsoil and/or probably

Fig. 3 The ASTER DEM of the studied region of the Satluj river basin, Himachal Himalaya, India



with thick vegetative cover (Nag 1998). The permeability of subsurface soil depends upon the interconnected pores which are majorly controlled by grain size distribution, grain shape, void ratio, degree of saturation and vertical over-burden.

Fig. 4 The Strahler stream order drainage map of the studied area of the Satluj river basin, Himachal Himalaya, India



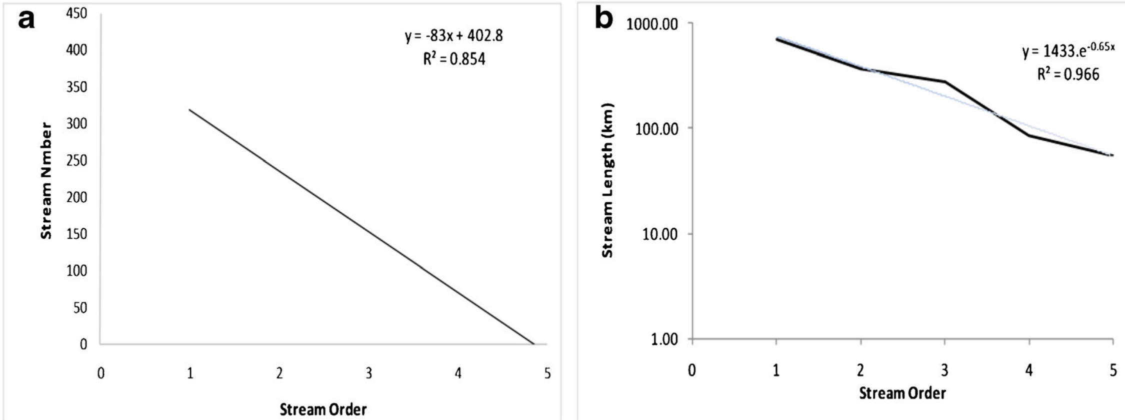


Fig. 5 **a** The plot between stream order and stream number. **b** Stream order and stream length of Satluj river basin, Himachal Himalaya, India

Further, the drainage density map indicates a relatively higher value along the river alignment indicating 'flashy' hydrograph with a steep falling limb (Fig. 6) vulnerable to landslide activities (Mandal and Mandal 2016).

The geometric shape parameter which includes form factor (0.31), circulatory ratio (0.38) and elongation ratio (0.645) of the basin points to elongated nature of the basin with high relief, steep slopes, permeable subsoil and structural control of the drainage basin. Moreover, the studied shape parameter suggests that high peak flow will continue for a longer duration of time and which makes the basin prone to the erosional hazard (Das and Gupta 2019; Kadam et al. 2019). It may also indicate to the rocky/impermeable strata as impermeable rocks will show less water retention leading to high peak flow. However, considering the permeability of subsoil, water retention by subsoil is an important parameter together with slope steepness and rocky strata with fewer joints that will also lead to high peak flow probably for longer duration in an elongated basin.

The slope is one of the significant geomorphic features that signify inclination of a basin with respect to the horizontal surface. The slope map prepared by using DEM in the ArcGIS environment indicates variation in slope ranging from 0 to 76.88° is an outcome of morpho-climatic processes, heterogeneous lithology and variable resistance rate (Fig. 7). The higher slope variation characterizes steep scarp with rapid runoff that facilitates high erosion vulnerability.

Morphotectonic characteristics

The calculated SL index of the Satluj basin exhibits remarkable variation with change in elevation along with the longitudinal profile of the river. The Satluj river around Rampur exhibits relatively higher SL value for the 4th-order drainage in comparison with the fifth-order drainage of the trunk river along the road alignment. Further, the SL curve also exhibits more fluctuation and intersection with the river longitudinal profile of the fourth-order drainage than fifth-order along the Satluj river in the region (Fig. 8a, b). The observations support the active tectonics which is more pronounced in the areas where 4th-order drainage of the trunk river passes (Ramírez-Herrera and Gaidzik 2017). The numerous minor fluctuations in the SL profile may be related to the presence of knick points resulting from basin upliftment in the region (Fig. 8a, b). The intersection of SL curve with the river elevation profile hints at structural abnormalities. The significantly higher

Table 1 Calculated stream order, streams number and bifurcation ratios of the studied area

Order	Stream number (Nu)	Bifurcation ratio (Rb)	Number of stream involved (Nu-r)	Rb × Nu-r	Rbwm
1	353	-	-	-	-
2	80	4.41	433	1910.61	
3	19	4.21	99	416.84	4.44
4	3	6.33	22	139.33	
5	1	3	4	12	
Total	456	18	558	2479	
Mean		4.49			

Su stream order, *Nu* number of streams, *Rb* bifurcation ratios, *Nu-r* number of streams used in the ratio, *Rbwm* weighted mean bifurcation ratio

Table 2 Calculated stream length and stream length ratio of studied basin

Order	Lu	Lu/Su	Lur	Lur-r	Lur-r × Lur	Luwm
1	698.63	1.98	-	-	-	-
2	364.45	4.56	2.30	1063.08	2447.06	
3	277.24	14.59	3.20	641.69	2055.34	
4	86.02	28.67	1.97	363.27	713.87	2.48
5	54.63	54.63	1.91	140.66	268.00	
Total	1480.98	104.44	9.38	2208.70	5484.28	
Mean			2.34			

Su stream order, *Lu* stream length, *Lur* stream length ratio, *Lur-r* stream length used in the ratio, *Luwm* weighted mean stream length ratio

concentration of SL values in the upper and middle reaches of the basin along with many sharp bending of the trunk stream may be a consequence of fault networks which has caused some upliftment in the topography due to tectonic activities (Fig. 9). The lineament density map of the basin also suggests the role of structural control in the drainage development and supports the above observation (Fig. 10).

