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River Profile Analysis to Identify Active Tectonic Imprints in Rossenna Watershed, Northern Apennines, Italy

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Abstract: Northern Apennines is tectonically an active fold and thrust belt. Digital Elevation Model (DEM) based drainage network was extracted to analyze river profiles to document the influence of neotectonics on landscape evolution in Rossenna river basin, northern Apennines Italy. This approach decodes the neotectonic signals by computing channel steepness, Hack stream-length gradient (HSLG) and knickpoints analyses. The main objective was to examine how spatially variable rock uplift relate to changes in river morphology. The results obtained are consistent with the recent tectonic uplift of the region. The presence of knickpoint anomalies and higher values of steepness and HSLG index in south west region and the lower segments of Rossenna River indicate high relative uplift in these areas, which is related to the presence of strikeslip and thrust faulting. It is concluded that these results are useful to constrain the active tectonics in a simpler and faster way using river profile analysis.

Keywords: DEM, neotectonics, river profile, steepness, knickpoints, Hack stream-length gradient index, Apennines

Introduction

The Apenninic chain is marked by localized Pleistocene and current uplift and moderate seismicity (Balestrieri et al., 2003; Viti et al., 2004; D'Anastasio et al., 2006; Thomson, 2010; Boccaletti et al., 2011; Siddiqui et al., 2017). For its complex geo-tectonic setting, the northern Apennines is considered as a natural laboratory to apply several kinds of geomorphological investigations using remote sensing data (DEMs) to surface processes. A regional morphotectonic analysis of the study area can be a most useful tool for producing the required basic neotectonic information (Chigariov, 1977). The remote sensing data (DEMs) are of particular use during reconnaissance studies at various scales especially for geomorphological, geological and surface deformation investigations (Kurz et al., 2007, Arrowsmith and Zielke, 2009). Digital Elevation Models (DEMs) are efficient tools to study active deformation using drainage network. The linkage between surface processes and quantitative geomorphic parameters extracted from DEMs, especially in the areas of active deformation has grown and established in recent years (Burbank and Anderson, 2001, Kurz et al., 2007, Arrowsmith and Zielke, 2009; Siddiqui et al., 2017). Rossenna River is located in a tectonically active region of northern Apennines, Italy. It is part of Secchia River basin, which is one of the river tributaries flowing from NW (Fig. 1).

River profiles serve as important markers of neotectonic deformation, as the drainage system preserve the spatio-temporal variations in the relative uplift of the region. The historical record of the seismicity and the presence of neotectonics in the study area is an evidence that the analysis of active deformation at local as well as regional scale using remote sensing data (DEMs) is inevitable (Viti et al., 2004; Castaldini et al., 2005b: Spagnolo and Pazzaglia, 2005; Tosatti et al., 2008, Vannucchi et al., 2008; Picotti and Pazzaglia, 2008; Surian et al., 2009; Boccaletti et al., 2004, 2011; Siddiqui et al., 2017). The main purpose of this research is to monitor active deformation and landscape evolution using DEM of 5m resolution by calculating morphometric parameters using tecDEM and ArcMap. The results are validated by correlating with existing geo-tectonic setting and the current seismicity of the region. The current research consists of integrated approach using different methodologies (Orientation analysis, river longitudinal profile and Hack stream-length gradient analysis), which are cost and time effective methods and provide instant information that can be used by government officials, policy makers and provincial management authorities to make better management practices in these areas. The results obtained from these methods will also help to design the local infrastructure according to the changing scenario of deformation pattern.

Seismotectonic and Geological Settings

Rossenna basin is located in Apenninic chain, which is strongly deformed in Pliocene and Quaternary periods and is in continuous uplift (Bartolini and Pranzini, 1983). Analysis of focal mechanism solutions within the study area indicates differential deformation fields with depth ranging from < 15 to >35 km (Figs. 2, 3; Lavecchia et al., 2003). The focal mechanism represents moderate earthquakes of 4 intensity in this area, related to thrust faulting, oriented NW and SE and normal and strike-slip faulting in the area of Pavullo nel Frignano. From geological point of view the River Rossenna cut out its bed on the layers of

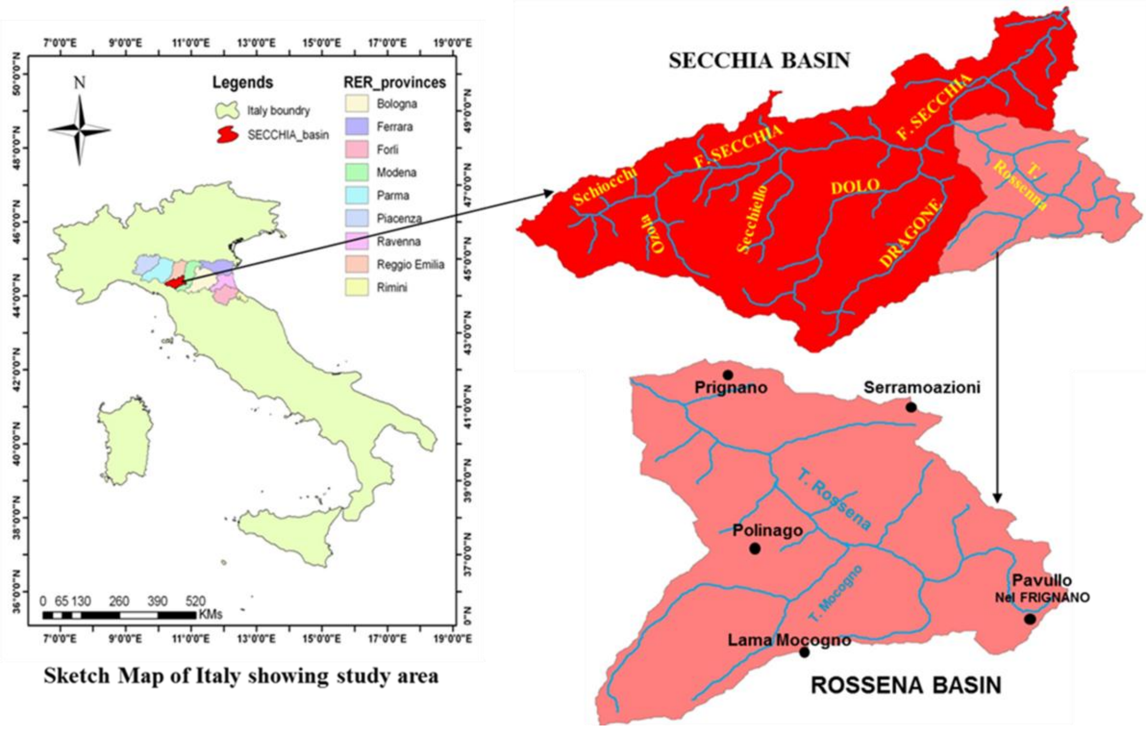

Fig. 1 Map showing spatial location of study area (Rossenna basin) and surrounding region.

