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The implications of disconnectivity for the study of contemporary geomorphic processes

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ABSTRACT

The emphasis on the understanding of contemporary geomorphic processes that has dominated Anglophone geomorphological literature over the past 50 years has seen huge progress but also some set-backs. We now have reliable measurements of mean rates of operation of all subaerial processes responsible for modification of landforms and landscapes and have made good progress in estimating the role of human activities as compared with “natural” processes. Some limited progress has been achieved in understanding the scale problem but problems remain. Perhaps the single most surprising development has been the recognition of the ubiquity of disconnectivity in geomorphic systems, the need to calculate virtual velocities of whole geomorphic systems and the relevance of this understanding to the general spatio-temporal scale problem. We have always known that most geomorphic processes operate intermittently but we have continued to depend on models that imply that mass and energy move freely through geomorphic systems and that conservation of mass and energy occurs uninterrupted at all temporal and spatial scales.

KEYWORDS

Disconnectivity; connectivity; coupling; contemporary geomorphic processes

1. Introduction

During the period 1960-1990 measurement and description of contemporary geomorphological processes on synoptic to seasonal scales and the construction of first-order theories to generalize the phenomena were the dominant geomorphological

studies (Schumm and Lichty, 1965; Church, 2010). This history is to a significant degree summarized in the pages of “Progress in Physical Geography” on subjects such as weathering; slope processes; soil erosion; river hydraulics, river morphology; karst;

coastal and beach processes; wind effects and glaciation. Since 1990 dramatic changes have occurred. These changes were summarized by Church (2010) as (a) improved technologies for remote sensing and surveying of Earth's surface; (b) recognition that geomorphology is a "system science"; (c) the reintegration of tectonics into geomorphology; (d) development of absolute dating techniques; and (e) increasing recognition of the dominance of contemporary human modification of Earth's surface. Slaymaker (2009) focussed on the future needs of geomorphology: (a) the emergence of a broader philosophical basis; (b) clearer definition of the objects of geomorphological study; and (c) an integration of geomorphological geohistory and process geomorphology. Slaymaker's discussion looks forward to a future geomorphology whereas Church's presentation is a real world perspective on the present trajectory of the field. But both approaches converge in predicting the necessity for geomorphologists to recognize that the

Anthropocene epoch requires new skills and intellectual perspectives.

Relief, climate, sea level and human activities have been identified as primary drivers of global terrestrial processes over longer time scales (Slaymaker *et al.*, 2009); but over centennial time scales relief and sea level can for most purposes be regarded as constant, and climate and human activities become the global drivers of change. Hence the contemporary emphasis on global hydroclimate change which should be tempered with an equal emphasis on the growing societal impact on land.

When attention turns to regional and local scale changes over contemporary time scales the assignment of drivers is more complex and is sometimes impossible. The spatiotemporal scale problem and associated problems of coupling, connectivity, disconnectivity and complexity have become prominent. This recent discussion in so far as it affects mountain environments has been summarized (Slaymaker and Embleton-Hamann, 2009).

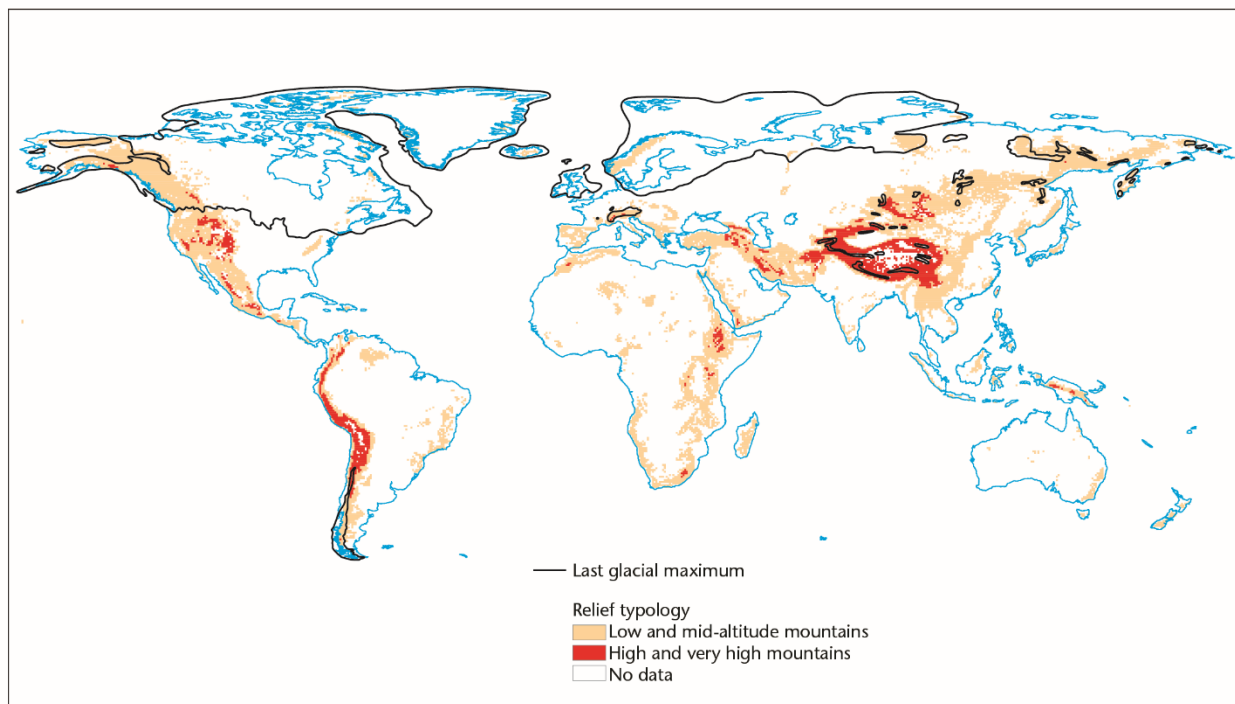


Figure 1 Map showing the global distribution of mountains (after Church and Slaymaker, 2016), with the extent of Late Pleistocene glaciation overprinted

2. Mountains and the high energy condition

High mountains, in view of their steepness and severe weather, are commonly reckoned to experience the highest rates of sediment mobilization on Earth. Glacier and or ice sheet cover in the past or at present complicates the relationship (Fig. 1).

It is an interesting question however to ask what becomes of sediment mobilized on steep mountain slopes. Much of it goes back into storage in slope base colluvium and alluvial fans, notable features of all the world's mountain ranges. The reasoning underlying this belief is that these regions are subject to the largest potential energy gradients on Earth's terrestrial surface. In fact, the sediment yield of mountainous areas is remarkably variable, stemming from the variation of geology, history, physiography and climate. Today, an increasingly important element of mountain history is the

growing dominance of human settlement in mountain landscapes, especially in Asia, Africa, South America and Europe. These populations are not only exposed to the hazards presented by sediment fluxes in the mountains, but their manipulations of the land surface affect the condition and tempo of the fluxes down valley.

The high energy condition has long been associated with the highest rates of energy expenditure and continuity of mass and energy flows has been assumed (Caine, 1974). It was unquestioned that the highest mountains were the sites of the greatest geomorphic work as illustrated, for example, in Fig. 2. That figure relies on a simplistic model from Summerfield and Hulton (1994) in which

$$\text{Denudation Rate} = 7.21 \times e^{0.0015 \times \text{elevation}}$$

where *Denudation rate* is expressed in $\text{m} \times \text{Ma}^{-1}$ and *elevation* is in meters.

