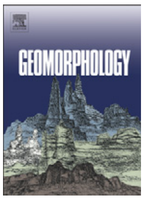

Volume 102, Issue 1
15 November 2008
ISSN: 0169-555X
ELSEVIER
GEOMORPHOLOGY
SPECIAL ISSUE
IMPACT OF ACTIVE TECTONICS AND UPLIFT ON FLUVIAL LANDSCAPES AND DRAINAGE DEVELOPMENT
Guest Editors: P.G. SILVA, F.A. AUDEMARD, A.E. MATHER
Acting Special Issue Editor: A. HARVEY

Geomorphology 102 (2008) 159–168

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph



The use of the Stream Length–Gradient index in morphotectonic analysis of small catchments: A case study from Central Italy

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ARTICLE INFO

Article history:
Accepted 28 June 2007
Available online 7 April 2008

Keywords:
Stream Length–Gradient Index
Neotectonics
River valleys
Marchean Apennines
Central Italy

ABSTRACT

The aim of this work is to test an integrated quantitative geomorphic approach based on Stream Length–Gradient Index (SL Index) analysis within the small catchment of the Tarugo River in the Northern Marchean Apennines (Central Italy). The Tarugo River basin, 92 km^2 wide, strikes SW–NE across the Marchean Ridge and the western sector of Marchean Piedmont. The area is characterized by a series of NW–SE trending, NE verging thrust folds affecting the Meso–Cenozoic bedrock that pass upward from dominantly carbonate to dominantly terrigenous rocks. The area investigated has been affected since the Pliocene by extensional tectonics, accompanying a regional uplift decreasing in rate north-eastwards. In this work the SL Index analysis has been integrated with the spatial analysis of the Amplitude of relief (A_r) and compared to geological and geomorphological field data. Results of this work indicate that the SL Index is a valid tool to detect the long wavelength structural effect on topography as well as the incipient local response to regional processes (i.e. regional uplift) that is often undetectable by other morphotectonic parameters. In contrast, the SL Index analysis seems not be a valid tool for discriminating the local lithological influence from the tectonic one.

1. Introduction

Some geomorphic indices have been developed to identify areas experiencing rapid tectonic deformation (Keller, 1986; Keller and Pinter, 1996 and references therein). Geomorphic indices are particularly useful in tectonic studies because they provide a rapid evaluation of large areas and can be obtained easily from topographic maps or aerial photos (Strahler, 1952). Moreover, in recent decades, the increasing usefulness of GIS software has made it easier to undertake quick and detailed processing of data.

Recently, in morphotectonic studies traditional geomorphic analysis has been integrated with morphometric analysis of landforms and with geostatistical topographic analysis (Keller et al., 1982; Mayer, 1990; Cox, 1994; Merritts et al., 1994; Lupia Palmieri et al., 1995; Lupia Palmieri et al., 2001; Currado and Fredi, 2000; Pike, 2002; Della Seta, 2004; Della Seta et al., 2004). The Stream Length–Gradient Index (SL Index) is one of the quantitative geomorphic parameters included in morphotectonic investigation (Hack, 1973). In tectonically active regions, and/or at the regional scale of analysis, the SL Index can be a useful tool to detect tectonic displacements (Keller and Pinter, 1996; Chen et al., 2003 and references therein; Zovoili et al., 2004). Nevertheless, the effectiveness of the parameter in detecting local active structures has not been confirmed for small catchments and/or in regions where tectonic activity is less intense (Chen et al., 2003 and references therein; Verrios et al., 2004). In small river basins the contribution of the lithological effect to anomalous values of the SL Index seems indistinguishable from the tectonic one.

In this work SL Index analysis was performed for the small Tarugo River drainage basin, located on the Adriatic flank of Apennine chain, in Central Italy. This case study was chosen with the aim of better defining the usefulness of SL Index analysis in detecting the impact of neotectonics on small river-valley development. The longitudinal profile and SL Index analyses were coupled with the geostatistical analysis of the Amplitude of relief (A_r), which proved to be a significant morphotectonic parameter (Ahnert, 1970; Ciccacci et al., 1988; Centamore et al., 1996; Della Seta et al., 2004).

2. Regional setting

The Marche Apennines is part of the Northern Apennine orogenic belt, which developed with an arcuate geometry as a consequence of the convergence between the African and Eurasian plates during the Neogene. The Apennines consist of a northeast-verging fold-and-thrust belt. The orogenic system progressively migrated towards the NE, along with extension in its inner domains (Patacca et al., 1992; Cavinato and De Celles, 1999; Faccenna et al., 2001). The approximately 5 km-thick Mesozoic–Cenozoic stratigraphic sequence (Boccaletti et al., 1971), changing upward from carbonate to terrigenous dominance (Coccioni et al., 1994), underwent about 30% shortening.

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doi:10.1016/j.geomorph.2007.06.020

In the study area evidence of two main structural phases are distinguished (Centamore et al., 1996). Firstly, a compressive phase (Miocene–upper part of Early Pliocene) was responsible for folds, thrusts and strike-slip faults. During the following phase (Late Pliocene–Pleistocene) the chain was dominated by extensional tectonics that accompanied a regional differential uplift and produced normal faults displacing the older geological structures (Di Bucci et al., 2003). The area has emerged progressively since the Middle–Late Pliocene as a result of the regional uplift, with higher rates at the end of Early Pleistocene (0.3–0.5 mm yr^{-1} during the last ~1 My; D'Agostino et al., 2001; Molin and Fubelli, 2005). Early during the later phase of Apennine development, perhaps during the Upper Pliocene–lowermost Pleistocene, the chain definitely emerged (Mayer et al., 2003). A drainage network developed with the main streams arranged in an overall sub-parallel pattern mainly SW–NE oriented and essentially perpendicular to the structural grain (Mazzanti and Trevisan, 1978; Alvarez, 1999). The main carbonatic anticlines are prominent ridges in the modern topography and the major streams flowing into the Adriatic Sea (Fig. 1) cross-cut them in deep and narrow gorges.