The measured value of HI in the Satluj river basin has been found as 0.33. The result of HI suggests that basin is predominated by fluvial erosional processes where channel processes are playing a key role. The hypsometric curve depicts a plot of proportion height (*h*/*H*) against the proportion area (*a*/*A*) (Fig. 11). The S-shaped curve is indicating moderately eroded watersheds (Strahler 1957; Delcaillau et al. 1998; Keller and Pinter 2002; Said et al. 2018).

The calculated values of the asymmetry factor (i.e. 56) suggest the asymmetric nature of the Satluj river basin. The absolute value of AF* has been found as 6.06 which depicts tilting of the basin from right to left due to active tectonics or lithological control. However, the values of AF and AF* for the 4th-order sub-basins in the study area also indicate asymmetric nature of the basin which is more intense in the downstream portion of the basin (Fig. 12). The observed value of '*T*' factor which varies from 0.1 to 0.75 (average = 0.37) supports the moderate tilting indicated by the asymmetry factor.

The analysed range of Vf has been observed to lie from 0.047 to 2.1 with an average of 0.18. The lower values of Vf (< 1) specify higher rates of uplift and incision as well as the V-shaped valley in the basin (Fig. 13) (Silva et al. 2003). The analysed value of basin shape for Satluj basin has been calculated as 2.87 which suggests the elongated nature of the Satluj basin under the influence of active tectonics. The index also indicates relatively younger drainage basin elongated parallel to the topographic slope of the mountain (Bull and McFadden 1977).

Relation of morphometric features with landslides

The occurrence of a varied range of landslides is susceptible in the Satluj basin due to its young geological and