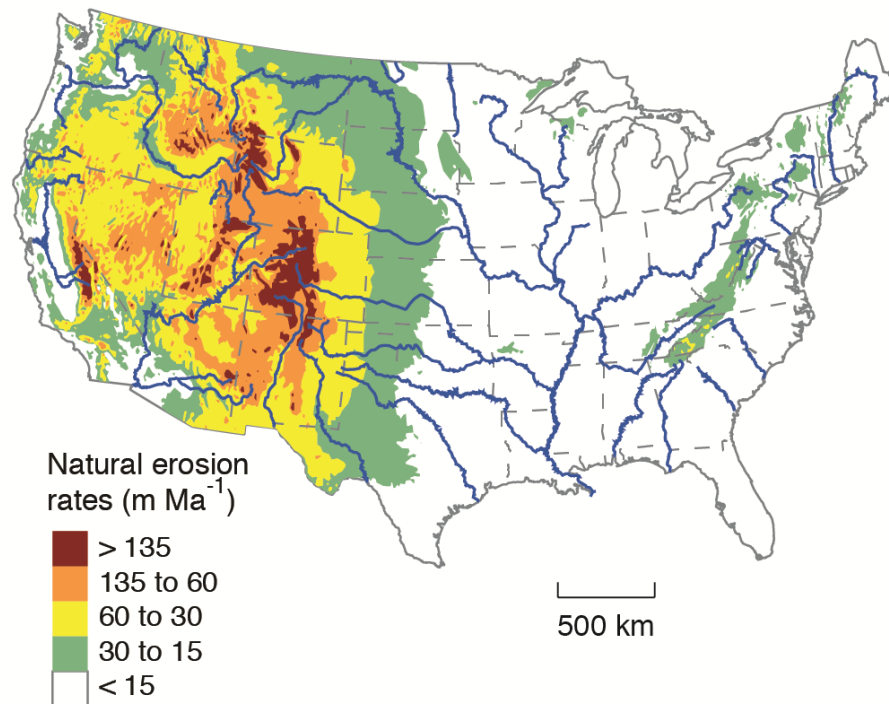


Figure 2 Estimates of average natural erosion rates inferred from GTOPO30 area-elevation data and global fluvial erosion-elevation relations from Summerfield and Hulton (1994) (from Wilkinson and McElroy, 2007). Units are in metres of denudation per million years

The implication of this model is that net annual erosion for large drainage basins ($>500,000 \text{ km}^2$) increases by 0.15% for every meter increase in maximum elevation. In other words, Fig. 2 is basically a hypsometric map.

Recent empirical data suggest that decoupling is more common than coupling even in the highest mountains. There are self-evident discontinuities in sediment production, transport and deposition (Fort *et al.*, 2009; Hewitt, 2009; Hewitt *et al.*, 2011). Geochemical surface lowering processes are distributed throughout the mountains but extreme landslides, for example, are highly localized (Korup *et al.*, 2007; Waller *et al.*, 2012; Slaymaker *et al.*, 2017). We now commonly ask the question “Where in the mountain landscape does the greatest amount of denudation occur?” rather than assuming that the highest and steepest slopes provide the answer.

The special emphasis on high mountain geomorphology (Holtmeier, 2015) was that the high mountain zone was unique, in part because of its high energy environment. Increasingly, evidence shows that work in the landscape is maximized in moderate relief mountains (Slaymaker, 2013), in some cases even in low relief regions (Kirchner and Ferrier, 2013; Willenbring *et al.*, 2013).

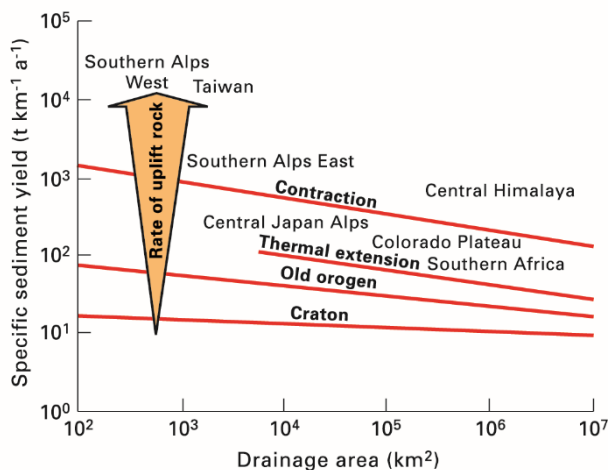


Figure 3 Specific sediment yield versus drainage area by tectonic setting (from Hovius, 1998)

Of great interest is the relation between tectonics and sediment yield as calculated by Hovius

(1998; Fig. 3). He insisted that sediment yield equations should always factor in the role of tectonic activity. Scaled for drainage basin area, sediment yields increase through almost five orders of magnitude from tectonic cratons to contractional mountains. He noted that tectonically active mountain belts not only provide relief to drive erosion processes but also combine high regolith loss with rapid uplift of new bedrock into the weathering zone to continually refresh the erosion processes and maintain high sediment yield (Korup *et al.*, 2014).

3. Sediment cascades

The study of sediment cascades from source to sink has become a central theme in mountain process geomorphology over the past three decades (Dietrich *et al.*, 1982). A major statement on the importance of sediment routing systems from source to sink is found in Allen (2008). When thinking about coupling and decoupling of slopes and channels the identification of preferred pathways for sediment fluxes is essential (Embleton-Hamann and Slaymaker, 2006) and the use of sediment budgets is recommended. But the comparative advantage of using such a model is frequently ignored by the exclusion of one or more components of the sediment-solutes-nutrients continuum. Sediment budgets incorporating sediment, dissolved solids and nutrient fluxes are scarce, but Filippelli *et al.* (2010) is an instructive example. Magnitude-frequency considerations in sediment budgets for arctic and sub-arctic catchments are also incorporated in Beylich and Kneisel (2009).

Chemical components of sediment budgets operate on different time scales from the clastics. One way of avoiding the problem of partial sediment budgets is to choose geomorphic locations in which clastic sediments dominate over all other mass fluxes. Examples such as sediment flux on a reach by reach assessment used to establish big picture sediment flux (Hassan *et al.*, 2011); and studies of rivers in which sediment flux is dominantly clastic (Yellow River, Miao, 2010) and upland gravel bed rivers (Raven *et al.*, 2010).

Schiefer *et al.* (2010) provided a rare example of total sediment flux accounting. Holocene and contemporary sediment budgets for a 324 km² cordilleran catchment have been estimated with the aid of seismic records, dated cores and sections in lake and alluvial fill sediments at Chilliwack Lake in the North Cascade Mountains, British Columbia (Tunncliffe *et al.*, 2012a; 2012b).

Use of the concept of process domains is popular in North America to demonstrate the connection between morphology and process. Examples of process domain influence on river long profiles and channel reach morphology (Brardinoni and Hassan, 2007) and the organization of process domains as part of the legacy of glaciation in Puget Sound (Collins and Montgomery, 2011) demonstrate the flexibility of this approach.