The Northern Marchean Apennines consist of three main morphostructural zones (Deiana and Pialli, 1994) each one showing particular topographic characteristics:

i) the Umbro–Marchean Ridge consists of calcareous and marly-calcareous anticlines with the highest elevations of the area, up to 1500 m a.s.l. (Nerone Mt. and Catria Mt.). Towards the east this structure terminates in the Inner Marchean Basin, a regional syncline that consists mainly of terrigenous deposits;

ii) the Marchean Ridge shows an average elevation of 800–1000 m a.s.l., with the Paganuccio Mt. (976 m a.s.l.) corresponding to an axial culmination of the structure. This structure rapidly plunges down both north-westwards and south-westwards (here it forms a wide topographic depression crossed by the Cesano valley). North-eastwards the ridge ends in a narrow syncline (named the Metauro syncline) that separates the Paganuccio anticline from the Cesane Mts. minor ridge;

iii) the Marchean Piedmont includes the minor ridge of Cesane Mts. with an average elevation of a few hundred of metres. The Marchean Piedmont is the foothill area where the compressional structures are buried by Plio-Pleistocene deposits and by Late Quaternary alluvium. In this area several extensional faults have been recognized (Savelli et al., 2001), oriented roughly N–S and associated with NE–SW trending oblique-slip transfer faults, with left-lateral offsets of tens of metres.

2.1. The Tarugo River basin

The Tarugo River basin is a 92 km^2 catchment, with the main stream striking SW-NE across the Marchean Ridge and the western sector of Marchean Piedmont (Fig. 1). In the upper portion of the basin, two main stream channels can be recognized (Figs. 2, 3). Downstream of their confluence, the Tarugo River flows approximately in SW–NE direction before joining the Metauro River, to the east of Fossombrone town (Fig. 3). In the confluence area the Tarugo River turns counter-flow describing a wide hook.

The bedrocks of the drainage basin belong to the Umbria–Marche stratigraphic sequence starting from Meso–Cenozoic Scaglia Rossa–Scaglia Cinerea Formations up to the Pliocene pelites belonging to the Argille Azzurre Formation (Cecca et al., 1999) (Fig. 2). Particularly, the flanks and the crests of the anticlines, consist of Createceous–Oligocene calcareous and marly-calcareous rocks belonging to the Scaglia Rossa–Scaglia Cinerea and Bisciaro Formations. Outcrops of marls, evaporites, pelites, arenites and marly-calcareous terrains, from the Schlier up to the Argille Azzurre Formation, show low elevations and gentle slopes, often affected by shallow landsliding.

A series of NW–SE trending NE verging folds characterizes the area, where several faults also occur (Fig. 2). In particular, a thrust fault crops out on the Paganuccio anticline forelimb.

Fig. 3 clearly shows the morphological evidence given by the ridges coinciding with calcareous and marly-calcareous bedrocks and the general SW–NE trend of the Tarugo River, perpendicular to the main folded structures (see also Fig. 2). Typically flat top surfaces markedly reflect the sub-horizontal/gently-dipping bedding of the hinge zone,

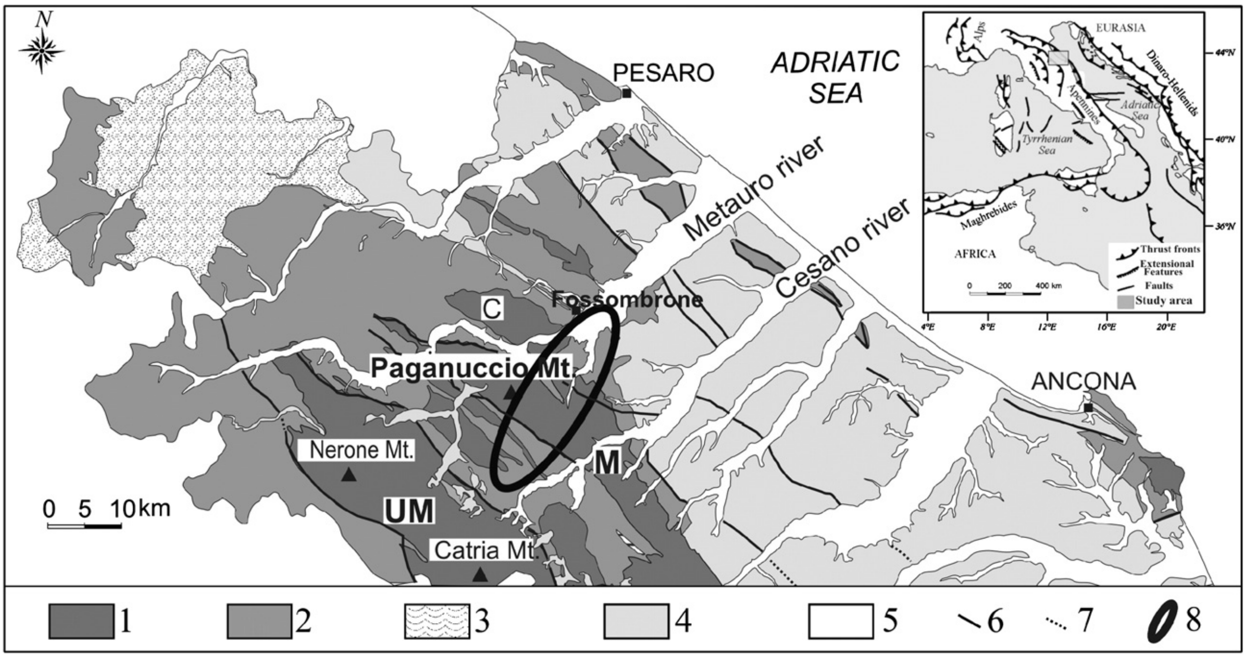

Fig. 1. Geological sketch of the northern Marche region and location of the study area. Legend: 1) Meso-Cenozoic calcareous and marly-calcareous units of the carbonatic ridge; 2) Cenozoic marly-calcareous, evaporitic and siliciclastic units; 3) Val Marecchia unit; 4) Plio-Pleistocene terrigenous units; 5) Middle Pleistocene–Holocene fluvial and coastal deposits; 6) fault; 7) uncertain fault; 8) study area; UM) Umbro–Marchean Ridge; M) Marchean Ridge; C) Cesane Mts. Ridge.