Flysch. The slopes are composed of Cretaceous-Paleocene Flysch and Epiligurian Sandstones and of the typical Scaly Clays (Argille Scagliose) which is intensely tectonized (Fig. 4, Carton and Panizza, 1983).

Materials and Methods

Historical data, archives, regional, national and international publications and research reports indicate the existence of neotectonics (Panizza and Castaldini, 1987) in the region. DEM at 5 m resolution were processed for the extraction of drainage network and

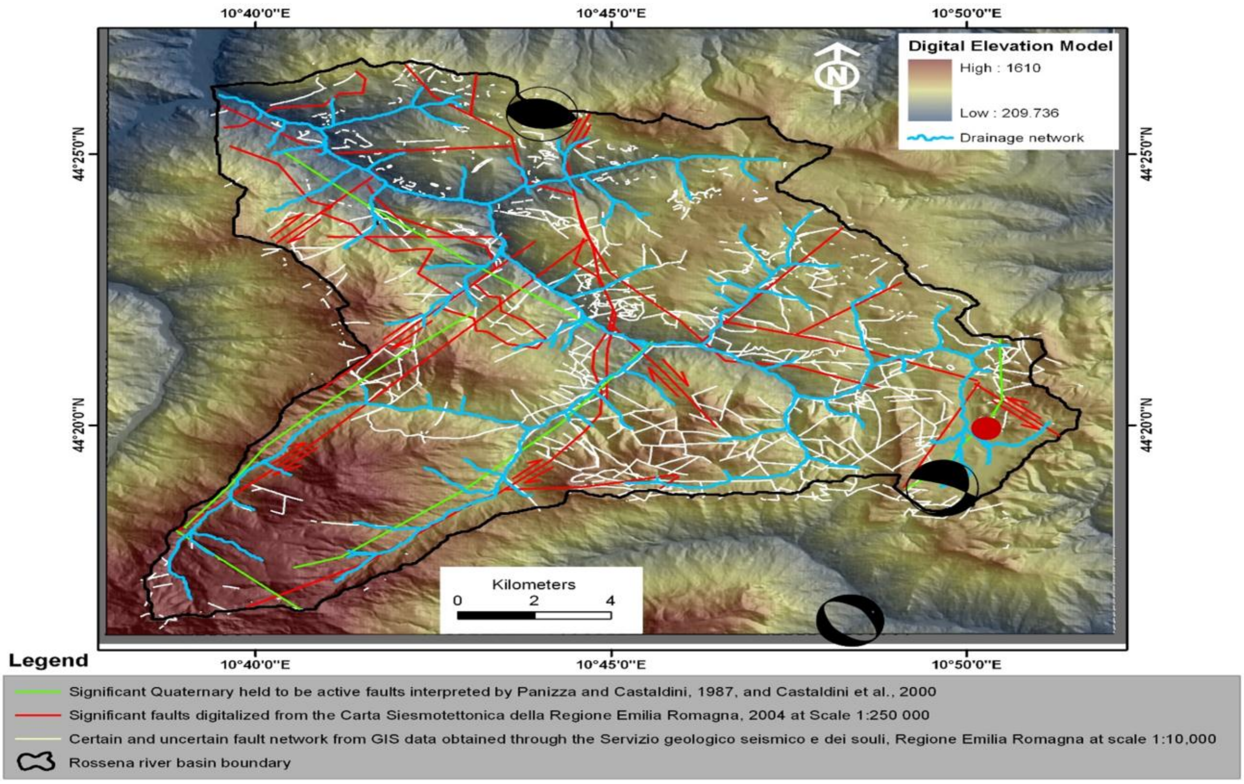

Fig. 2 Map showing major faults, lineaments, earthquake focal solutions and location of epicenter (red dot) recorded by the INGV between 1981 and 2016.