4. Coupling

Coupling in general is the extent to which surface and subsurface channels and slopes are physically connected (Harvey, 2002). More specifically, coupling considers the variety of ways in which water, sediment and dissolved solids move through a system or are obstructed from moving between source areas and the river system. Where hillslopes and river channels are tightly coupled there is a continuous or semi-continuous flow of water, sediment and dissolved solids from slopes to channels. Water and dissolved solids commonly follow preferred pathways from headwaters to the outlet of a river basin whereas clastic sediments accumulate at preferred locations in the basin, such as breaks of slope or lake basins. The rate at which morphological changes propagate through the system (or virtual velocity) depends directly on the degree of coupling. Tight coupling implies relatively rapid change; decoupling implies slow change. This coupling model is consistent with the sediment cascade model by which the rate and nature of movement of sediments from source to sink and the associated rates of denudation of the mountain landscape can be estimated by determining all components of a sediment budget.

Degrees of coupling are recognized in the literature as, for example, discontinuities in mountain streams (Lu and Richards, 2008). Geomorphic coupling between hillslopes and channels has been documented in the Swiss Alps (Savi *et al.*, 2013) and coupling of landslides and rivers has been identified in the Carpathian and Sudete Mountains (Malgorzata *et al.*, 2015).

The various morphological elements in the glacierized Lillooet-Harrison River basin (7,870 km²) in the Pacific Ranges of the Coast Mountains of British Columbia, have been mapped according to the extent of their coupling to the mainstream river (Slaymaker *et al.*, 2017). Three examples focus on ridge tops, hillslopes subject to infrequent large mass movements and debris avalanches:

(a) Ridge tops and accordant summits with low local relief are coupled to the valley primarily through water and dissolved solids moving along sub-surface pathways. Clastic sediments are commonly decoupled on ridge tops.

(b) Hillslopes subject to infrequent large mass movements are episodically coupled

(c) Debris avalanches and debris flow channels directly couple hillslopes with valley bottom (Fig. 4).

The temporal episodic coupling and the spatial decoupling of individual processes guarantees an overall complex response to disturbance. Jefferson *et al.* (2010), working on the western slopes of the Cascade Range in Oregon, USA, have partitioned hydrologic flowpaths between surface and sub-surface flow. They have proposed that landscape evolution in basalt terrains is entirely constrained by the coupling and decoupling of surface and sub-surface flow (Jefferson *et al.*, 2010)

Young basalt terrains are highly permeable, allowing one to examine timescales and processes of geomorphic evolution via surface and sub-surface flow. On Holocene and late Pleistocene lava landscapes, groundwater systems transmit most of the recharge to large springs with very steady hydrographs. In watersheds >1 million years old, springs are absent, and well-developed drainage networks fed by shallow subsurface stormflow produce flashy hydrographs.



Figure 4 The 2010 Capricorn debris avalanche in the Mount Meager Volcanic Complex, Pacific Ranges, Coast Mountains, British Columbia (oblique photograph taken on August 29, 2010 by John Clague)

5. Connectivity and disconnectivity

One important recent development in understanding of mountain geomorphology is the idea of connectivity, a concept that has been explored by Fryirs and Brierley (2009; 2013). Connectivity formed the central focus of the 2016 Binghamton Symposium (Wohl and Beckman, 2014). This idea clearly grows out of the idea of coupling, but it gives greater emphasis to the fact that most geomorphic systems, even mountain systems, are characterized more by decoupling than by coupling. The reason, self-evidently, is the lack of connectivity between the various components of the sediment cascade (Tunncliffe and Church, 2011). Sediment yield in fluvially dominated mountains is systematically scaled in the landscape; that is to say there is a well defined relationship between drainage basin area and specific sediment yield.

By contrast, in glaciated mountains, tectonically active mountains and mountains heavily perturbed by human activity the well-defined relationship between basin area and specific sediment yield ceases to hold because of different perturbations of sediment storage areas that produces multiple scaling (Church and Slaymaker, 2016). Not only is there a spatial discontinuity problem, but temporal discontinuity is equally important.

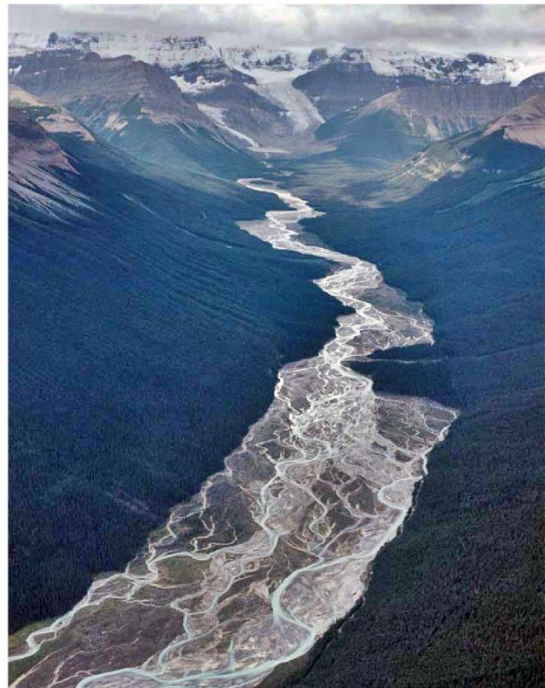


Figure 5 Connectivity from Mt. Alexandra, through Alexandra Glacier to the braided channel of the Alexandra River, Banff National Park, Alberta (Photo by Robert Sandford)

6. Disconnectivity in independent process systems

Each process system whether glacial, fluvial, glacial lake outburst flood or mass movement has its own internal disconnectivity issues as follows:

6.1 Glaciers and Glacial lake outburst floods (GLOFS)

The Mt. Alexandra-Alexandra Glacier-Alexandra River connectivity is exceptionally unbroken (Fig. 5).

More commonly, the connectivity between glacial sediment production and downstream sediment fluxes is significantly reduced by the development of proglacial lakes and intermittent tributary debris flows.

Suspended and solute sediment fluxes from the proglacial zone of the retreating Obersulzbachkees glacier, Hohe Tauern, Austria are strongly controlled by the presence of proglacial lakes (Geilhausen *et al.*, 2013). Three glacier basins in Norway have been shown to have totally different sediment budgets because overdeepened bedrock basins define the locations of proglacial lakes. Despite an expected increase in sediment yield from the glacier, little sediment will pass these lakes and downstream sediment delivery will be reduced markedly (Bogen *et al.*, 2015).

Sandurs provide disconnectivity in space; the periodic nature of jokulhlaups produces disconnectivity over time. Jokulhlaups figure prominently in proglacial landscape change at Sólheimajökull in southern Iceland from 1960 to 2010. Changes in glacial meltwater runoff regimes, glacier terminus position, sediment supply and episodic events such as jokulhlaups are implicated.

Heckmann *et al.* (2016) have provided a valuable overview of the state of understanding of GLOFS.

6.2 Mountain rivers

Kasprzak and Migon (2015) commented on the importance of fluvial erosion by comparison with mass movement in the Sudetes Mountains in Poland. In providing an overview of morphodynamics of steep-mountain channels (Brardinoni *et al.*, 2015), the complexity of the behaviours of coarse and fine sediment plus large organic debris in steep mountain channels is illustrated from research in Canada, Austria and Italy. In the tectonically active Chugach Mountains in Alaska the rates of hillslope erosion are an order of magnitude below the rate of glacial sediment export because the very high landslide rates are periodic and localized and the very high glacifluvial sediment flux is continuous over time (Uhlmann *et al.*, 2013). There is surprisingly little progress in incorporating the role of weathering in regional calculations of denudation in steep watersheds in spite of the recommendations by Church *et al.* (2006) for increased attention to this topic.