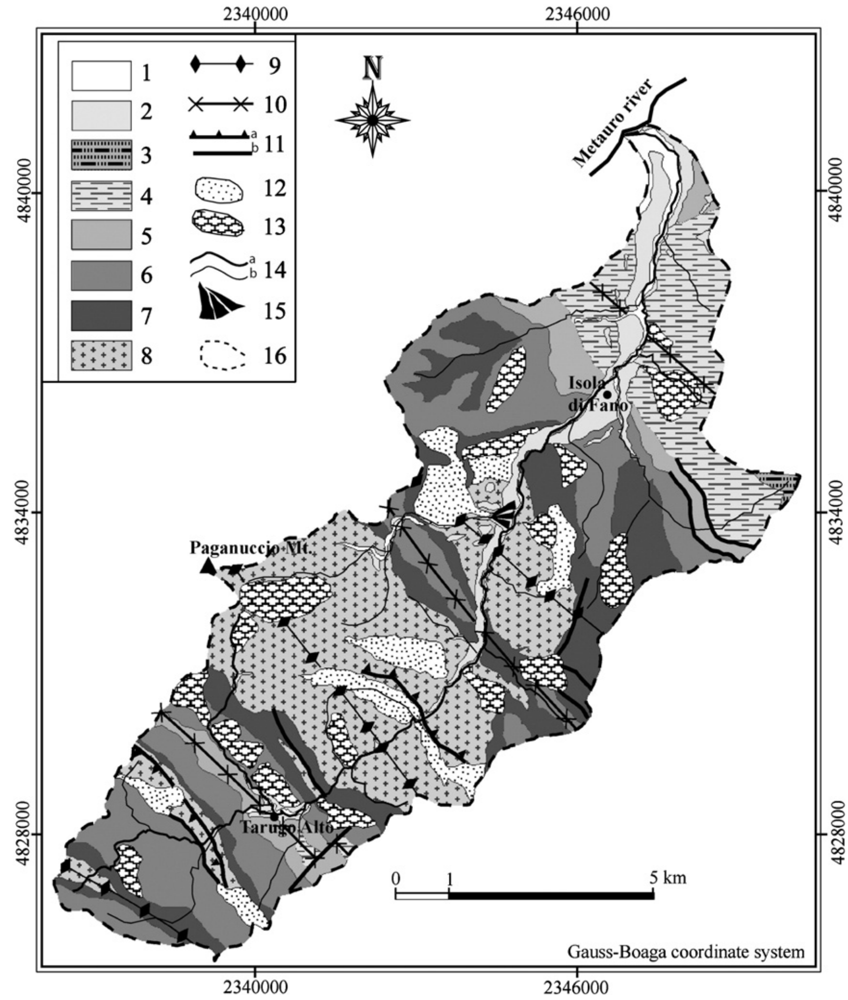

Fig. 2. Geological map of the Tarugo River basin. Legend: 1) Holocene fluvial terrace and present flood plain deposits; 2) fluvial terraces (Middle–Late Pleistocene); 3) Argille Azzurre Formation (Pliocene); 4) Gessoso–Solfifera and Colombacci Formations (Messinian); 5) Marnoso–Arenacea Formation (Tortonian); 6) Schlier Formation (Langhian); 7) Bisciaro Formation (Lower Miocene); 8) Scaglia Rossa–Scaglia Cinerea Formations (Upper Cretaceous–Oligocene); 9) anticline axis; 10) syncline axis; 11) thrust fault (a), uncertain fault (b); 12) slope deposits; 13) landslides; 14) Tarugo River (a), main tributaries (b); 15) Late Pleistocene alluvial fan; 16) Tarugo River basin divide.

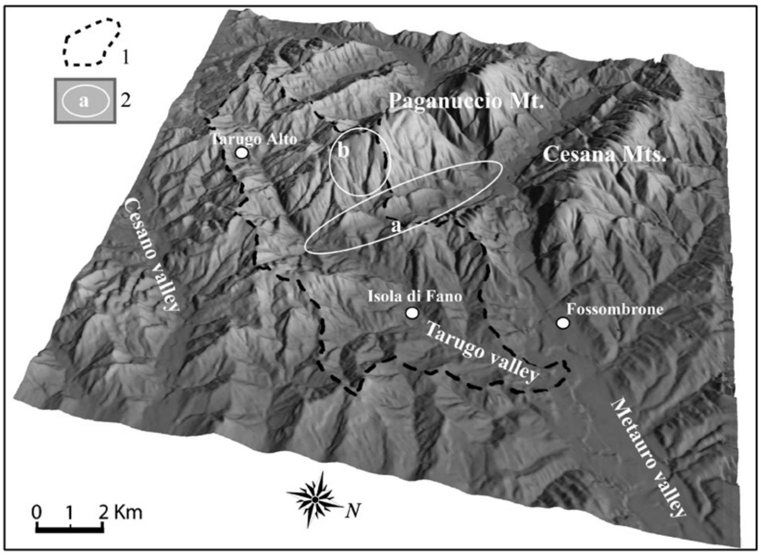

Fig. 3. Digital Terrain Model of the study area (kriging grid, 25 m resolution; vertical amplification: 2). Legend: 1) Tarugo River basin divide; 2) flatirons (a), deep-seated landslide (b). Please see the text for details.