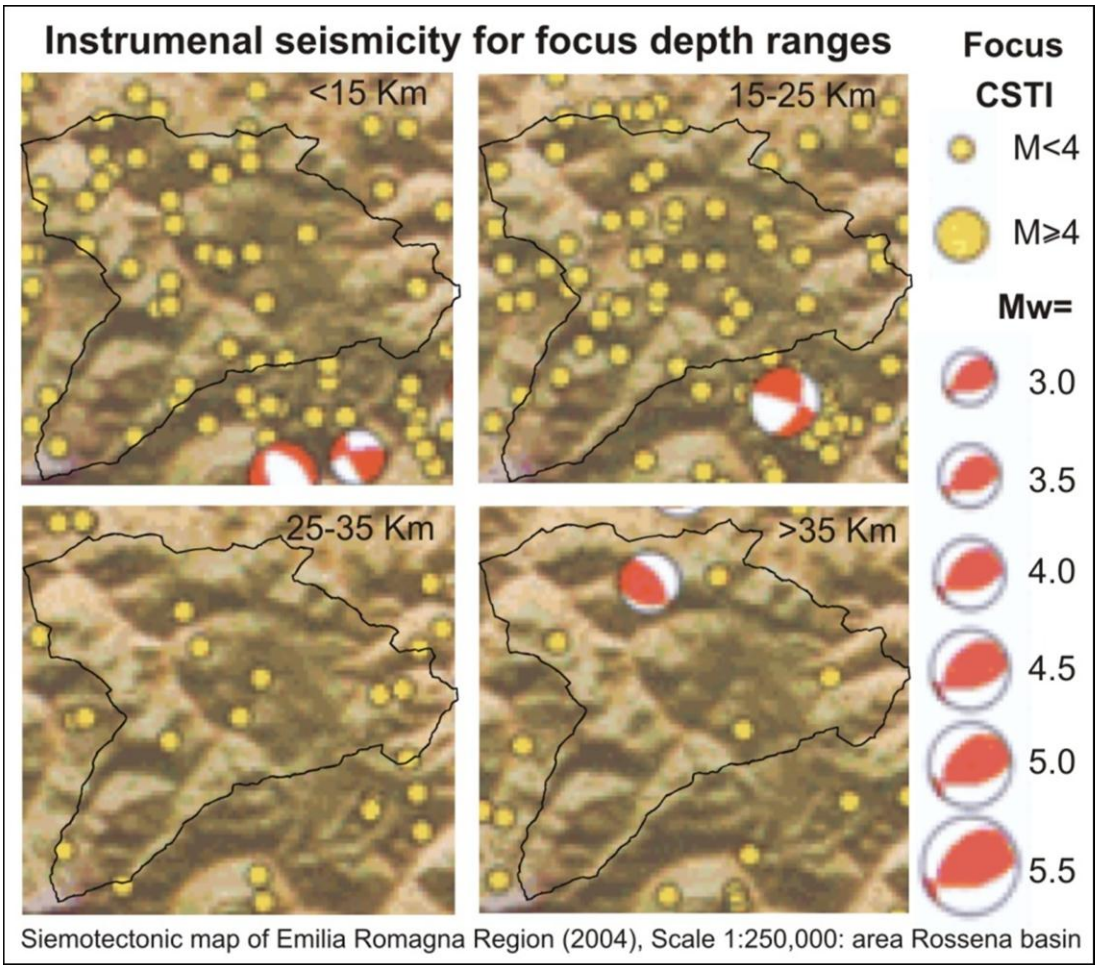

Fig. 3 The instrumental earthquakes recorded by the INGV between 1981 and 2016.

landscape metrics. Geological map of Emilia Romagna region at 1:10.000 scale was used to superimpose regional trends in channel steepness values and locations of the studied knickpoints to establish potential association with lithological contacts and/or geological structures (Hack, 1957; Kirby et al., 2003; Wobus et al., 2006; Phillips et al., 2010). Aerial photographs were used for the visual interpretation of different anomalies in geomorphic features and drainage pattern.

DEM-based automatic drainage extraction

DEM always have some errors in the form of depressions and pits, to remove these anomalies DEM filling algorithms are needed to be used to get a smooth and continuous drainage network. For the automatic extraction of drainage network D8 flow grid algorithm have been applied on DEM. This method extracts the water flows direction on steeper slope in 8 possible sides (Jenson and Domingue, 1988; O’Callaghan and Mark, 1984).

River longitudinal profile

River longitudinal profiles serve as an important marker of neotectonic deformation as the drainage system preserve the spatio-temporal variations in the relative uplift of the region and deformation (Hack, 1973; Burbank and Anderson, 2000; Snyder et al., 2000; Wobus et al., 2006; D’Alessandro et al., 2008; Ascione et al., 2008; Troiani and Seta, 2008). In tectonically active areas, rivers set the rate of incision by lowering the landscape due to erosion and mass removal (Snyder et al., 2000). Therefore, river longitudinal profiles can provide a good approximation of the role of internal and external geomorphic processes. Various empirical studies were found quite useful to evaluate the spatial variation in uplift rate due to endogenic processes in active orogens (Hack, 1973; Howard, 1983; Snyder et al., 2000; Wobus et al. 2006)

The streams chosen for this analysis consist of different spatial distribution to investigate the spatial distribution of tectonic and erosional processes. DEM-based automatic drainage network were extracted for geomorphic indices analysis (Jenson and Domingue, 1988, O’Callaghan and Mark, 1984). Various landscape metrics and indices e.g., concavity, steepness and Hack stream-length gradient can be derived from river profiles that give information on the localization of the neotectonic deformation. Concavity and steepness indices help in understanding about basin morphology, underlying rock strength and spatial