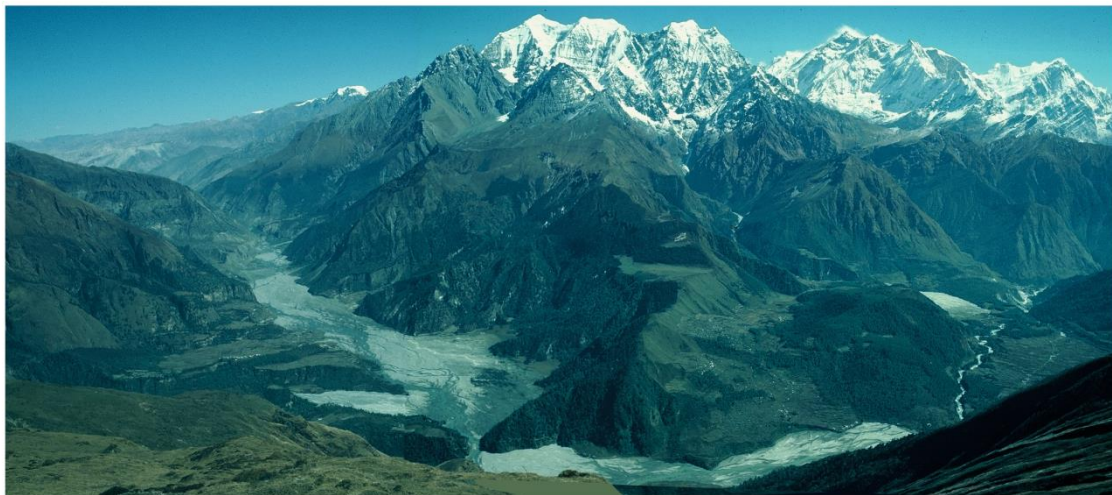


Figure 6 Disconnectivity created by the large, prehistoric Dhumpu-Kalopani rock avalanche in the Nepal Himalayas (photo by Monique Fort) (after Fort *et al.*, 2010)

6.3 Mass movement

The intermittency of mass movement processes has generated the need to improvise specific new

techniques of field analysis. For example, a multi-temporal record of erosion (1963–2005) of a rock slope in the Swiss Alps identified slope failures that affect 70% of the study slope and produced an

inventory of ~2500 failures ranging over 6 orders of magnitude in volume. Rockslides and rockfalls of high magnitude and relatively low frequency make up 99% of the total failure volume from highly fractured and weathered quartzites and are thus responsible for the high erosion rate (Scapozza *et al.*, 2014).

Mass movement processes are all intermittent with the possible exception of soil and rock creep. Therefore it is not surprising that disconnectivity within mountain regions is the norm. Work in the Karakoram Himalayan region of Pakistan has produced some of the finest examples of disturbance regimes in which massive mass movements have generated disconnectivity over periods from centuries to millennia (Hewitt, 2009; Fort *et al.*, 2010; Hewitt *et al.*, 2011; Hewitt, 2014) (Fig. 6).

6.4 Drainage systems

Catastrophic rock failures are also discussed by Hewitt *et al.* (2008). Their distinctive morphology is commonly a legacy of past catastrophic events, consisting of partial obstructions by landslide barriers that “create a chronically fragmented drainage system” (Hewitt, 2006).

Mountain geomorphic processes can be envisaged as a cascade of disturbance processes that alter stream and riparian geosystems (Fig. 7). The affected stream and riparian landscape can be viewed through time as a network containing a shifting mosaic of disturbed patches. Linear zones of disturbance are created by the cascading geomorphic processes.

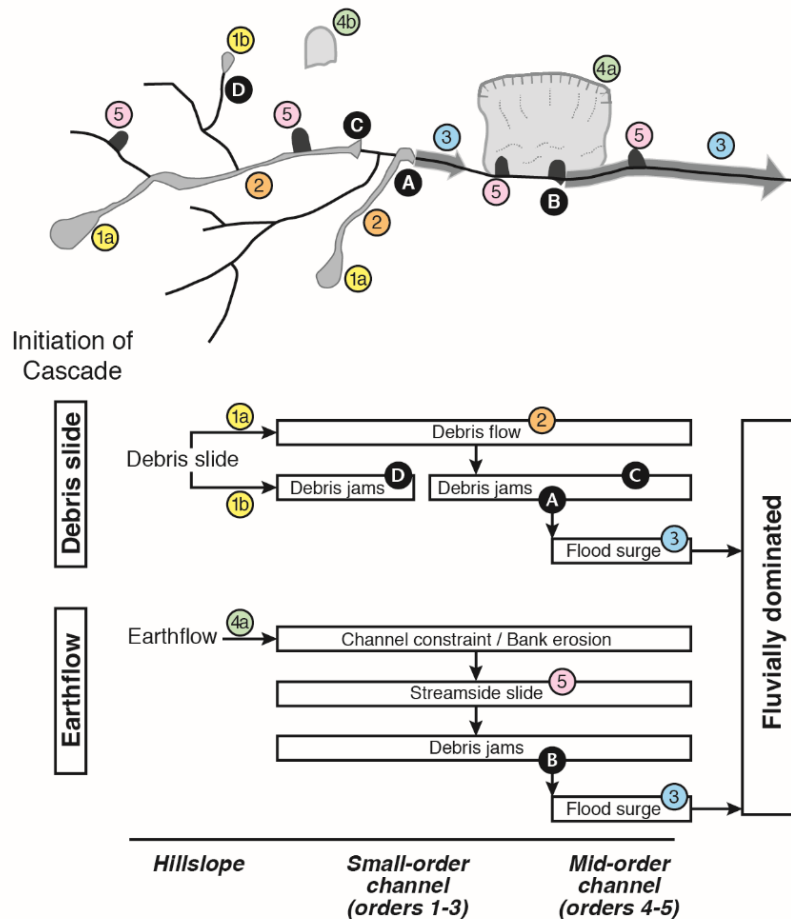


Figure 7 Disconnectivity within disturbance cascades: interaction among processes drainage system-wide (after Nakamura *et al.*, 2000). Log and debris dams at sites A, B, C and D promote system resilience

Ecological disturbances range in severity from effects of debris flows, which completely remove colluvium along steep, narrow low order channels to localized patches of trees toppled by floating logs along the margins of larger channels. Because disturbances by human activities have become so much more common land use changes can affect the frequency and spatial pattern of events and the quantity and size distribution of material removed (Slaymaker and Kovanen, 2017). However a well-developed network of stream and riparian systems may lend resilience in the face of major disturbances by providing widely distributed storage areas (Fig. 7).

The above two examples of watershed disturbance are end points of a spectrum that ranges from small, low order streams, typical of North America's forested mountains, to the huge rock avalanches of central Asia. Each is characterized by major disconnectivities that lend resilience to the landscape.

7. Conclusion

Recent research on mountain geomorphic systems has emphasized the importance of disturbances and disconnectivities by contrast with earlier work that identified coupling as a distinctive feature of mountain systems. Because disturbances caused by both mountain geomorphological processes and human activities produce disconnectivities in the landscape the recognition and analysis of these features has become of increasingly applied significance in watershed management.