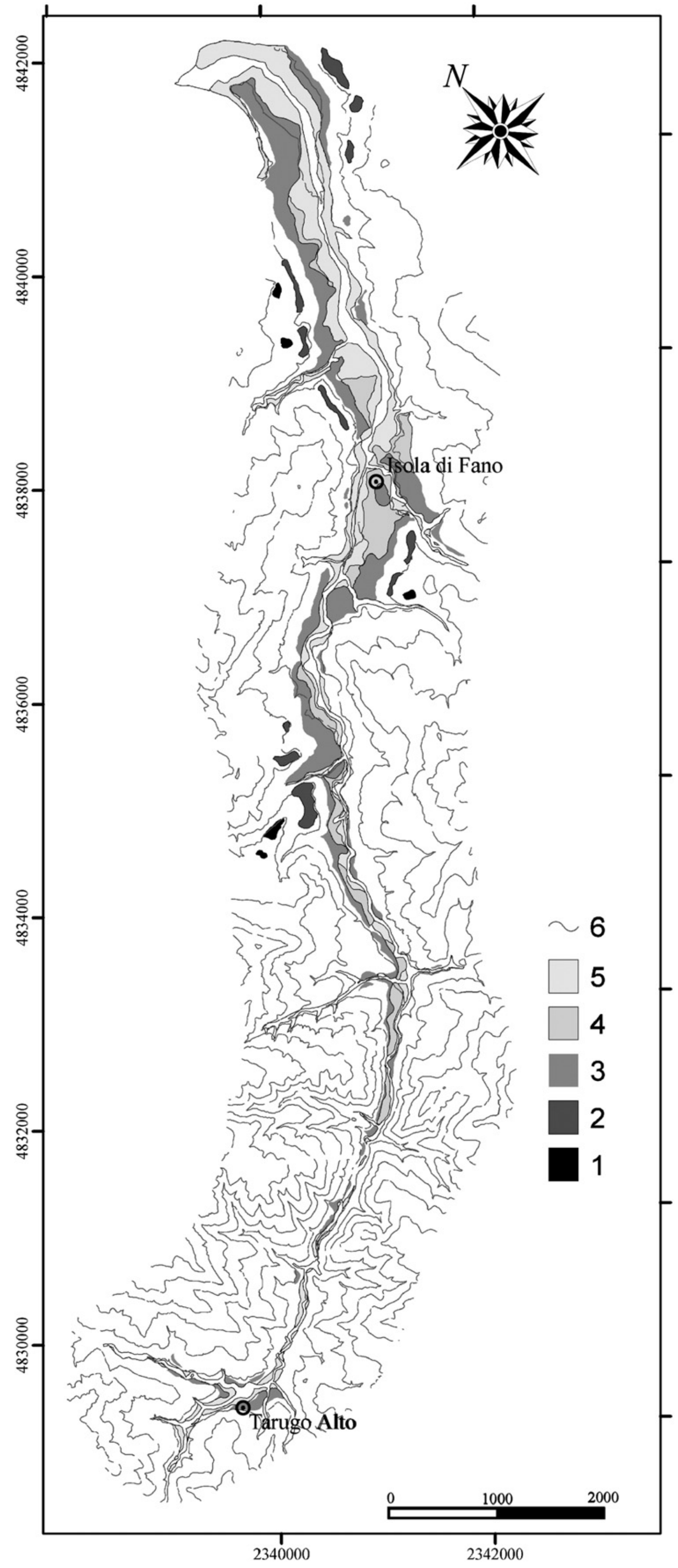

Fig. 4. Map of terrace alluvium deposits of the Tarugo River valley. Legend: 1) Middle Pleistocene fluvial terrace; 2) late Middle Pleistocene fluvial terrace; 3) Late Pleistocene fluvial terrace; 4) Late Pleistocene–Early Holocene fluvial terrace; 5) Holocene fluvial terrace; 6) contour lines (interval: 50 m).

while the flanks show slope angles approximating the downslope dip of the bedrock layers. Moreover, on the north-eastern foothills of Paganuccio Mt. a series of flatirons (Bartolini, 1992) are clearly evident, which coincide with the Bisciaro Formation outcrops (Fig. 3).

The Tarugo River transversely breaches the main folds and forms a gorge in the calcareous and marly-calcareous Paganuccio anticline, in the middle sector of the basin (Fig. 3). The flanks of this structure are often affected by large deep-seated landslides (Fig. 3) triggered by the dip-slope bedding of strata and by the occurrence of marly horizons within the carbonatic units. The occurrence of intense local rock fracturing is an effective additional factor (Burattini et al., 1989; Diligenti et al., 2005) and gravitational sagging and collapse of the anticline flanks can be identified in the field (Capaccioni et al., 2004). Generally, the landslide head areas display tension cracks and trenches, scarps and counter-slopes. The landslide bodies appear more disrupted and chaotic down slope (where thicknesses often reach more than 100 m) and are affected by deep gully dissection.

Both sides of the Tarugo River valley are characterized by fluvial terraces formed as response to aggradational and erosive phases associated to Quaternary climatic oscillations and regional uplift (Calderoni et al., 1991; Coltorti et al., 1991; Fanucci et al., 1996). The Tarugo fluvial terraces are arranged in at least four main levels recognized at different heights above the valley floor (Fig. 4). They are characterised by deposits having thicknesses from few metres up to 30 m and ages from the Middle Pleistocene to the Holocene (Nesci et al., 1995).

3. Methods

A quantitative geomorphic approach based on SL Index analysis was followed. The longitudinal profile and SL Index analyses were integrated with the geostatistical analysis of the spatial distribution of Amplitude of relief. Moreover, geomorphological and geological field data were collected in order to discriminate the lithological controls on the basin configuration from those probably introduced by neotectonics. Detailed SL Index and Amplitude of relief maps were generated, after having performed field surveys and photo aerial interpretation. Particularly, the aerial photo interpretation was performed using 1:12,000 (1974) and 1:33,000 (1955) aerial photos which allowed us to identify and map, well preserved, fluvial terraces, slope deposits and landslide bodies. Results of qualitative geological and geomorphological analysis are shown in the geological sketch of the area where both marine bedrocks and Quaternary continental covers are mapped (Fig. 2).

3.1. Longitudinal profiles

Deviations from a concave-up shape of stream longitudinal profiles may indicate a disequilibrium state of channels due to tectonic, climatic or rock-type perturbations (Mackin, 1948; Molin and Fubelli, 2005 and references therein). In particular, convex segments can be investigated to evaluate tectonic perturbation at different scales, from the whole chain to local structures (Seeber and Gornitz, 1983). The longitudinal profiles of the present thalweg of the Tarugo River and of the drainage divide were generated using 1:10,000 topographic maps (Fig. 5). Two topographic profiles of the late Middle Pleistocene and Late Pleistocene terrace treads were also made, by projecting their elevations along the present thalweg. Successively, the longitudinal profiles were compared to the general longitudinal trend of the ancient alluvial plains (Fig. 5).

3.2. SL Index analysis

The SL Index correlates to stream power (Hack, 1973). The total stream power available at a particular channel reach is an important hydraulic variable as it relates to the capability of a stream to transport sediments and to erode its bed. The SL Index is a practical tool for measuring perturbations along stream longitudinal profiles, since it is sensitive to changes in channel slope (Burbank and Anderson, 2001). It is known that a good relationship exists between rock resistance and SL Index. Furthermore, SL Index may be used to detect recent tectonic activity by identifying anomalously high index values on a specific rock type (Merritts and Vincent, 1989; Keller and Pinter, 1996; Brookfield, 1998; Chen et al., 2003; Zovoili et al., 2004).