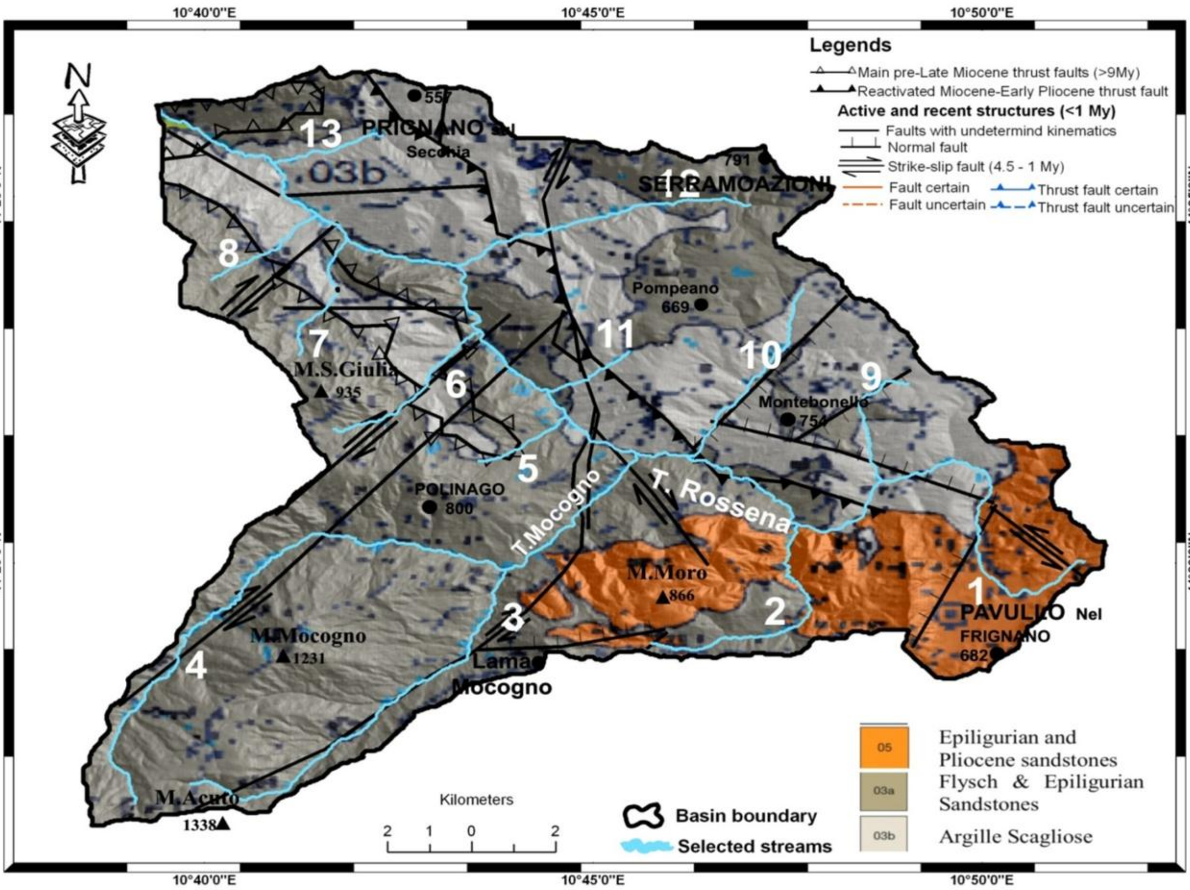

Fig. 4 Map showing distribution of major geological units and faults (modified from Boccaletti et al, 2004, Carta Siesmotettonica della Regione Emilia Romagna, Bertolini et al, 2008, the geological landscape of Emilia Romagna.

variations in rock uplift rates. Using these indices we can separate the stream units with lithologic and fault boundaries (Wobus et al., 2006).

Concavity indicates the variation in heights (high, low etc.) along stream profile and ranging between 0.4- 0.6 (Wobus et al., 2006). In practice the normalized steepness index is very useful as compared to concavity index for assessing active tectonics especially for the short channel segments e.g. T. Mocogno. In tectonically active regions, we assume that channels with high normalized steepness index are categorized as the high uplift areas, while those with low normalized steepness index are characterized as the low uplift areas (Snyder et al., 2000; Kirby and Whipple, 2001; Vanlaningham et al., 2006; Cristea, 2014; Jiang et al., 2016; Siddiqui et al., 2017).

First, slope area profiles were constructed using stream power law (Lague, 2014). For regression analysis trends were selected on slope-area data for individual stream segments to calculate concavity (θ) and steepness (Ks) values. Trends are selected based upon breaks in scaling in slope-area data (Wobus et al., 2006; Lague 2014; Siddiqui et al., 2017) using following equation (Eq. 1) based on Flint's empirical power-law that relates the slope (S) to the upstream contributing drainage area (A).

$$S = K_s A^{-\theta} \qquad \text{(Eq. 1)}$$

Where K_s is steepness index and θ is stream concavity. *Ks* and θ are computed directly by regression analysis of the slope-area data (Montgomery et al., 1996; Homke et al., 2004; Whipple, 2004; Wobus et al., 2006). Secondly, the normalized steepness index (K_{sn}) is calculated for the selected stream segments using a reference mean concavity (θ_{ref}) of 0.45 using following equation (Eq. 2):

$$K_{sn} = K_s A_{cent}^{(\theta \text{ref-}\theta)} \qquad \text{(Eq. 2)}$$

Where K_{sn} is the normalized steepness index, θ and *Ks* are computed by regression for each individual stream segment, A_{cent} is the drainage upstream area in the stream segment's midpoint and θ_{ref} is a given reference concavity (Cristea, 2014; Siddiqui et al., 2017). However, relative differences in K_{sn} do not depend on the choice of θ_{ref} (Duvall et al., 2004; Wobus et al., 2006). Matlab based software TecDEM (Tectonics from Digital Elevation Model) were used to apply slope-area regression analysis (Whittaker et al., 2007a, Whittaker et al., 2007b; Shahzad and Gloaguen, 2011a) according to the methods and tools developed by Snyder et al. (2000) and Kirby and Whipple (2003). these irregularities in the river profile were associated with the lithologic contact, structural features or mass wasting events.