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Extreme geomorphic events in the contemporary evolution of forested slopes in a Central European mountain range, the Sudetes

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ABSTRACT

Forested slopes of the Sudetes have long been implicitly considered as stable under contemporary environmental conditions, with little geomorphic change throughout the Holocene. This view is difficult to sustain and this review-type paper brings together evidence that infrequent but potent surface processes locally cause significant remodelling of slopes and regolith removal or redistribution. These processes are debris flows, shallow and deep-seated landslides, episodes of efficient linear water erosion and windthrows. All are triggered by exceptional meteorological events such as heavy rain or strong wind, but additional factors of slope steepness and suitable lithology play a role. Scarce database does not permit to firmly establish recurrence intervals of such events but they seem to occur at least once per decade (within the entire mountain range) for rain-induced phenomena and two-three times per century for wind-induced phenomena.

KEYWORDS

Geomorphic system; hillslope geomorphology; debris flows; landslides; windthrow

1. Introduction

Most mountainous terrains in Central Europe (i.e. those in Germany, Czechia, Poland, Slovakia, Hungary) reach only moderate altitudes of 800–1500 m a.s.l. and hence, do not rise above the timberline. Thus, their hillslopes remain forested, unless land cover has changed due to human use,

and likely remained so throughout the Holocene. The continuous forest cover implies less geomorphic activity than on bare slopes present above the timberline where both physical weathering is more efficient and sparse vegetation does not act as a significant obstacle to superficial

mass movements (Kotarba and Starkel, 1972). An additional factor controlling surface dynamics is bedrock lithology and structure. Whereas in flysch settings, e.g. in the Outer Carpathians, landslides are common and capable of large-scale hillslope remodelling (e.g. Rączkowska *et al.*, 2012; Pánek *et al.*, 2013), in basement rocks typifying mountainous terrains of the Bohemian Massif and the Mittelgebirge belt further west in Germany such high-magnitude slope processes are infrequent. Here, the general view is one of implied overall geomorphic stability of forested hillslopes, slow and continuous pedogenesis, and considerable periglacial inheritance recorded in landforms and cover deposits (e.g. Jahn, 1989; Kleber and Terhorst, 2013). Nevertheless, extreme geomorphic events within the slope denudational systems do occur in these basement-dominated terrains too, although their significance in the long-term landscape evolution is uncertain. 'Extreme' in this context means events both rare and capable of producing

significant, even if local, geomorphic effect in short time (minutes, hours, days).

The purpose of this paper is to look at these apparently infrequent extreme events affecting the forested hillslopes in a broader perspective. The area discussed is the mountain range of the Sudetes – the highest terrain within the Bohemian Massif that straddles the Czech/Polish boundary along the length of c. 300 km (Fig. 1). Although the most elevated parts of the Sudetes rise above the timberline, such areas have very limited extent (57 km² in total, after Trembl and Banaš, 2003) and the majority of hillslopes are forested. However, the long-term human impact and intense forest exploitation, whose onset dates back to the late medieval times (12–14th century) (Valde-Nowak, 1999) and which continues nowadays, resulted in significant alterations of forest stands. Therefore, the forest belt of the Sudetes cannot be considered a natural environment, except for a few isolated small areas.

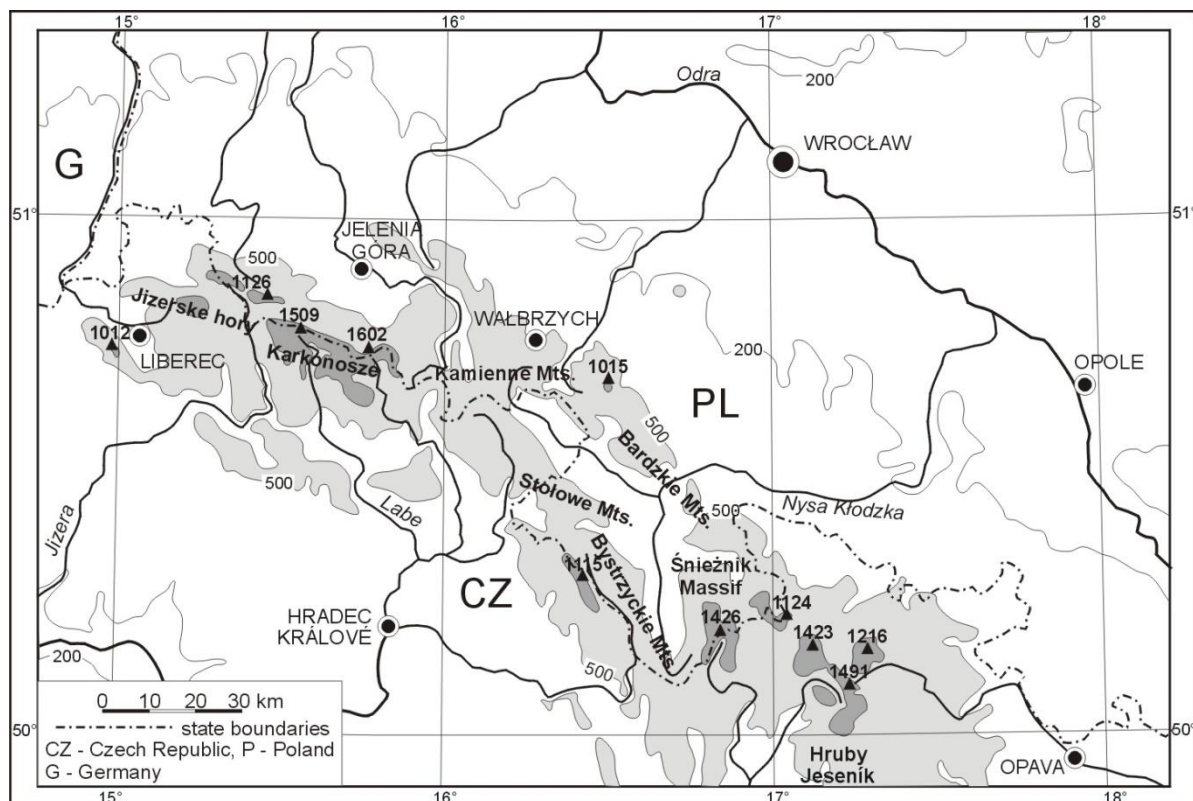


Figure 1 The study area of the Sudetes

The structure of the paper, which is mostly of review type, is bipartite. First, various types of extreme geomorphic events and their geomorphic impacts will be presented. The focus is on hillslope processes (mass movements, erosion, windthrow), leaving aside floods, extensively treated elsewhere (e.g. Kasprzak and Migoń, 2015). Second, their spatial and temporal context will be discussed, followed by considerations of their significance for the contemporary and Holocene geomorphic system of the Sudetes. This paper provides also an opportunity to revisit and update information about extreme geomorphic events presented by Migoń *et al.* (2002).