The SL Index analysis was performed using 1:25,000 topographic maps and following Hack's (1973) method. The whole dataset was collected calculating the values along longitudinal profiles of the most stream network, for 100 m long reaches, from the divide towards the valley floor. The dataset obtained was georeferenced and processed

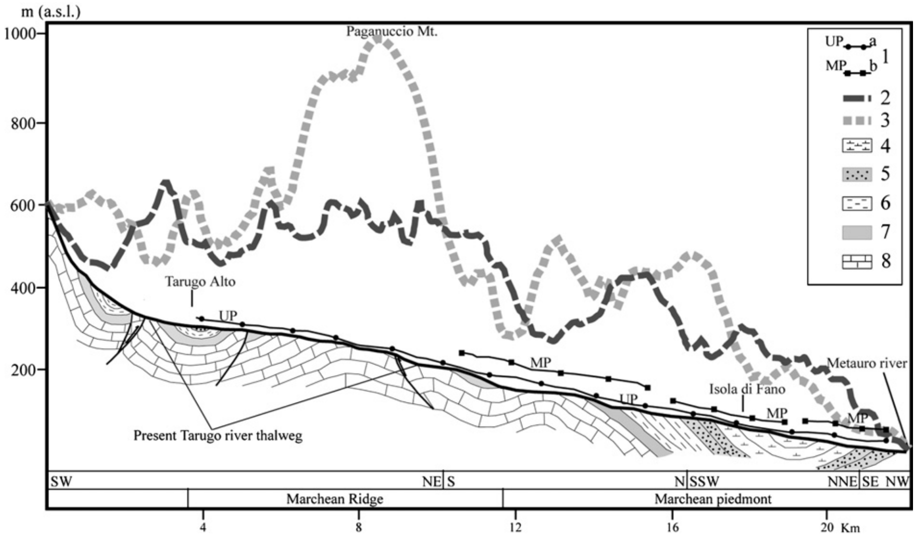

Fig. 5. Longitudinal profile of present Tarugo River thalweg, profiles of basin divide and reconstructed topographic profiles for the late Middle Pleistocene and Late Pleistocene alluvial plains. Legend: 1) Reconstructed topographic profile of the Late Pleistocene alluvial plain (a) and of the late Middle Pleistocene alluvial plain (b); 2) right-side (SE) basin divide; 3) left-side (NW) basin divide; 4) Gessoso–Solfifera and Colombacci Formations (Messinian); 5) Marnoso–Arenacea Formation (Tortonian); 6) Schlier Formation (Langhian); 7) Bisciaro Formation (Lower Miocene); 8) Scaglia Rossa–Scaglia Cinerea Formations (Upper Cretaceous–Oligocene).

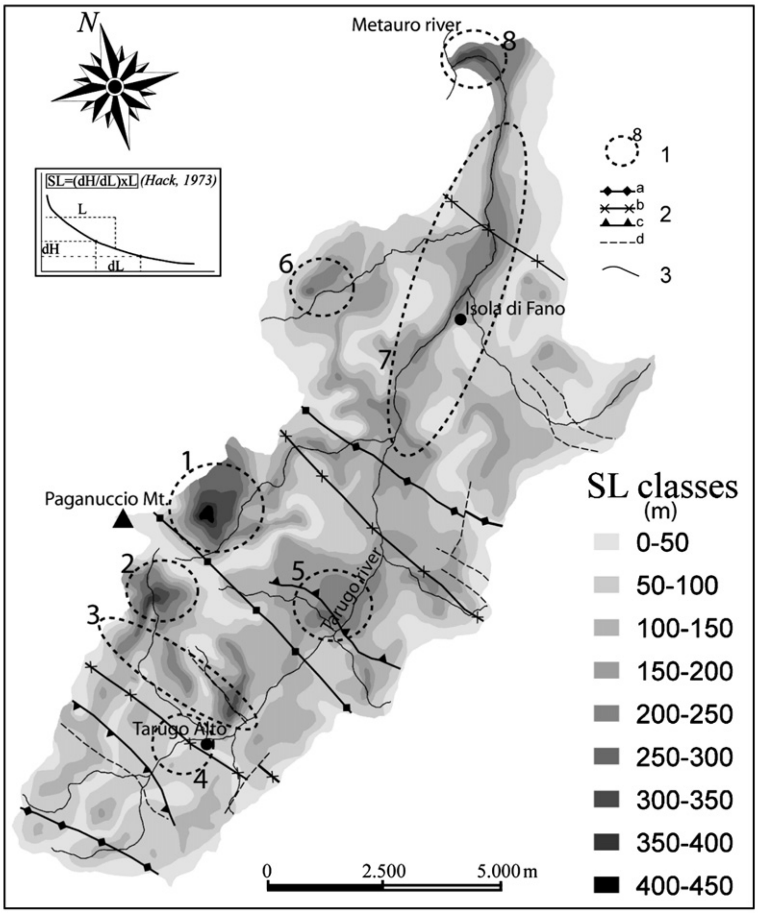

Fig. 6. Stream Length–Gradient Index map. 1) anomalies described in the text. 2) main geological structures: anticline axis (a), syncline axis (b), thrust fault (c), uncertain fault (d); 3) main streams.

with GIS software in order to obtain a contour map by using linear interpolation. Thus, a grey-scale contour map, with a resolution of 100 m, was produced to show the spatial distribution of the SL parameter (Fig. 6).

3.3. Amplitude of relief analysis

In order to integrate the above analyses, the orographic configuration of the study area was statistically analysed through the Amplitude of relief (A_r) parameter, which provides a measure of fluvial erosive action (Ahnert, 1970). It was already tested that, all conditions being equal, the spatial distribution of the A_r parameter can provide information about active or recent vertical displacements (Ciccacci et al., 1988; Ciotoli et al., 2003).