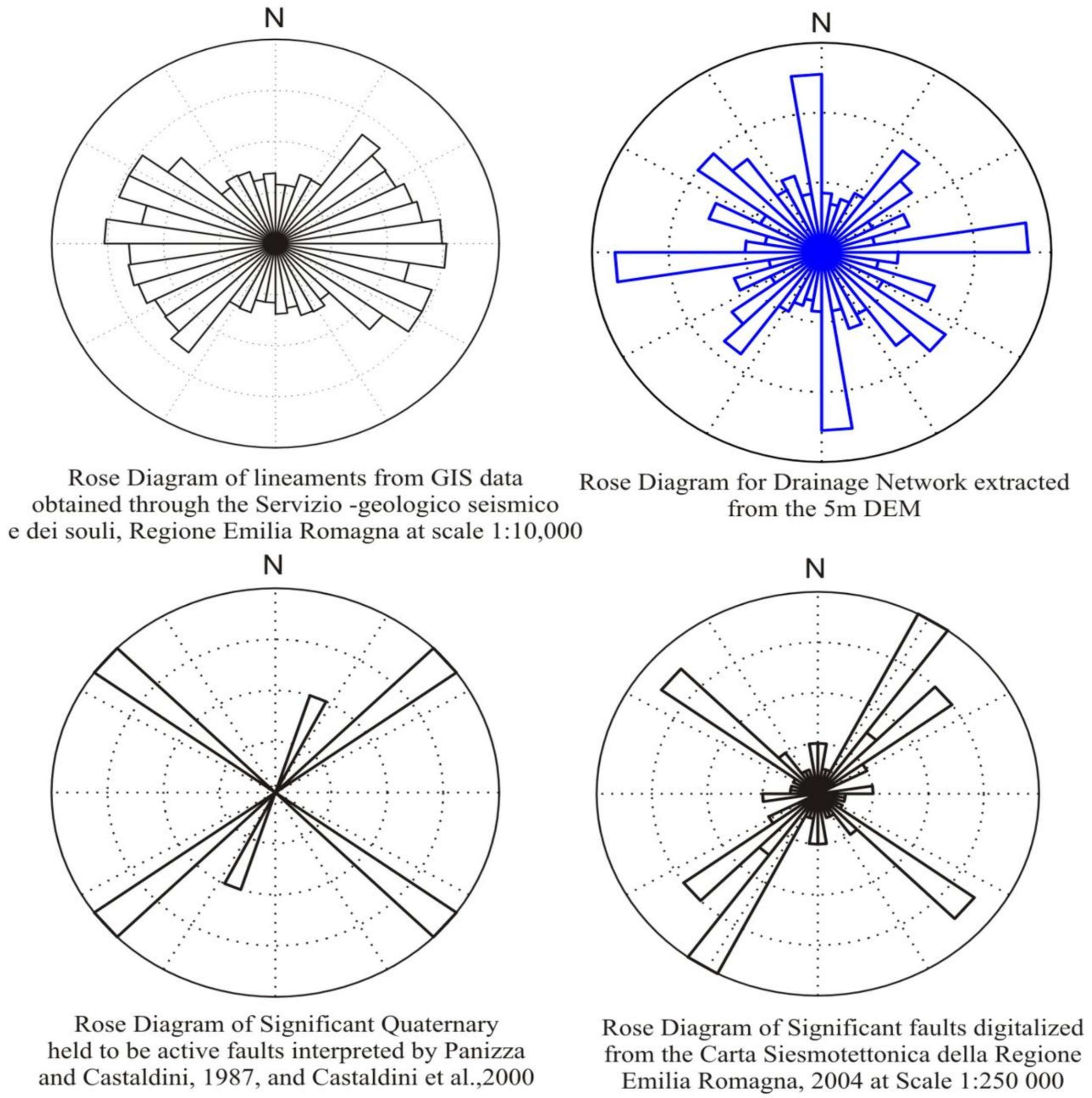

Fig. 5 Rose diagrams of faults at differnt scales (black colour) and drainage network (blue colour) showing orientation style.

Knickpoints (Kps) in the extracted river profile are indicators of young erosional events and represent local steepened part of the stream (Siddiqui et al., 2017). DEMs are considered reliable for qualitative identification (i.e., presence/absence) of knickpoints (Phillips et al., 2010). The possible causes of Kps are tectonics, lithological variation, waterfalls, lakes, mass movements etc. Kps were identified based on breaks in scaling of the stream dataset and the trends were marked for regression analysis accordingly. These data were examined based on validation from geological maps and aerial photographs to see whether any of

Hack stream-length gradient index

Hack stream-length gradient (HSLG) index spot active tectonics by detecting abnormally high index values on a particular rock type (Hack, 1973, Merrits and Vincent, 1989; Zovoili et al., 2004; Chen et al., 2006; Brookfield, 2008; Siddiqui et al., 2017). HSLG index computes the changes along stream longitudinal profiles, as it is sensitive to changes in channel slope or steepness (Burbank and Anderson, 2001). An area of high HSLG values on soft rock, such as shale, may indicate recent tectonic activity. Extremely low HSLG values can also be related to the tectonic activity along strikeslip faults because the rocks in such cases are often crushed by fault movement, and streams flowing in these valleys should have lesser slope (Hack, 1957, 1973).

The HSLG index for specific stream segment can be calculated by following equation (Eq. 3):

$$SL = (\Delta H / \Delta L) * Lt \quad \text{(Eq. 3)}$$

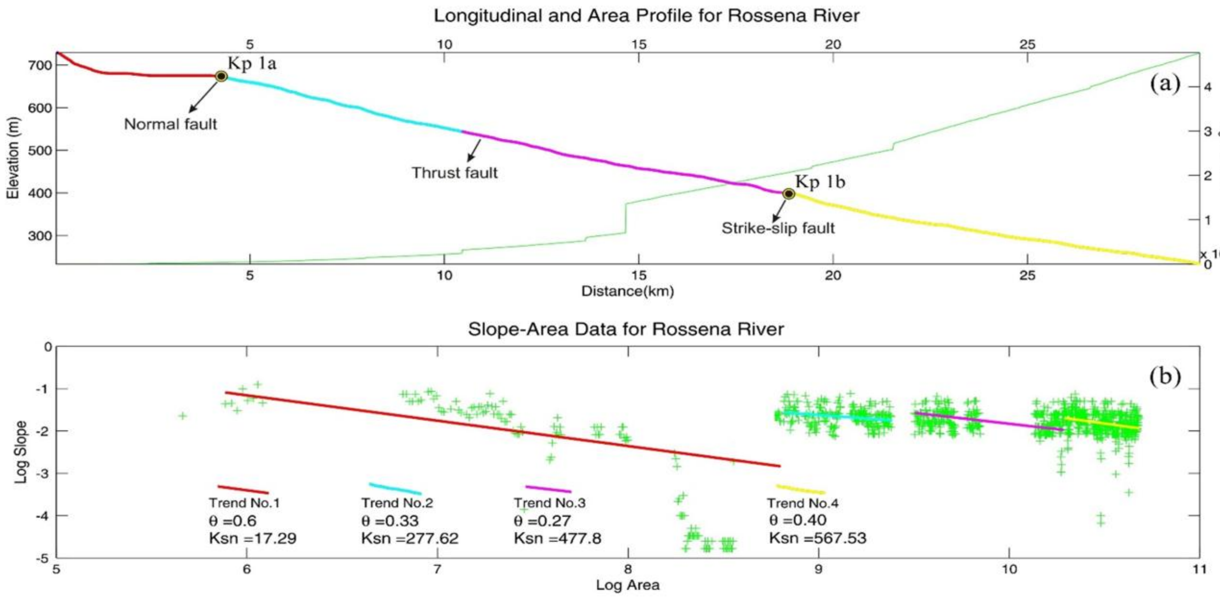

Fig. 6. (a) Longitudinal and area profile for Rossenna River in northern Apennines. Linear regressions of slope-area data are shown as colour lines in both stream longitudinal profile and on slope-area data. Point symbols (Black-yellow) are showing location of identified knickpoints on stream longitudinal profile. Location of faults along stream profile is shown using black arrows. (b) The slope-area data showing trends (linear regressions), and the corresponding value of steepness (K_{sn}) and theta (θ). Notice that the steepness index is increasing anomalously when the stream crosses normal fault at knickpoint 1a (Kp 1a) and strikeslip fault at knickpoint 1b (Kp 1b) location.