2. Study area

2.1 Altitudes and landforms

The Sudetes are perhaps the most representative among the Central European mountains and uplands outside the Alpine/Carpathian belt. Along with their neighbours, they are an old Variscan orogen, hence the predominance of pre-Permian igneous (granites) and metamorphic rocks (gneisses, schists), which was rejuvenated in the late Cenozoic in response to the crustal stresses exerted by the rising Alps and the Carpathians. However, Permo-Carboniferous and Mesozoic sedimentary cover rocks occur too, especially in vast intramontane depressions. Differential uplift and subsidence have produced the complicated topography of the present-day Sudetes, with secondary uplifted blocks, moderately elevated uplands and intramontane basins (Migoń, 2011). The highest terrains in the Sudetes exceed 1400 m a.s.l. (Karkonosze – 1602 m, Hruby Jeseník – 1492 m, Śnieżnik Massif – 1425 m), although the most common altitude of watershed ridges is 800–1000 m a.s.l. The floors of intramontane basins, in turn, lie at 300–500 m a.s.l., creating altitude contrasts reaching locally 1000 m. The average altitude of the timberline is 1230 m a.s.l. in the Karkonosze (West Sudetes) and 1310 m a.s.l. in the Hrubý Jeseník range (East Sudetes) (Treml and Banaš, 2003), whereas the upper limit of deforestation for agriculture reached 800–900 m a.s.l. (Latocha, 2007,

2009). However, the extent of deforestation was clearly slope-dependent and steep slopes with stony soils were left forested even in the foothills belt, below 400 m a.s.l.

It is very difficult to generalize about morphology and landforms for the region of such complicated topography and geology. Nonetheless, major landforms within the forest belt are (Fig. 2): (a) low-relief water divide surfaces, regarded as remnants of pre-Neogene planation surfaces, but some are clearly structure-controlled, following the sub-horizontal dip of strata; (b) deeply incised fluvial valleys, with valley sides locally as steep as 30–40°; (c) moderately inclined (10–20°) slopes, connecting (a) and (b); (d) isolated steep-sided elevations on more resistant bedrock variants, most commonly volcanic, with slope inclinations locally above 50°.

2.2 Climate and extreme weather events

The contemporary climatic conditions of the Sudetes reflect regional circulation patterns within Central Europe (Sobik, 2005). Advections of humid polar maritime air masses from the west are most common and occur during c. 65% of the year on average, 14% among them being the cases of fairly quick movement over western Europe that takes less than 24 hours to reach the Sudetes. They are associated with cyclonic circulation and may bring considerable rainfall along the cold front. Strong wind may accompany the westerly circulation, taking the form of a foehn wind across major topographic barriers. Bora winds are characteristic too, being channelized by chains of intramontane troughs and basins. In turn, polar continental air masses arriving from the east account for c. 31% days of the year on average.

Mean annual temperatures reach 7°C in the foothills and intramontane basins, dropping to 0°C on the highest peaks, consistent with the general altitude-temperature relationship. However, the effects of altitude are modified by the foehn effect and leeward sites typically have higher mean annual temperatures than dictated by the altitude alone. The mean summer temperatures reach 16°C in the foothills and 12–13°C at 800–900 m a.s.l., whereas the respective values for winter are -2°C and -5°C.

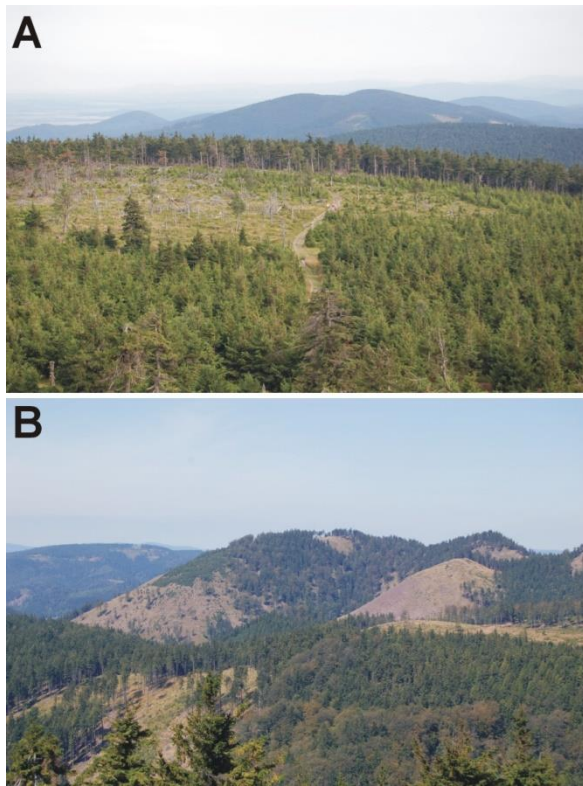


Figure 2 Two representative scenes from the forest belt of the Sudetes: (A) low-relief, subdued water divide surfaces (Sowie Mts.), (B) moderately steep slopes within fluvial valley

Likewise, annual precipitation reflects the combined effects of altitude and relief. It reaches 700–800 mm in the foothills and 1200–1500 mm on elevated planation surfaces, with the westernmost parts of the Sudetes being much rainier than the eastern parts. The role of rain shadow is significant, accounting for less rainfall on leeward slopes and basins. Snow cover remains from 50 days per year in the foothills to 200 days in the parts of the West Sudetes directly exposed to the advection of humid air masses from the west.

Although the climate is generally considered as temperate and mild, extreme atmospheric events occasionally occur (Sobik and Błaś, 2010). From the geomorphological perspective, two types of events are of prime importance: heavy precipitation and strong wind. The former is associated with two situations. First, longer periods of intense rain are generated by macroscale convergence in cyclonic circulation patterns. They may last from one to five

days and extend over considerable area. For example, extremely high rainfall in early July 1997, exceeding 500 mm in five days, affected nearly half of the Sudetes, along with the adjacent part of the Carpathians (Czerwiński and Żurawek, 1999). Second, localized convection and the development of Cumulonimbus clouds leads to brief (even less than 1 hour), but very efficient episodes of very heavy rain (cloudbursts). The most extreme examples recorded were 176 mm/75 minutes (year 1914), 183 mm/90 minutes (1968) and 193 mm/2 hours (1951), but intensities in the range of 50 mm/hour are more common (Sobik and Błaś, 2010).

Similarly to precipitation, strong winds may be divided into two groups (Sobik and Błaś, 2010). First, the Sudetes are occasionally affected by large-scale cyclonic events, when atmospheric pressure in the centre drops below 970 hPa and the wind speed exceeds $100 \text{ km}\cdot\text{h}^{-1}$. A recent example is provided by the Kyrill storm on 18–19 January 2007 which brought significant damage, particularly to the forest stands (Pawlik, 2012). Second, some foehn winds may be associated with wind speed above $60 \text{ km}\cdot\text{h}^{-1}$ and their devastating effects are exacerbated by the tunnelling effect of deeply incised valleys (Kwiatkowski, 1969)

Not much of solid knowledge about the climatic conditions during an earlier, pre-observation period can be provided. Likewise, the climatic record of the Holocene is poorly documented and insufficiently constrained. Therefore, it seems more appropriate to address these issues in the subsequent discussion, in section 4.

3. Extreme events – processes and landforms

3.1 Debris slides and flows

Debris flows are a typical component of a high-mountain denudational system such as the Tatra Mountains in the Carpathians (Kotarba *et al.*, 1987, 2013). However, they may occur in medium-altitude mountains such as the Sudetes too and indeed, this mountain range stands out among the other Mittelgebirge ranges in terms of frequency and dimensions of debris flows. Debris flows are known

from the glacial cirques of the Karkonosze, but in the context of this paper debris flow occurrences in the forest belt are of particular significance. Furthermore, two situations need to be distinguished: (a) flows generated above the timberline which reach the forest belt and become dissipated within it; (b) flows whose source areas are within the forest.