The maximum difference in elevation has been measured within unit areas of 0.0625 km^2 using 1:10,000 topographic maps. Following a geostatistical approach a grey-scale contour map of the amplitude of relief was obtained (Fig. 7a). In particular, the A_r values were associated with the coordinates of the mid point of each unit area, thus deriving a dataset grid with 250 m of lag. The Amplitude of relief map, with a grid resolution of 100 m, was obtained by applying the kriging method to the original dataset (Cressie, 1990). Since A_r values in the study area range between 0 and 180 m, they have been grouped in 18 classes with 10 m intervals. Moreover, a correlogram analysis was performed to identify possible anisotropies in the overall A_r distribution (Ciotoli et al., 2003) (Fig. 7b). Results of this analysis were expressed in a contour map showing the auto-covariance of the grid. Finally, specific contour maps were made, which show the distribution of three significant classes of A_r values (Fig. 8).

4. Results

4.1. Longitudinal profile analysis

The longitudinal profile of the present thalweg of the Tarugo River has an irregular, generally concave-up, shape. Minor convexities may be observed with two main wavelengths (Fig. 5). The wider convexity, showing a wavelength of about 9 km, marks the profile between 4 and 11 km away from the divide. This area corresponds to the Paganuccio anticline. Short wavelength (1–2.5 km) convexities are superimposed on the wider one and also characterize the Tarugo River longitudinal profile between 11 and 17 km away from the divide. In this zone the river flows on Holocene alluvial deposits, but locally cuts bedrock. Some short wavelength convexities locally affect the longitudinal profile of the river where either a significant lithological change or a minor structure occurs. A steep profile, interrupted by a knickpoint, about 2 km away from the divide, characterizes the head sector of the Tarugo River. This knickpoint coincides well with the boundary between marly-calcareous rocks of the Bisciaro Formation and marls of the Schlier Formation (Fig. 5). Another knickpoint occurs coinciding well with a thrust fault tip, at the forelimb of the Paganuccio anticline (Fig. 5).

The topographic profile of the Late Pleistocene fluvial terrace shows the ancient shape of the alluvial plain from Tarugo Alto town to the Tarugo–Metauro confluence area (Fig. 5). Some short wavelength convex-up portions characterize the profile. The main one was detected 12 km from the divide in correspondence with a Late Pleistocene re-incised alluvial fan, coeval to the alluvial plain deposits (Fig. 2). At the forelimb of the Paganuccio anticline, about 9 km away

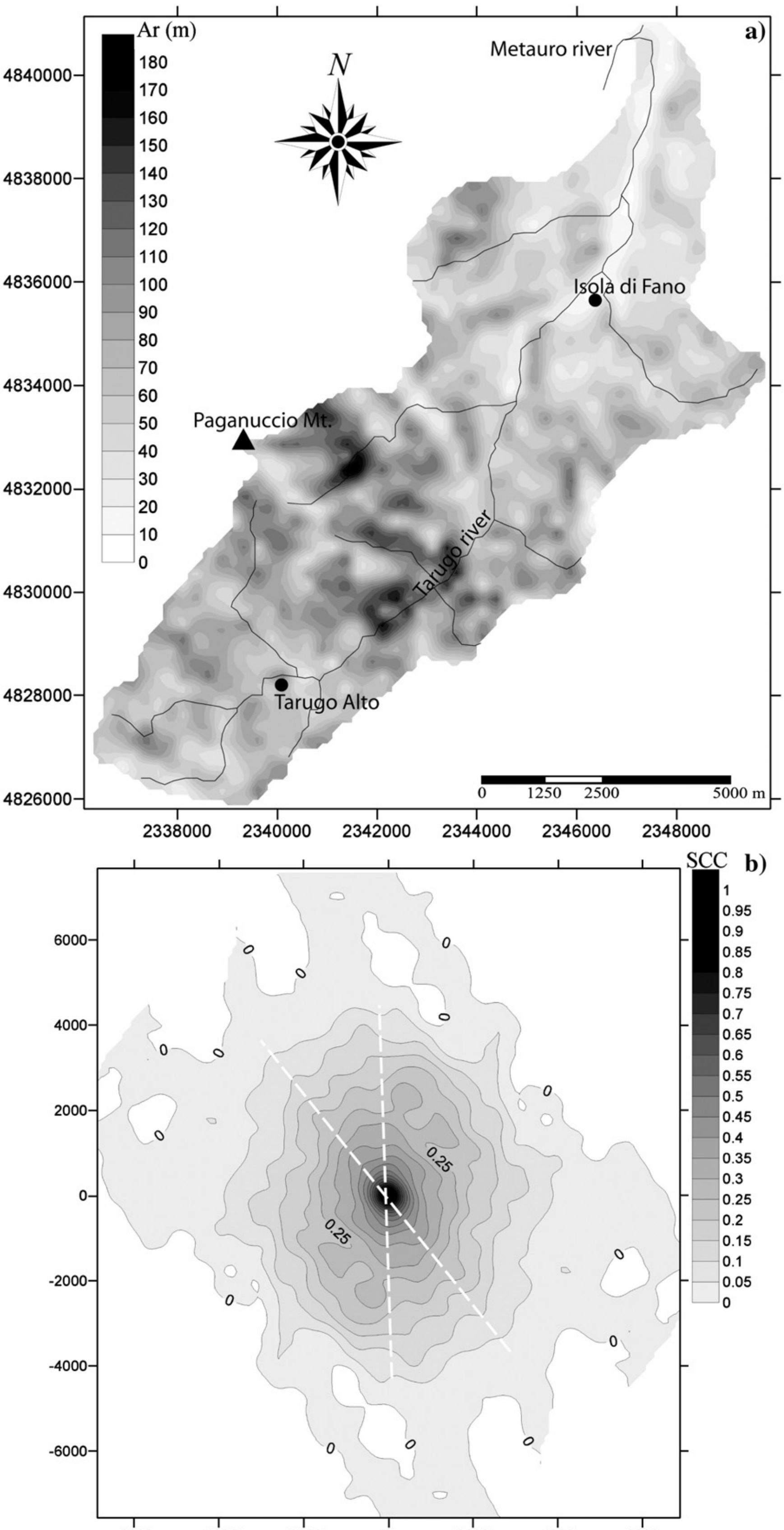

Fig. 7. Amplitude of relief geostatistical analysis. a) Amplitude of relief (A_r) contour map obtained by gridding the original dataset of A_r values with the kriging method; b) Amplitude of relief (A_r) correlogram map (please see the text for explanation), with the color scale showing the *spatial correlation coefficient* (SCC) values.