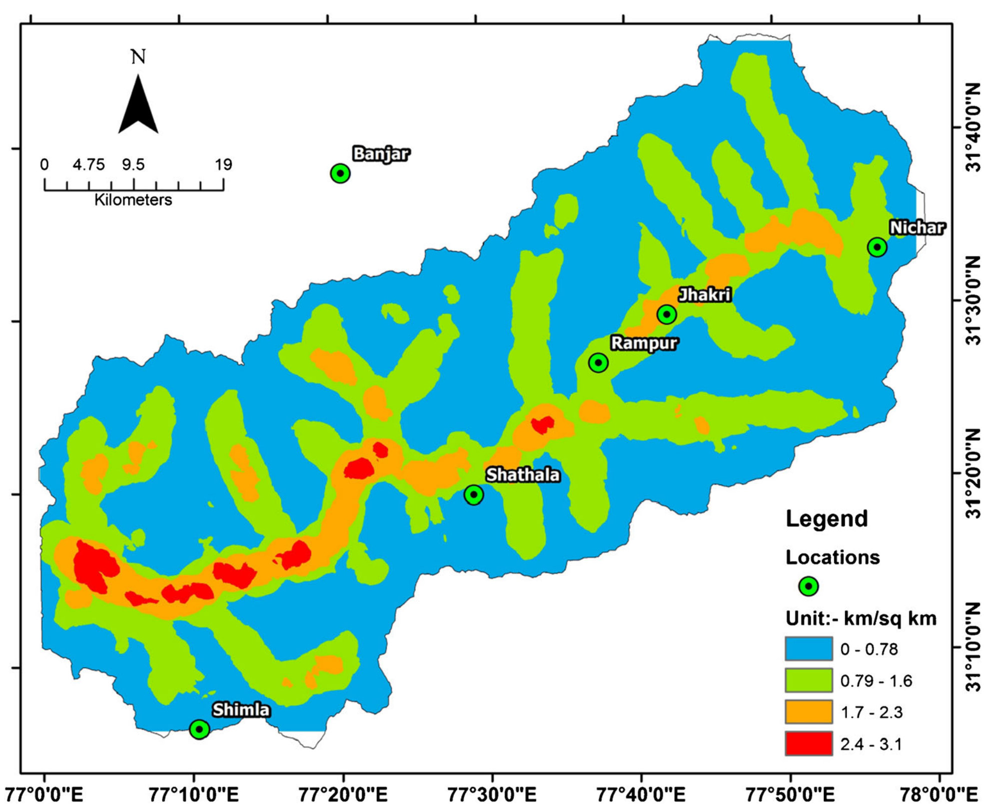


Fig. 6. Drainage density map of the Satluj river basin, Himachal Himalaya, India

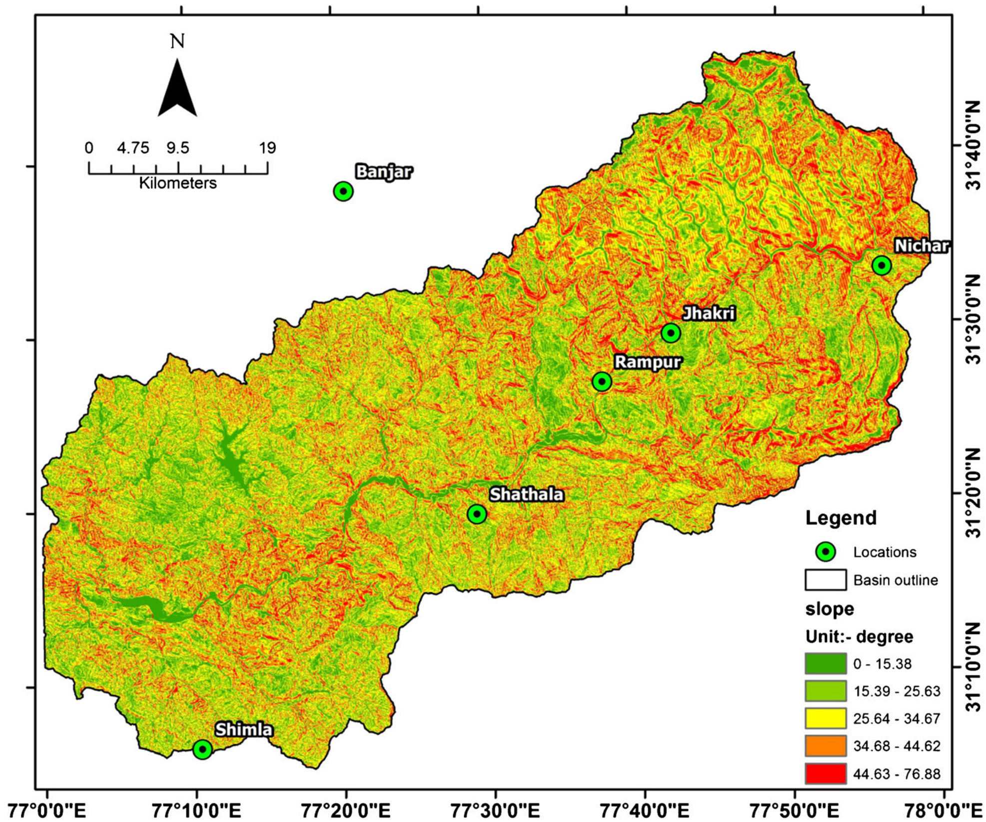


Fig. 7 Slope distribution map of the Satluj river basin, Himachal Himalaya, India

geomorphological characteristics incorporated with active tectonics, climate and anthropogenic actions (Bartarya et al. 1996; Kumar et al. 2018; Singh et al., 2018a; Jamwal et al. 2019). In addition, widespread ongoing development activities related to infrastructure and hydroelectric projects have always stimulated landslides in the Satluj basin (Kuniyal et al. 2019). Several authors have studied and reported the structurally controlled landslides in this area (Sarkar et al. 2016; Mahanta et al. 2016; Kundu et al. 2017; Singh 2018; Acharya et al. 2020). The river erosion–induced landslides are also common and previously reported in the basin (Gupta and Sah 2008a; Gupta and Sah 2008b) and observed in this study

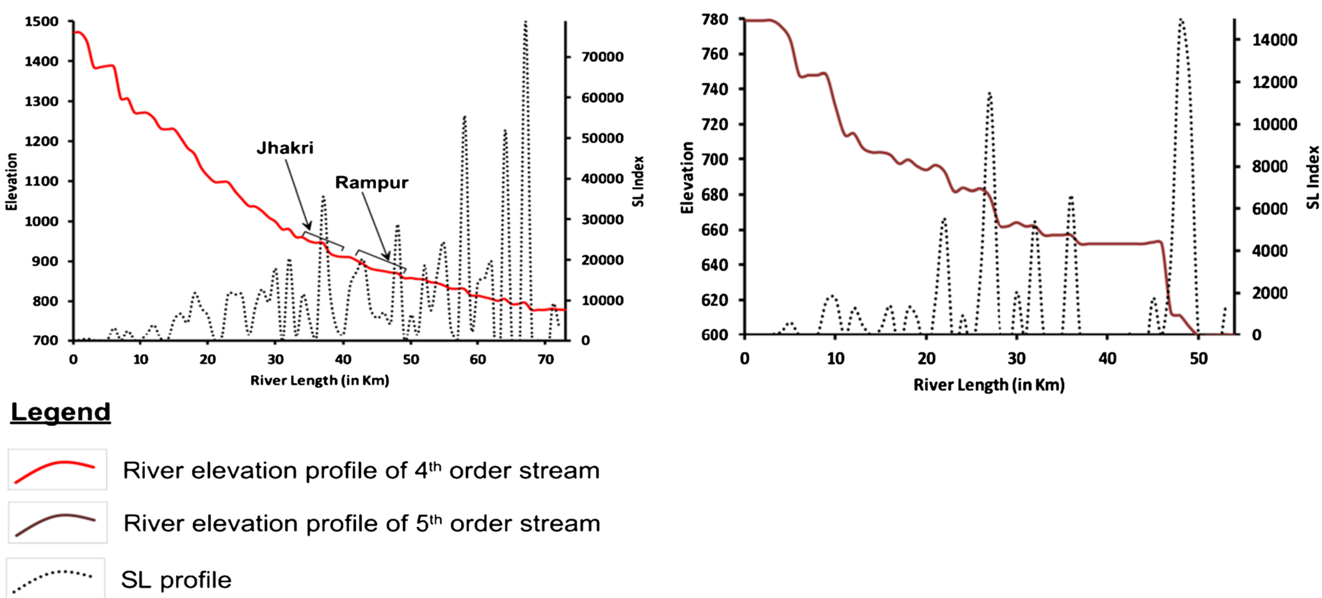


Fig. 8 The SL curve (dotted line) for **a** the 4th-order portion of the main river channel versus **b** the 5th-order portion of the Satluj river basin, Himachal Himalaya, India (longitudinal river profile represented by the solid line)