Debris flows of the first type are common in the Karkonosze, especially in the deep, glacially-remodelled valleys in the eastern part (Pilous, 1977; Migoń and Parzóch, 2008). They are generated above the timberline, in joint-controlled ravines or within convex slopes with thin regolith cover, and continue movement after reaching the forest boundary (Fig. 3). The length of tracks within the forest is from 100 m to as much as 300 m, i.e. two

thirds of the total length. Flows of the second type commence as shallow slides of the regolith cover, usually very thin (c. 1 m thick), within forested slopes of considerable steepness ($>25^\circ$). They have been recorded in the Karkonosze, Jizerské hory, Śnieżnik Massif and, particularly, Hruby Jeseník range (Hrádek, 1984; Pilous, 2011; Parzóch *et al.*, 2012; Roštínský *et al.*, 2013). Some transform into flows and move along a narrow track (in respect to length), whereas others continue sliding down to the valley floor across a wider zone up to 30 m such as the debris slide in the Śnieżnik Massif in 2011 (Parzóch *et al.*, 2012). The length of flow tracks/slide-affected zones varies from a few tens of metres to 1 km (Pilous, 2011), depending on the available slope length.

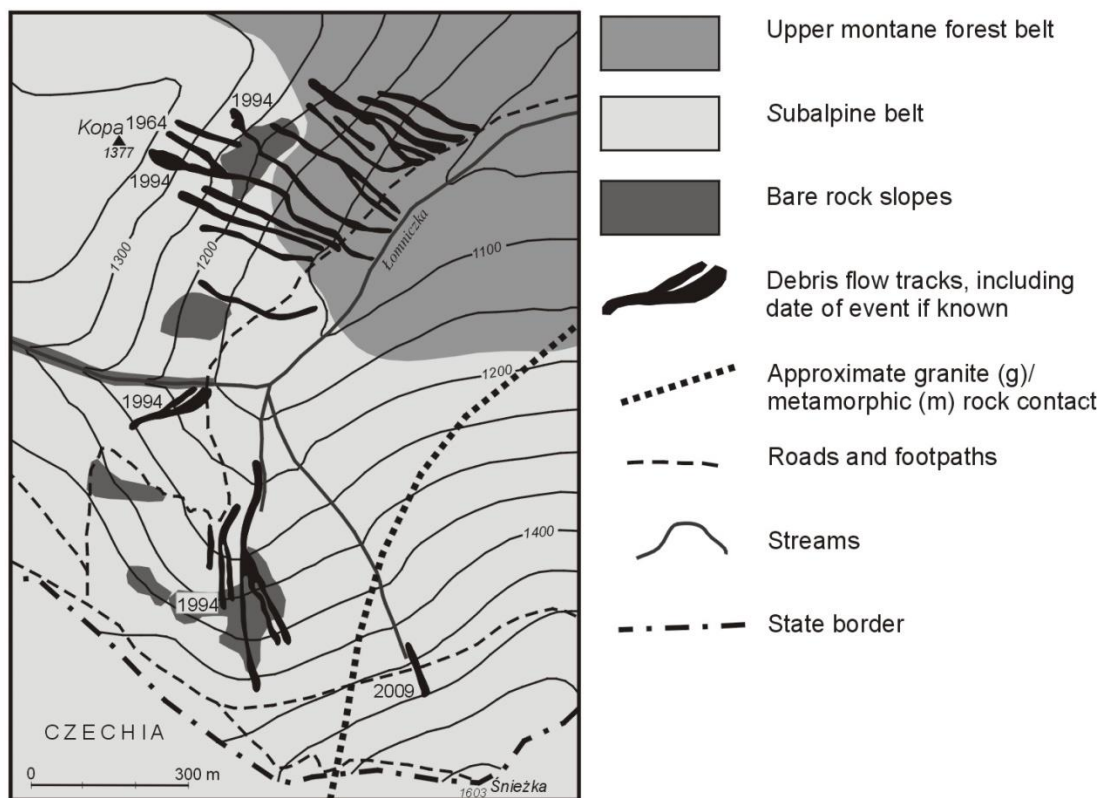


Figure 3 The distribution of debris flow tracks in the Łomniczka Valley, Karkonosze Mts. (after Parzóch and Migoń, 2010)

Typical landforms indicating debris flow tracks are central troughs and lateral levees, the latter up to 2 m high (Fig. 4). Troughs may still host remnant regolith but complete erosion down to bedrock may occur too. If this is the case, the longitudinal profile

of a track is irregular, with rocky sections alternating with the regolith-covered ones. Boulders as big as 3 m high were observed within the levees. Distal deposition may occur in the form of a distinct toe, but along other flow tracks one can observe gradual

disappearance of characteristic landforms or the flow reached the channel and continued as hyperconcentrated flow (e.g. 1921 event in Hruby Jeseník or 2010 event in the Jizerské hory).

3.2 Deep-seated landslides

Deep-seated landslides, in contrast to shallow debris slides requiring thin regolith and steep slope, are much more geology-dependent. The predominant basement rocks of the Sudetes, only superficially weathered, do not provide a setting conducive to deeply rooted slide displacements. However, in special geological circumstances such as the occurrence of tough, heavy but jointed volcanic rocks over weaker, deformable sedimentary formations landslides do form. The best researched area in this respect is the range of Kamienne Mountains in the Central Sudetes, where around 50, apparently relict landslides have been identified under forest, with the most extensive ones covering > 10 ha, some joining into landslide complexes up to 40 ha (Migoń *et al.*, 2010, 2014, 2017). Further, but fewer examples were reported from the adjacent Wałbrzyskie Mountains, the tableland of the Stołowe Mountains (Duszyński *et al.*, 2017), Kaczawskie Mountains (Kowalski, 2017), Bystrzyckie Mountains (Różycka *et al.*, 2017) and Bardzkie Mountains (Jancewicz and Traczyk 2017), including a large historic (1598) translational slide in the Nysa Kłodzka gorge which dammed the river (Oberc, 1957; Parzóch and Migoń, 2010).

Morphology and morphometry of landslides suggest that they represent different genetic types (Migoń *et al.*, 2017; Różycka *et al.*, 2017). Some show geomorphic signatures of rotational slides, with arcuate rocky or debris-covered head scarps, back-tilted benches, locally multiple, closed hollows and convex toes. Others lack back-tilted blocks and seem to result from translational wedge-type failures. In turn, elongated hummocky landslide bodies confined to valleys, with scattered boulders of different size, indicate complex movement involving slide and flow. Exposure of head scarps in jointed bedrock initiated further gravity-driven movements of individual rock fragments and the development of angular scree (Fig. 5).



Figure 4 Geomorphic and ecological consequences of a recent (2010) debris flow in the Jizerské hory (Czechia). (A) The complete removal of hillslope regolith and exposure of bedrock along the track, (B) Boulder and woody debris accumulation in the distal part

The age of the majority of landslides is not known and only a few can be safely linked with historical events such as the 1598 landslide in Bardo (Oberc, 1957). A rare example of a recently (2016) developed slide in Wleń was described by Kowalski (2017). Otherwise, even the episodes of heavy rainfall (1997, 1998, 2006 and 2010) triggered only shallow regolith-confined slides within valley sides (Aichler and Pecina, 1998; Żurawek 1999), but no deep-seated bedrock-rooted landslides were activated. However, there are indirect indicators that at least some landslides originated or were reactivated during the Holocene. These include differences in soil characteristics (Kacprzak *et al.*, 2013), sparse radiocarbon dates from closed depressions within two landslides in the Kamienne Mountains (Synowiec, 2005), dendrochronological signals of considerable stress exerted on trees

growing on landslides (Malik *et al.*, 2016), various signals of activity of scree slopes below head scarps (Remisz, 2012; Remisz and Bijak, 2012) and evident differences in the clarity of geomorphic features of landslides, suggesting a variety of ages.