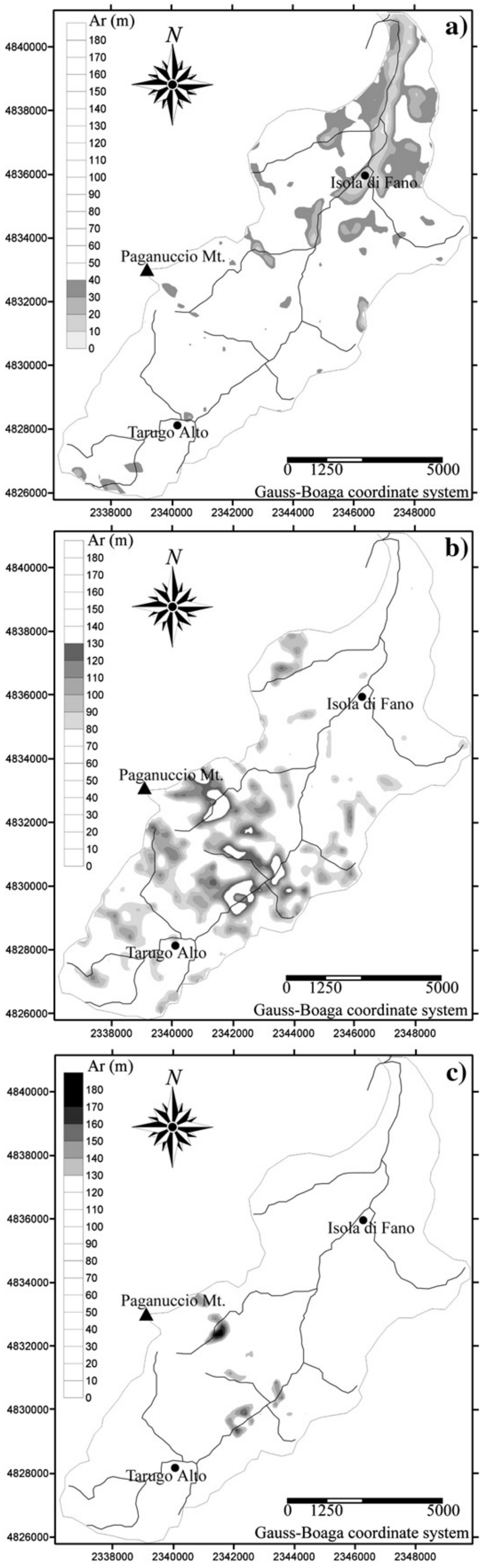

Fig. 8. Amplitude of relief geostatistical analysis. Amplitude of relief (A_r) contour maps showing the distribution of A_r intervals from 0 to 40 m (a), from 80 to 130 m (b) and from 130 to 180 m (c).

from the divide, a small step characterizes the Late Pleistocene terrace profile. Close to the Tarugo–Metauro confluence the terrace profile displays a knickpoint and a general divergent trend from the present Tarugo River longitudinal profile.

The profile for the late Middle Pleistocene fluvial terrace starts 10 km from the present divide (Fig. 5). It shows a very irregular geometry, mainly characterized by an apparent step about 15 km away from the divide. This step is defined by the lower elevation of this terrace level close to the Isola di Fano town, where less resistant rocks crop out. A secondary cut-and-fill phase during the late Middle Pleistocene, along with a main incision phase, could explain this specific profile geometry, as already detected for the lowest terrace levels of the main Adriatic valleys within the Marche region (Fanucci et al., 1996). Down to the confluence, the profile generally follows the trend of the Late Pleistocene one, diverging from the present thalweg.

4.2. SL Index analysis

In the study area, the SL Index values range between 10 and 440 m. In the SL Index map (Fig. 6) the values are grouped in 9 classes with an interval of 50 m. Two classes of values (50–100 and 100–150) widely occur within the Tarugo River basin. Nonetheless, several zones show SL values that trend away from these two classes, reaching positive anomalies with the highest values up to 440 m.

In detail, the highest values (anomalies 1 and 2 in Fig. 6) are located along both flanks of the Paganuccio anticline, where the SL Index reaches the maximum value of 440 m in correspondence with a deep-seated landslide affecting its north-eastern slope (Fig. 2). Anomalous high values are also recorded along the middle sector of Tarugo river at the Paganuccio anticline. In particular, a value of approximately 350 m is reached on the forelimb of the anticline (anomaly 5 in Fig. 6) coinciding with the occurrence of a NW–SE trending thrust. Close to Tarugo Alto town, in correspondence with a syncline axis (anomaly 4 in Fig. 6) where the marly and marly-arenaceous beds of the Marnoso–Arenacea Formation crop out, the SL Index reaches the lowest value, about 10 m. Immediately downstream, the SL Index values increase to approximately 300 m (anomaly 3 in Fig. 6) in correspondence with a NW–SE trending fault and landsliding (Fig. 2). To the south of Isola di Fano town high anomalies can be found with a general NW–SE trend, coinciding with local outcrops of the Bisciaro Formation. A few of kilometres to the west of Isola di Fano town a value of about 280 m occurs (anomaly 6 in Fig. 6) coinciding with a local outcrop of marly-calcareous rocks of the Bisciaro Formation (Fig. 2). In the area between Isola di Fano town and the Metauro–Tarugo Rivers confluence (anomaly 7 in Fig. 6) anomalously high values on the valley floor form a narrow belt with a SSW–NNE general trend, which approximately follows the Tarugo River thalweg. Finally, at the Tarugo–Metauro confluence a value of about 350 m occurs (anomaly 8 in Fig. 6).

4.3. Amplitude of relief analysis

The spatial distribution of the A_r parameter generally shows the highest values in correspondence with the flanks of the main NW–SE trending folded structure and the lowest ones located at valley floors as well as at both syncline axes and flat tops of anticlines (Fig. 7a). The correlogram map of Fig. 7b evidences a major NW–SE oriented anisotropy direction in the distribution of A_r values, corresponding well with the regional trend of the fold axes. A minor N–S oriented anisotropy is also recorded in the correlogram map, coinciding with the strike of some active extensional faults already recognized in the middle and lower sectors of the Metauro River basin (Savelli et al., 2001). However, evidence for such faults within the Tarugo River basin has not been quoted yet in the literature.