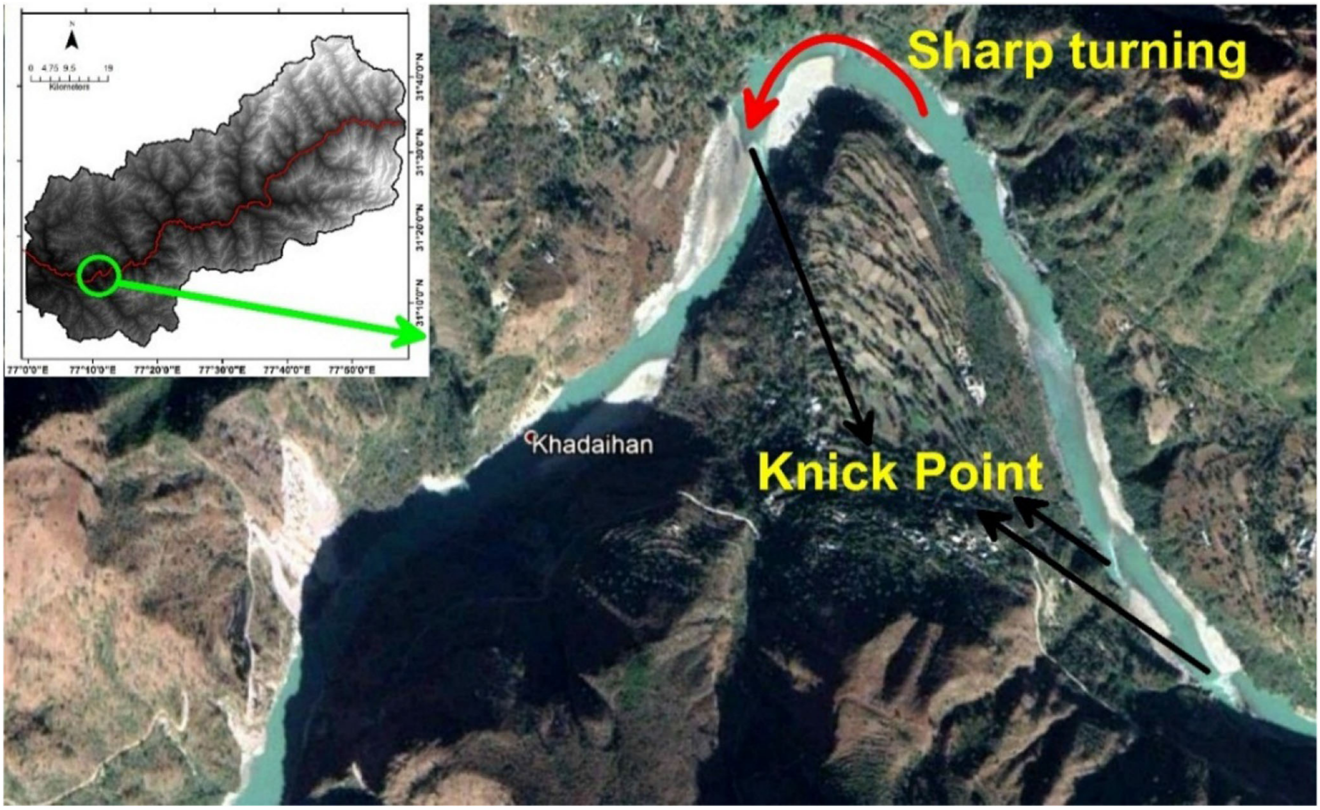
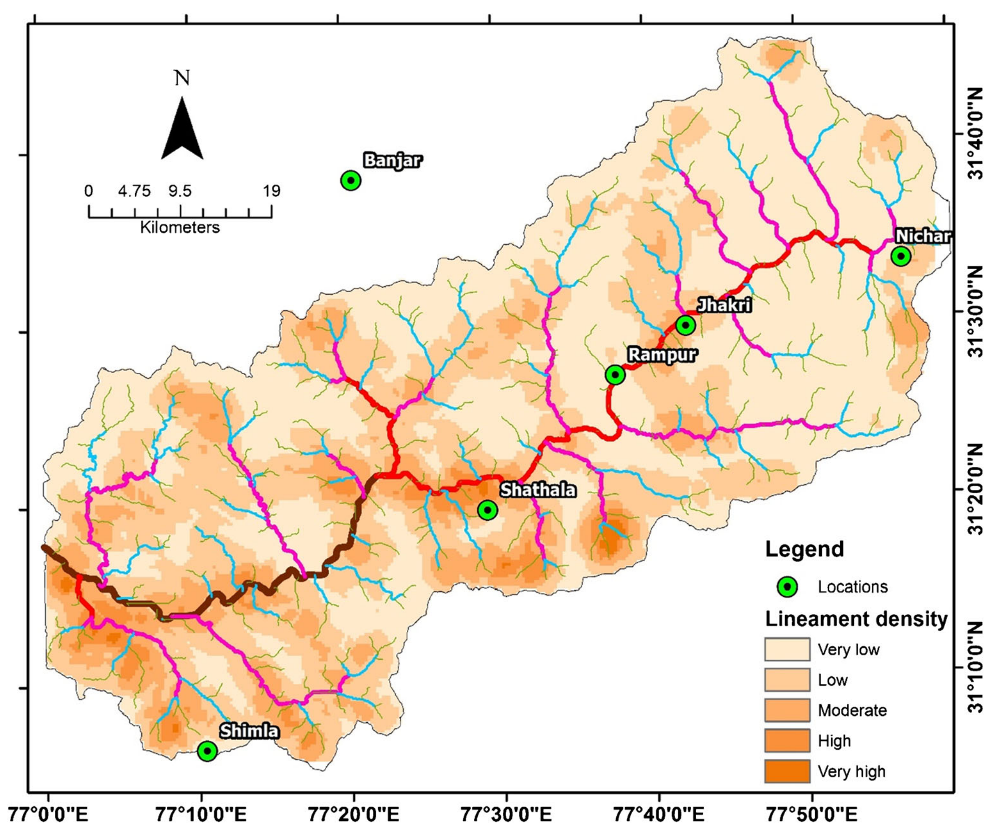