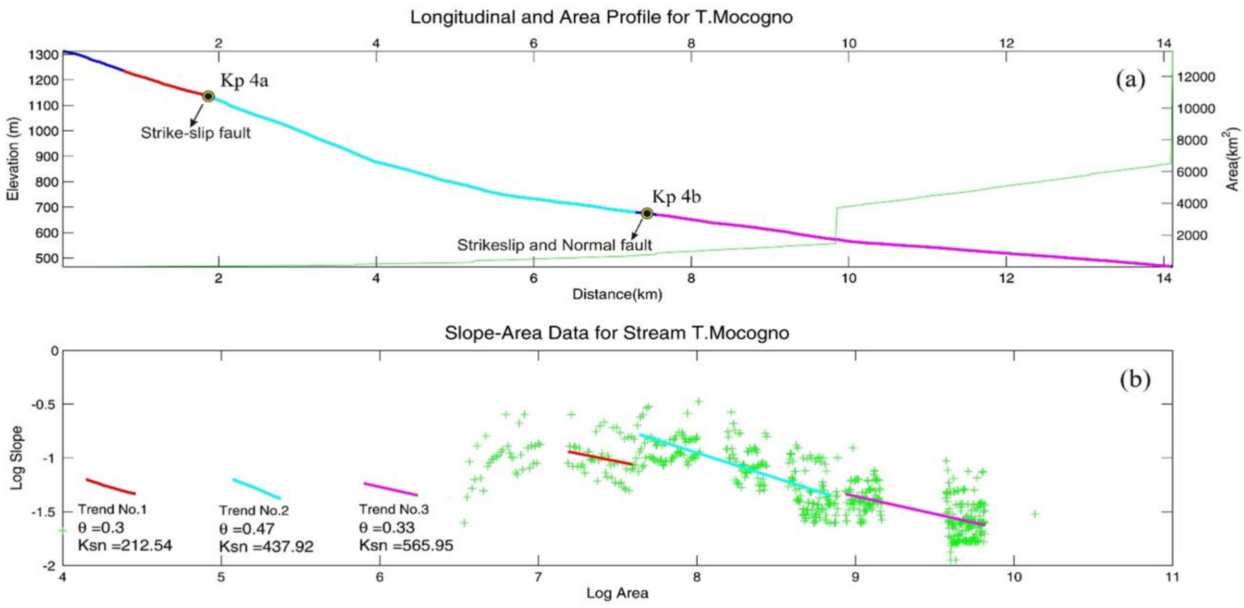

Fig. 7. (a) Longitudinal and area profile for T. Mocogno River in northern Apennines. Linear regressions of slope-area data are shown as colour lines in both stream longitudinal profile and on slope-area data. Point symbols (Black-yellow) are showing location of identified knickpoints on stream longitudinal profile. Location of faults along stream profile is shown using black arrows. (b) The slope-area data showing trends (linear regressions), and the corresponding value of steepness (K_{sn}) and theta (θ). Notice that the steepness index is increasing anomalously when the stream crosses strikeslip fault at knickpoint 4a (Kp 4a) and strikeslip and normal fault at knickpoint 4b (Kp 4b) location.

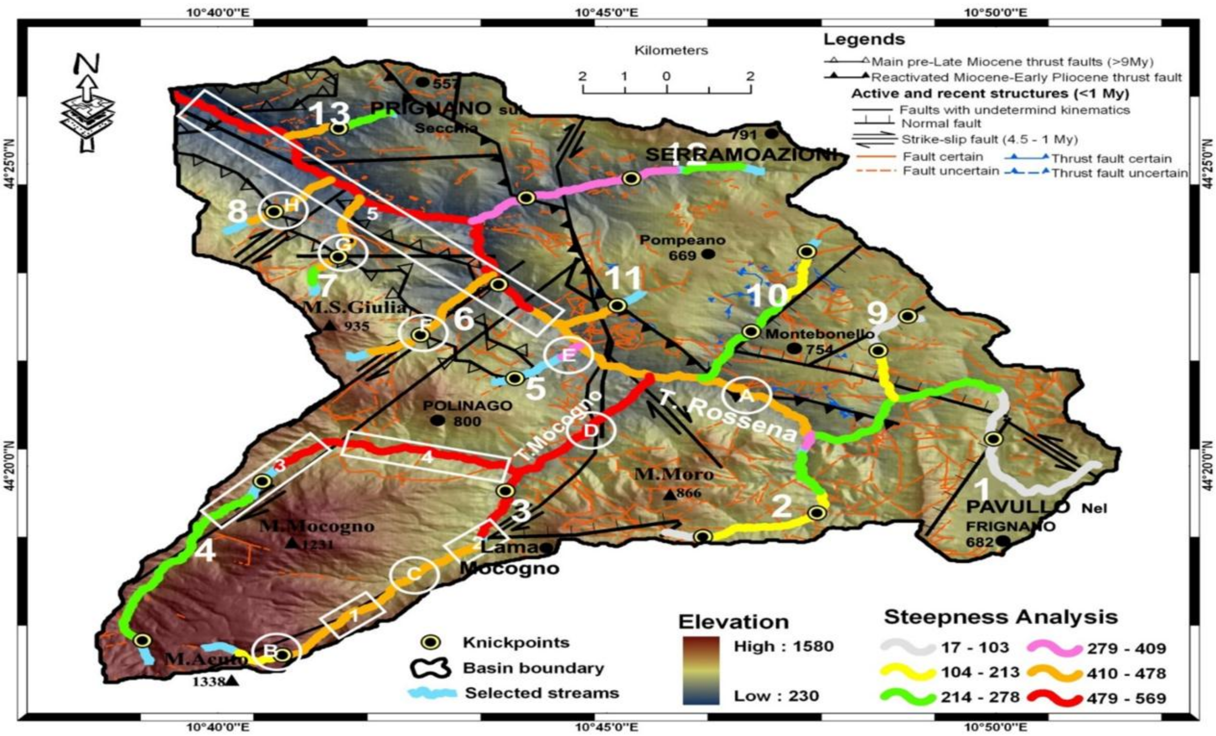

Fig. 8 Map showing spatial distribution of steepness index values along selected stream segments. White rectangles are showing zones of very high steepness index and white circles are showing areas of high steepness index values and thus relate to very high and high relative uplift rates in these areas.