In detail, A_r values ranging from 0 up to 40 m (Fig. 8a) concentrate mainly close to the confluence between Tarugo and Metauro Rivers, following the N–S direction of the lowest Tarugo reach. In this sector of the basin soft rocks crop out (Messinian marine deposits and fluvial terraces). Some minor areas showing low A_r values correspond to structural sub-horizontal surfaces located also in the uphill portion of the basin (the tops of anticlines) (see also Fig. 5) and to the axial zone of synclines where softer rocks crop out. Values between 80 and 130 m (Fig. 8b) are recorded in the upper and middle sectors of the basin, and particularly on the flanks of the Paganuccio anticline, with a NW–SE trend. Far from this structure, slightly lower values (up to 120 m) fit with the outcrops of the Bisciaro Formation. Finally, in Fig. 8c the highest A_r values (130–180 m) can be observed on the upper slopes of the Paganuccio anticline and in correspondence with a straight gorge in the middle sector of the Tarugo River (see also Fig. 3).

5. Discussion

The comparison between results of the analyses performed has led to some interesting considerations. High values of the A_r parameter fit well with some of the highest SL Index values. This fact occurs at the Paganuccio anticline. In more detail, in this zone with relatively high values of both SL Index and A_r, the Tarugo River longitudinal profile shows a convexity with a wavelength of about 9 km. This convexity fits quite well with the wavelength of the topography of the folded structure (Fig. 5). This convexity also fits with the theoretical bulge (showing the same amplitude) delineated by the distribution of both SL Index and A_r values, affecting most of the middle sector of the Tarugo basin (Figs. 6, 7a). Nevertheless, positive anomalies of SL Index show peak values coinciding with short wavelength convexities localized along the present Tarugo River thalweg. Since SL Index peak values, coinciding with short wavelength convexities of longitudinal profile of the present Tarugo River, occur either at significant lithological changes or at fault outcrops we infer that SL Index can help to discriminate the tectonic effects on morphology from the lithologic ones only if these two factors act with different wavelengths (i.e. a topographic convexity at a fold structure and a knickpoint at a significant lithological boundary).

In the study area we recognised a sector where the integration of different morphometric analyses helped significantly to distinguish the tectonic influence on morphogenesis from the lithologic one, even if the morphometric anomalies are limited to a small area. The forelimb of the Paganuccio anticline corresponds to this sector. At this structure the SL Index records a peak value (see anomaly 5 in Fig. 6), and the Ar records relatively high values (Fig. 7a). Moreover, in correspondence with this structure a knickpoint affects the present Tarugo River longitudinal profile and a small step also occurs along the reconstructed profile of the Late Pleistocene fluvial terrace (Fig. 5). In this case, the concomitance of morphological and morphometric evidence allows us to distinguish a sector in the Tarugo River basin affected by active tectonic deformation. On the other hand, the dataset at our disposal do not allow us to single out which active structure promoted the observed morphological anomalies. Although a thrust fault affects this portion of the river basin, the neotectonic activity of the thrust-fold system in this sector of the north Marchean Apennines is still the object of a meaningful debate (Di Bucci et al., 2003 and references therein). In accord with Savelli et al. (2001), we infer that the roughly N–S oriented normal fault system, already recognized within the middle and lower reaches of the Metauro River basin, might be responsible for the morphometric perturbation recognized in this area, rather than neotectonic activity of the thrust-fold system. In addiction, this hypothesis could be supported by the minor N–S oriented anisotropy recorded in the A_r correlogram map shown on Fig. 7b.

Where deep-seated landslides occur, high values of SL Index with a relatively wide extent can be found; this occurs at both flanks of the Paganuccio anticline. Some high SL Index values correspond however to some of the lowest A_r values, especially at valley floors (see anomaly 7 in Fig. 6). These high SL Index values are likely to reflect the present day stream incision trend within the Tarugo River basin. This trend to incision could be related to the adjustment of the local Tarugo River base level (i.e. the Metauro River) in response to the regional uplift at the increased rates that have occurred since the Early Pleistocene. The A_r parameter is not able to detect this trend because the very long wavelength of the regional uplift does not generate sufficient local relief in the Quaternary alluvial deposits, with respect to those generated by the emplacement of individual compressional structures.

Finally, the distribution of the lowest SL Index values follows the location of divides or corresponds with the occurrence of wide structural sub-horizontal surfaces (tops of anticlines). In the latter case they coincide with minimum values of the A_r parameter.

6. Conclusions

This work has focused on the use of the SL Index as a tool to investigate the orographic configuration of small catchments. The study area is part of the north Marchean Apennines and coincides with the Tarugo River basin, where only a few and uncertain data concerning neotectonic activity are available (Di Bucci et al., 2003 and references therein; Mayer et al., 2003] and references therein). Therefore, we focused our efforts on the use of morphometric analysis to distinguish the effects of neotectonics on the morphology from those of lithology.

Longitudinal profile and SL Index analyses were coupled with the spatial analysis of the Amplitude of relief (A_r) parameter. Above all, from the methodological point of view, the results obtained provided some interesting suggestions:

a) the comparison between SL Index and A_r values in small river catchments allowed us to distinguish the topographic anomalies caused by relatively long wavelength tectonic features from those related to local disturbances. Nonetheless, among local disturbances, in many cases, it is difficult to discriminate the effects of lithology from those caused by neotectonic activity. On the other hand, in some cases, the integration of morphometric data could be a helpful methodology to recognize neotectonic-related small wavelength perturbations.
b) the SL Index seems to be a valid tool to detect local uplift as well as the incipient local response to regional processes (i.e. regional uplift) that is often undetectable by other morphotectonic parameters, such as the Amplitude of relief;
c) in areas where a good correlation is recognizable between extreme SL Index and A_r values, the presence of large deep-seated landslides was observed. These landslides could have been triggered by the same litho-structural and topographic conditions determining the strong high values of both the parameters.

Acknowledgements

Authors thank D. Savelli, O. Nesci and P. Fredi for their precious comments and constructive revision of the manuscript, and M. Tramontana for needful advise about structural geology. Authors also appreciated the helpful suggestions by P.G. Silva, A.M. Harvey and an anonymous reviewer.

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