Fig. 9 The Satluj river showing a sharp bend and knick points near Khadaihan area of Satluj basin, Himachal Himalaya, India

Fig. 10 Lineament density map of the Satluj river basin, Himachal Himalaya, India



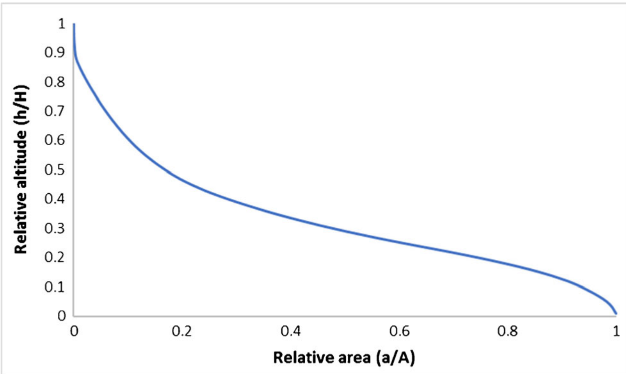


Fig. 11 The HI curve of the Satluj river basin, Himachal Himalaya, India

as well (Fig. 14). Apart from the influence of inherent physico-mechanical factors and valley-slope geometry (Ambrosi and Crosta 2011), landslide distribution is significantly controlled by the basin morphometric features (Rybchenko et al. 2018; Bayer Altın and Gökkaya 2018). Hence, in this section, the influence of geomorphic features on landslide activities is examined.

The field investigations along with the analysed geomorphic and morphotectonic parameters give insight into the landslide susceptibility in the basin. Sparse vegetation covers along with immature topography, high relief and steep slopes have further enhanced the complication. High frequency of first- and second-order streams can also be associated with landslide susceptibility in a basin (Bayer Altin and Gökkaya 2018) which observed to be a significant morphometric factor in the study basin. The bifurcation ratio depicts the strong control of geological structures over the drainage pattern that consequently yields control over the occurrence of landslides in the study basin. The stream order (5th order) of the Satluj drainage basin around Rampur suggests a greater rate of erosion in the low-lying area of the basin. The greater discharge with higher stream velocity enhanced the bank erosion (Costa 1987) as well as toe erosion of the valley slopes which is found a significant association with the landslides in the study area (Fig. 14). These landslides further develop coupled with triggering factors like rainfall and anthropogenic activities. The areas having 4th- and 5th-order streams depict the higher concentration of landslides within the studied basin (Fig. 2)

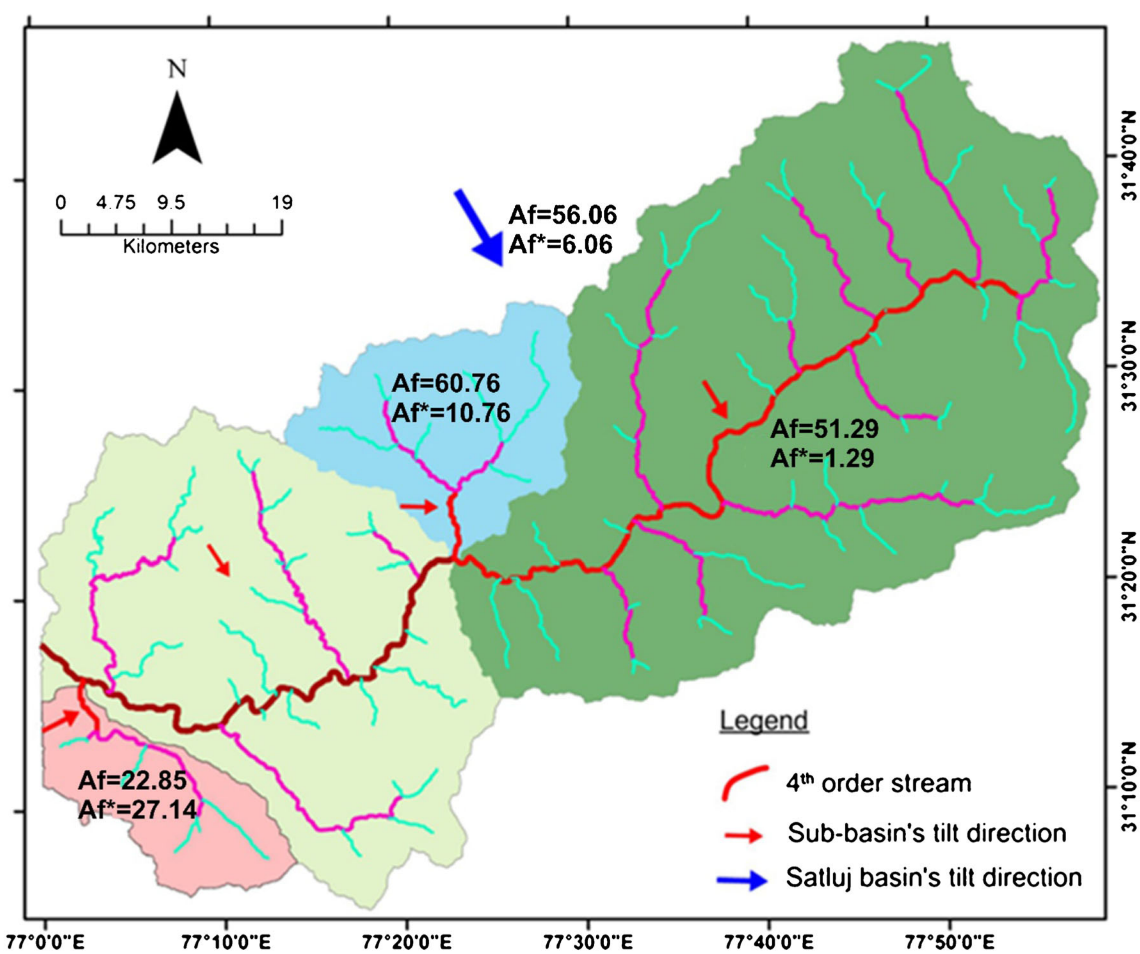


Fig. 12 Illustration showing the spatial distribution of different AF values and tilting of the Satluj river basin, Himachal Himalaya, India (arrow indicates tilting of the basin)