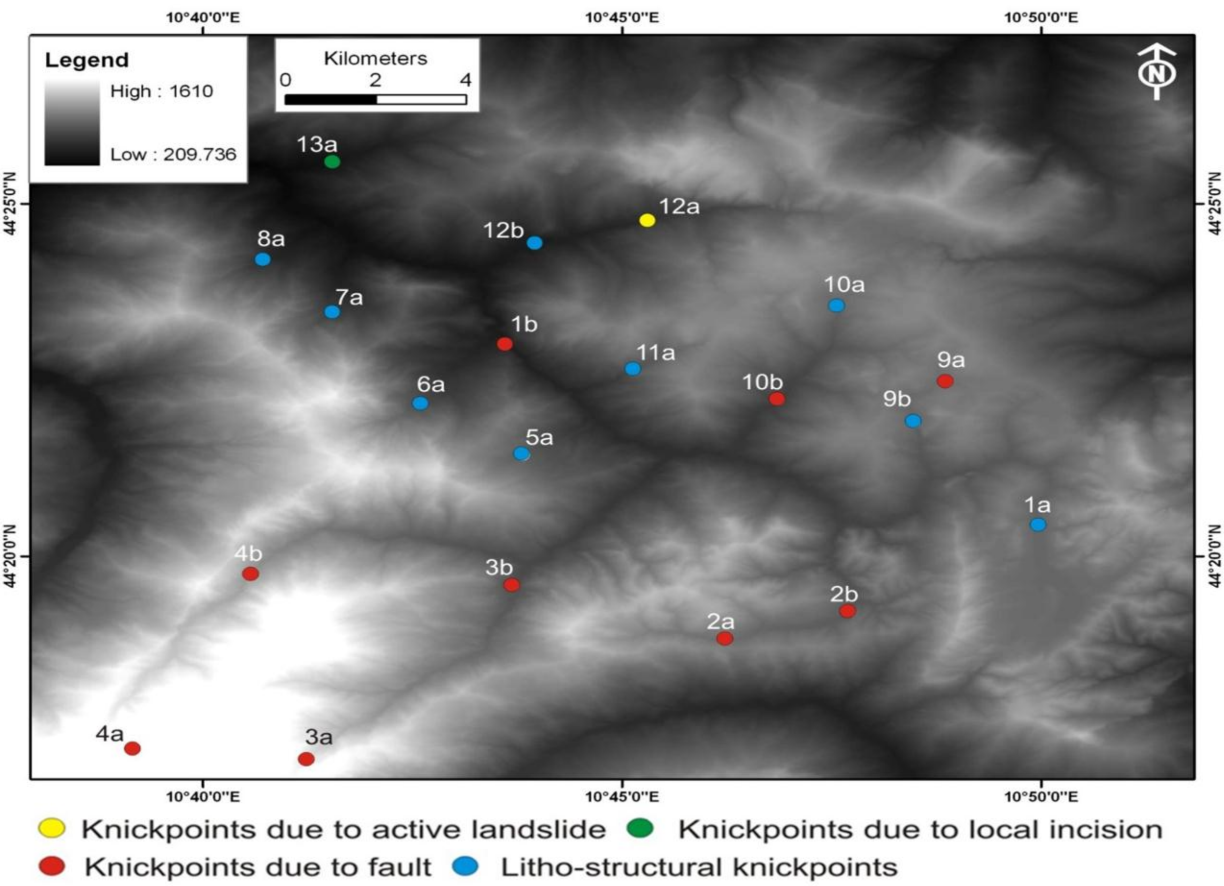

Fig. 9 Map showing spatial location of selected knickpoints/knickzones on DEM. The possible cause of knickpoint origin is highlighted using differnt coloured dots.

upper and the lower channel segments, *ΔL* is the length of the selected channel segment and *Lt* is the total channel length from the highest point of the channel (channel source) to the middle of the selected stream segment. An interval of 150 m was selected as *ΔH*. The whole methods were implemented in TecDEM and the calculated values of all indices were plotted on maps using ArcGIS 10.3 to identify areas of spatial variations and their relation to underlying structures and rock strength. Relative differential uplift were recognized in the context of normalized steepness index (*Ksn*) and Hack stream-length gradient index as recommended by Wobus et al. (2006) and Hack (1973).

Results and Discussion

Orientation analysis of lineaments and drainage network

Orientation analysis of both lineaments and drainage network gives information about the surface deformation trend. Both automatic and manual lineaments were used for this purpose (Fig. 5). The rose diagram of lineaments from GIS data at 1:10,000 scale shows that the most of these lines are oriented NE-SW and NW-SE quite parallel to the strikeslip and thrust faults present in the area. The major faults (right lateral strikeslip and thrust faults) and the main streams (i.e. Rossena River and Torrent Mocogno) show NE-SW, NW-SE and almost N-S, E-W orientation respectively. The rose diagram of small lineaments and streams shows complex and same orientation style fairly distributed in all direction which indicates that this area is intensely tectonized (Carton and Panizza, 1983). The difference in orientation style of both lineaments and drainage network actually gives information about the complexity of the deformation style and presence of certain anomalies that could be related to erosional or neotectonic processes. The similarity in the orientation style of drainage patterns and lineaments clearly indicate that in the study area the neotectonics are controlling and influencing the drainage network.

The Rossenna River longitudinal profile shows 4 segment morphology (Fig. 6). The first segment (Trend No. 1) is concave as compared to second, third and fourth segments (Trend No. 2, Trend No. 3 and Trend No. 4). The steepness value is gradually increasing