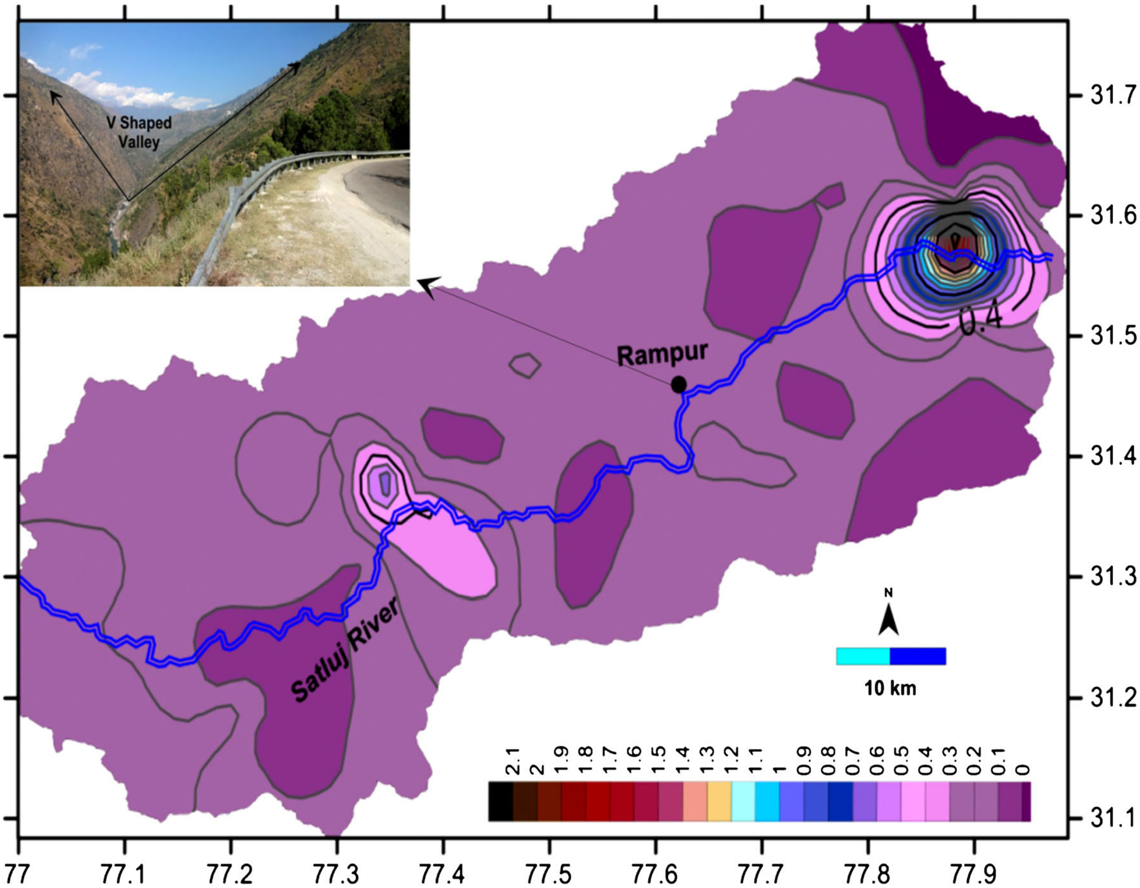


Fig. 13 Spatial distribution of Vf values in the Satluj river basin and V-shaped valley present near Rampur in the Satluj river basin, Himachal Himalaya, India

that indicates that the areas of lower order streams possess relatively competent lithologies. The mean stream length suggests undulating topography that signifies the occurrence of small-scale landslides in the basin (Fig. 15a–d) that would have been attributed by the permeable nature of cover soil as observed from low drainage density (Nag 1998).

The Himalayas is well known for its regional active thrust systems with numerous local active thrusts named after their locality. One such active thrust is also reported in the study area called Jhakri thrust (Pandey et al. 2004). The collected earthquakes swarm's data suggest multiple events at active Jhakri thrust (Table 3) that signify the ongoing neotectonic activities around Rampur region which are also confirmed by the SL profile. Moreover, earthquakes with a magnitude of 4.0 and above are considered a trigger source of landslide activity in a basin (Tatard et al. 2010). Therefore, it is very obvious that these small swarms can be associated with landslide

Fig. 14 River erosion and active landslide near Nigulsari, Satluj river basin, Himachal Himalaya, India

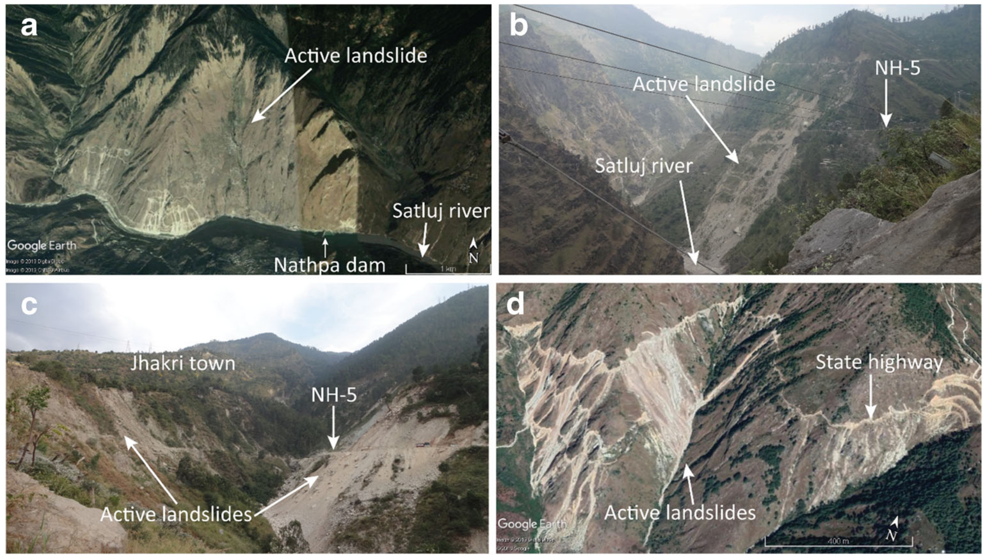


Fig. 15 Google imageries (**a**, **d**) and field photographs (**b**, **c**) of some active landslides in the studied basin **a** near Nathpa dam (location: N 31.5358°, E 77.9671°) and **b** near Nigulsari village (location: N 31.5643°, E 77.8863°) and recurring landslides **c** near active Jakhri thrust (location: N 31.4858°, E 77.6940°) and **d** near Darshai village, Rampur (location: N 31.4238°, E 77.6959°)

activities (Ghosh 2015; Singh et al. 2015a). Further, the ongoing interaction between basin uplift associated with active tectonics (ongoing collision between the Indian and Eurasian plates) and powerful stream erosion due to active downward incision of the river are significant factors that control landslides in the studied basin.

Table 3 List of earthquake events occurred in and around Rampur area

Date	Latitude (N)	Longitude (E)	Focal depth (km)	Magnitude	Data source
19/02/1977	31.581	78.22	33	4.7	USGS_Earthquake_ Catalogue
10/08/1981	31.263	77.935	33	4.6	USGS_Earthquake_ Catalogue
15/12/1984	31.284	77.805	33	4.7	USGS_Earthquake_ Catalogue
13/12/1990	31.573	77.438	33	4.7	USGS_Earthquake_ Catalogue
20/01/1991	31.532	77.463	33	4.9	USGS_Earthquake_ Catalogue
21/07/1992	31.473	78.046	33	3.9	USGS_Earthquake_ Catalogue
05/09/1995	31.214	77.863	45.7	4.2	USGS_Earthquake_ Catalogue
04/09/2002	31.23	77.76	33	4.1	USGS_Earthquake_ Catalogue
15/12/2003	31.527	78.151	33	4.4	USGS_Earthquake_ Catalogue
15/12/2003	31.622	78.203	33	4.5	USGS_Earthquake_ Catalogue
20/07/2006	31.58	77.928	10	3.5	USGS_Earthquake_ Catalogue
20/07/2006	31.604	77.905	35	3.5	USGS_Earthquake_ Catalogue
20/07/2006	31.642	78.038	35	4	USGS_Earthquake_ Catalogue
21/02/2007	31.373	77.752	36.6	4.1	USGS_Earthquake_ Catalogue
03/06/2007	31.412	77.711	30	3.6	USGS_Earthquake_ Catalogue
21/10/2008	31.655	77.465	17.1	4.5	USGS_Earthquake_ Catalogue
27/08/2016	31.473	77.673	5.6	2.6	USGS_Earthquake_ Catalogue
27/08/2016	31.481	77.654	7.4	2.1	USGS_Earthquake_ Catalogue
27/08/2016	31.49	77.647	7.3	2.1	Singh et al. 2018b
27/08/2016	31.485	77.655	8.23	1.7	Singh et al. 2018b
27/08/2016	31.475	77.649	7.42	2.3	Singh et al. 2018b
27/08/2016	31.488	77.636	7.8	4.4	Singh et al. 2018b

Table 3 (continued)