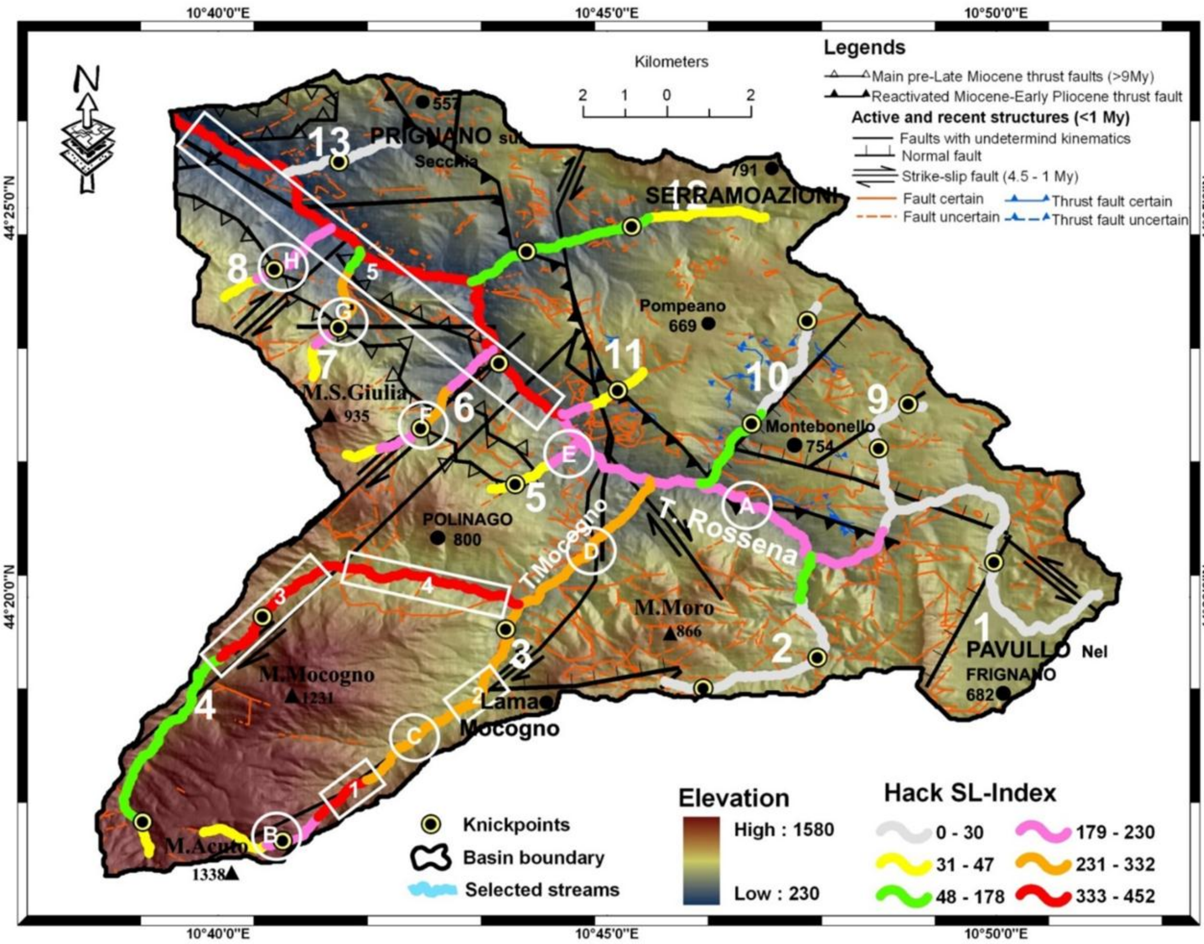

Fig.10. Map showing spatial distribution of Hack stream-length gradient index (HSLG) values along selected stream segments (segment interval is 150 m). Major tectonic units are shown on the map in black colour. Anomalously high HSLG values are highlighted by white rectangles while high to moderate HSLG values are highlighted by white circles. The anomalously high and high HSLG values correspond to steepest slopes (Fig. 7) and are mainly present along the fault margins.

from the first segment towards the fourth segment downstream due to interaction of stream with some significant strike slip and thrust faults due to lithological variation at some places.

The T. Mocogno River profile shows 3 segment morphology (Fig. 7), the steepness index for the first segment is less (212.54) as compared to the second (437.92) and third (565.95) segments. T. Mocogno profile shows an excellent example of differential uplift conditions on the similar rock types because a right lateral strikeslip fault interacts with the stream at this location in the middle and lower segments. The spatial distribution of steepness index of all selected streams is shown in Fig. 8, which is the most important parameter as it is directly related to the relative uplift (Whipple et al., 1999; Snyder et al., 2000; Robl et al., 2008). The higher values of steepness can be observed in SW and lower segments of Rossenna River that are related to the presence of strikeslip and thrust faults in these areas and thus confirms the active tectonic control in these locations.

Knick points show the local steepened part in the stream profile. 20 knick points were identified on selected stream segments in Rossenna basin (Fig. 9). After validation from geological maps, neotectonic map and aerial photographs, it is verified that these irregularities (KPs) in the river profiles are associated with active faults (KPs: 1b, 2a, 2b, 3a, 3b, 4a, 4b, 9a, 9b and 10b), litho-structural boundaries (KPs: 1a, 5a, 6a, 7a, 8a, 10a, 9b, 11a, 12b), mass wasting events (KP: 12a) and local incision (KP: 13a).

Hack stream-length gradient index analysis

White boxes and circles are showing areas of anomalously high and high HSLG index and steepness index values respectively. Downstream of Rossena River, there is an abrupt increase in HSLG index values which shows an increase of slope gradient after stream interaction with thrust and strikeslip faults and also change in lithological boundaries at some places (Fig. 10).There is a slight decrease in the HSLG value due to the change in underlying rock type downstream which again correspond to the presence of strikeslip fault, fault with undetermind kinematicas and number of other lineaments. Downstream of T. Mocogno, there is an abrupt increase in HSLG index value on the similar rock type which clearly indicates neotectonic activity (Hack, 1957, 1973) because a right lateral strikeslip fault interacts with the stream at this location (Fig. 10).

Conclusion

Tectonic geomorphology research based on remote sensing data (DEMs) has the potential to yield results significant to the tectonics and geology of the active orogens. The results obtained through the analysis of river profiles and morphometric indices that are extracted from digital elevation model, helps to develop and interpret the morphometric maps to identify the localized neotectonic deformation. The results of present study show that drainage network of Rossenna River basin established its course along the main tectonic structures. Its evolution however, especially in recent era, is strongly related to the ongoing tectonic activity and secondly, to the differential lithological competence. The variation in orientation style of faults, lineaments, drainage network and linearized streams gives information about the complexity of the deformation style that could be related to erosional or neotectonic processes. 20 knickpoints were identified on selected stream segments in Rossenna basin. After validation it is verified that these KPs are mainly associated with active faults and litho-structural contacts. In practice the normalized steepness index is very useful than the concavity data for evaluating active tectonics especially for the short channel segments e.g. T. Mocogno. Higher values of steepness and HSLG in SW and lower segments of Rossenna River correspond to presence of strikeslip and thrust faults and thus confirm the active tectonic control in these locations. In the Holocene, climatically modulated variations in watershed hydrology, and/or anthropogenic activities in the study area may increase the discrepancy between down cutting and uplift at local scale. Nonetheless, in both cases, the active deformation and the topography of the Rossenna basin seems to be governed by the interplay between erosion and tectonic processes.

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