Date	Latitude (N)	Longitude (E)	Focal depth (km)	Magnitude	Data source
27/08/2016	31.471	77.675	5.44	3.1	Singh et al. 2018b
27/08/2016	31.455	77.624	9.15	3.1	Singh et al. 2018b
27/08/2016	31.471	77.644	8.27	2.7	Singh et al. 2018b
27/08/2016	31.48	77.685	7 2	0.8	Singh et al. 2018b
27/08/2016	31.49	77.627	9 3	0.5	Singh et al. 2018b
27/08/2016	31.478	77.649	8.5	2.7	Singh et al. 2018b
27/08/2016	31.48	77.681	7.9	2	Singh et al. 2018b
27/08/2016	31.476	77.643	7.2	9 2	Singh et al. 2018b
27/08/2016	31.469	77.625	7.6	4.1	Singh et al. 2018b
27/08/2016	31.464	77.605	10.25	2.6	Singh et al. 2018b
27/08/2016	31.469	77.646	8.17	2.1	Singh et al. 2018b
27/08/2016	31.478	77.632	9.7	2.1	Singh et al. 2018b
27/08/2016	31.468	77.635	9.7	2	Singh et al. 2018b
27/08/2016	31.48	77.635	8.58	2.6	Singh et al. 2018b
27/08/2016	31.475	77.65	8.35	1.8	Singh et al. 2018b
27/08/2016	31.481	77.675	5.36	2.1	Singh et al. 2018b
27/08/2016	31.476	77.627	8.76	1.8	Singh et al. 2018b
27/08/2016	31.473	77.655	7.5	2.2	Singh et al. 2018b
27/08/2016	31.473	77.633	8.3	6 3	Singh et al. 2018b
27/08/2016	31.478	77.647	7.87	2.3	Singh et al. 2018b
27/08/2016	31.463	77.64	8.96	2.2	Singh et al. 2018b
27/08/2016	31.463	77.641	7.42	2.3	Singh et al. 2018b
27/08/2016	31.463	77.639	11.8	1.9	Singh et al. 2018b
27/08/2016	31.443	77.62	10.6	1.9	Singh et al. 2018b
27/08/2016	31.481	77.617	7.5	4	Singh et al. 2018b
27/08/2016	31.478	77.655	6.4	2.9	Singh et al. 2018b
27/08/2016	31.46	77.644	9.4	2.3	Singh et al. 2018b
27/08/2016	31.476	77.655	7.75	1.9	Singh et al. 2018b
27/08/2016	31.467	77.631	8.76	2.1	Singh et al. 2018b
27/08/2016	31.487	77.648	7.7	2.3	Singh et al. 2018b
27/08/2016	31.468	77.646	7.7	1.8	Singh et al. 2018b
27/08/2016	31.474	77.633	8.3	2.4	Singh et al. 2018b
27/08/2016	31.462	77.632	9.3	2.1	Singh et al. 2018b
27/08/2016	31.459	77.589	9.7	2 2	Singh et al. 2018b
27/08/2016	31.466	77.622	9.75	2.2	Singh et al. 2018b
27/08/2016	31.473	77.654	8.27	1.8	Singh et al. 2018b
27/08/2016	31.464	77.631	6.3	9 2	Singh et al. 2018b
27/08/2016	31.473	77.651	7.13	2.3	Singh et al. 2018b
27/08/2016	31.48	77.655	6.91	1.9	Singh et al. 2018b
27/08/2016	31.471	77.636	8.9	3.5	Singh et al. 2018b
27/08/2016	31.466	77.623	7.1	3.7	Singh et al. 2018b
27/08/2016	31.469	77.639	7.3	1.9	Singh et al. 2018b
27/08/2016	31.466	77.665	7.2	1.8	Singh et al. 2018b
27/08/2016	31.464	77.633	10	1.6	Singh et al. 2018b
27/08/2016	31.468	77.627	12.4	1.7	Singh et al. 2018b
27/08/2016	31.493	77.639	7.4	2.2	Singh et al. 2018b
27/08/2016	31.473	77.658	8.3	1.7	Singh et al. 2018b
27/08/2016	31.471	77.635	6.4	2.5	Singh et al. 2018b
27/08/2016	31.479	77.626	7.5	2	Singh et al. 2018b
27/08/2016	31.471	77.643	7.3	1.9	Singh et al. 2018b
27/08/2016	31.455	77.618	7.87	1.5	Singh et al. 2018b
27/08/2016	31.47	77.66	7.9	1.7	Singh et al. 2018b
27/08/2016	31.4834	77.6806	10	4.5	Singh et al. 2018b
27/08/2016	31.4746	77.7102	10	4.6	Singh et al. 2018b
27/10/2017	31.951	77.434	31	4.1	USGS_Earthquake_ Catalogue

The fluvial/channel processes also control landslides and associated erosional activities, which is evident by the measured HI value for the studied basin. At various places in the Satluj basin, the peculiar characteristic of drainage development, viz., channel straitening, channel offset and sudden bending of channels, has been observed which suggests their development along lineaments as well as active nature of the basin. Numerous active fault–related features, viz.

Fig. 16 River Satluj exhibiting knick points **a** near Rampur city and **b** near Jhakri, Himachal Pradesh

triangular facets and knick points, have been observed in the region (Figs. 16 and 17).

Conclusions

The morphometric and morphotectonic analysis was carried out for the Satluj river basin in the vicinity of Rampur area which is of 5th-order drainage. The basin possesses mainly trellis, rectangular and sub-dendritic drainage patterns which indicate heterogeneity of texture and structural control. The geological structures (lineaments, active faults) have a significant influence on drainage pattern development in this region. The basin has a compact nature of the bedrock lithology in the upper reaches whereas in the lower reaches bank erosion and toe erosion predominate; therefore, the basin is prone to erosional hazard. The basin has elongated nature with high relief and steep slope having permeable subsoil. The analysed SL index suggests relatively more neotectonic activity in the upper part of the Satluj river basin. The region of higher SL values may be a result of reactivation of faults in the vicinity. The HI index and HI curve indicate moderately eroded watershed predominated by fluvial erosional processes. The HI index along with Vf suggests thick accumulations of alluvium and colluvium in the lower reaches of the catchments. The basin is of asymmetric/tilted in nature and also possesses deep V-shaped valley as a result of ongoing upliftment and incision under the influence of neotectonism. The data of the earthquake swarm in the region illustrates its concentration along the major faults in the region which suggests its active nature.

These neotectonic activities may be responsible for the reactivation of major faults in the region which results in the occurrence of moderate to the large earthquake and consequently initiation as well as reactivation of landslides in the region. Further, the majority of the landslides appear to be concentrated along the region of higher stream order that signifies the lithological control on landslides under fluvial processes. The morphometric and morphotectonic parameters used in the present study provide conclusive outcomes for the detection of high-risk zones and they appear to correlated well with landslides activities occurred in recent past.

Fig. 17 Triangular facets along the northern side of the Rampur city, Satluj river basin, Himachal Himalaya, India

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