Figure 5 Contemporary activity of a scree slope at the foot of a landslide head scarp, Mt. Suchawa, Kamienne Mts.

The geomorphological diversity of landslides suggests also that displacements may have occurred with different rates. Certainly, as the historical records from Bardo inform, some may have been produced almost instantaneously and were 'extreme events' *sensu stricto*. Others could go through long preparatory phases, analogous to ongoing lateral spreading deformation at Lesista Wielka (Migoń *et al.*, 2010), followed by brief episodes of significant movement. Finally, some may have been of creeping type throughout their lifetimes, consistent with rather subtle dendrogeomorphological signals (Malik *et al.*, 2016). Thus, their 'extremism' is related to the spatial scale of slope remodelling rather than to the rate of movement.

3.3 Windthrows

Geomorphological dimension of wind-induced tree-throw events has long remained a neglected subject, despite recurring windthrow calamities (e.g. Kwiatkowski, 1969). A. Jahn went even that far as to say that "*gravitational dynamics of soil ends when the slope becomes forested*" (Jahn, 1989). Recent work on the effects of the 2007 Kyrill storm on

forest stands (Pawlik, 2012, 2013) has redressed the balance and further studies in other parts of the Sudetes (Pawlik *et al.*, 2016, 2017) confirmed the view that significant remodelling of slope morphology and disturbance of slope cover deposits take place in the consequence of massive tree uprooting.

At the scale of an individual uprooted tree the direct effects include the origin of a pit in the place of a former root plate, detachment of bedrock material (soil, cover deposits, but occasionally also jointed solid rock) and its horizontal displacement (Fig. 6). As the degradation of the airlifted root plate proceeds, a mound forms next to the pit, leading eventually to the origin of characteristic paired pit-and-mound topography of the forest floor. Dimensions of pits and mounds vary but relatively recent landforms may be up to 1.5 m deep and high, respectively, whereas their diameters are within the 2–5 m range. Over time, pits become infilled and mounds flattened and it is estimated that lifetimes of these minor landforms are of the order of 100 years. If bedrock is at shallow depth and roots are strong, bedrock mining occurs and quite large rock fragments, in excess of 1 m, can be brought to daylight (Pawlik *et al.*, 2013).



Figure 6 Geomorphic effects of windthrow: origin of pits and initiation of considerable mixing of regolith

Despite relatively short lifetimes, pit-and-mound associations are fairly common in the Sudetes, indicating that wind-driven tree uprooting is a frequent phenomenon. The density of pits and mounds may reach 40 pairs per hectare and the

spatial coverage approaches 5%. However, the distinctiveness of pits and mounds is also related to the type of tree, its age and the depth of regolith. Thus, widespread tree uprooting took place in the volcanic terrain of the Kamienne Mountains during the Kyrill storm (Pawlik, 2012), but not too many pits originated on steep slopes with rather thin regolith. Nevertheless, mixing of regolith was extensive, stepped microtopography of the slope started to evolve and any older sedimentary structures within cover deposits were destroyed.

In addition to the direct effects, tree uprooting brings about various secondary consequences. Pits and fallen logs affect pathways of overland flow, diverting it from downslope movement, with pits acting as local depositional basins. Mounds in turn are affected by surface flow, soil creep and ground ice development. Surface flow acts selectively, washing away the fines, and gravel armours form at the expense of mounds (Pawlik *et al.*, 2013).

3.4 Episodes of extreme linear erosion

In undisturbed mixed or coniferous forest, which are native plant associations in the Sudetes, little erosion is accomplished through either linear or surface flow. However, centuries of forest management, still ongoing except limited areas under strict protection, have resulted in the development of an extensive network of forest roads, logging paths and hiking trails. Their density may be considerable and reaches 10 km per 1 km² (Kasprzak, 2006). Their surfaces are occasionally paved but much more often they are not and hence, concentrated flow during heavy rainfall episodes is capable to efficiently erode bare surfaces of communication tracks. Singular rainfall and surface flow events may result in the origin of incisions exceeding 1 m deep (Fig. 7) (Parzóch and Migoń, 2010), with extreme values of nearly 4 m recorded in the Karkonosze in September 1994 (Parzóch, 2002) and more than 4 m during the protracted period of heavy rain in July 1997, in the Śnieżnik Massif (Czerwiński and Żurawek, 1999). Such massive erosion is matched by extensive deposition on local mid-slope flats and at valley confluences, although most of eroded material reaches channels and is included into bedload.



Figure 7 An example of heavy linear erosion due to one rainfall episode (August 2006) within an anthropogenically disturbed ground

In fact, gullies under forest are quite common in certain parts of the Sudetes (Latocha, 2014), especially in the vicinity of old (late medieval – early modern times) centres of mining and ore processing. Their depth reaches 3 m and the length is of the order of hundreds of metres. It may be speculated that dense networks of gullies have developed progressively, with older roads abandoned after rainfall episodes made them too deep and narrow to be used any longer.

4. Discussion

4.1 Extreme events in space

Generally, extreme events in the hillslope geomorphological system of the Sudetes exert local rather than regional impact. In historical times, large parts of the Sudetes did not experience any significant geomorphic change consequent to high magnitude atmospheric processes. Even if heavy

rain or strong wind affects an area of the order of tens of square kilometres, geomorphic effects may still be quite localized. For example, only one debris slide occurred on the slopes of the Czarna valley in the Śnieżnik Massif in 2011, despite the heavy rain affecting the entire drainage basin (Parzóch *et al.*, 2012). Similarly, the episode of severe convective rain over the upper catchment of Bystrzyca Dusznicka produced shallow landslides only along steep valley sides in sedimentary bedrock (Żurawek, 1999), with no comparable processes in the adjacent metamorphic part of the catchment. For most of the forested part of the Sudetes, the state of “no sudden change” seems indeed a norm. Even if processes acting over longer time intervals are considered, the tendency towards spatial clustering can be still observed. The Łomniczka valley in the Karkonosze is notorious for debris flows and more than 25 distinct tracks have been identified until 2006, with all of them on the western valley side and in the valley head, and none on the eastern valley side (Fig. 3) (Migoń and Parzóch, 2008). This indicates the role of local factors, in addition to the atmospheric triggers. In this example, debris flows were confined to granite bedrock and apparently absent on metamorphic substratum (or so infrequent that old examples have been completely erased). However, in 2009 a small debris slide/flow occurred on the metamorphic rock (although above the timberline). At a larger spatial scale, Hrádek (1984) linked spatial clustering of debris flows in the northern part of Hruby Jeseník (Keprník massif) and their absence in the southern part (Praděd massif) with the presence of well-developed foliation planes, broadly accordant with the slope and acting as sliding surfaces, in the former area.

At a more local scale, geomorphic events considered in this paper may be divided into those whose effects are linear (debris flows, forest road erosion) and those whose effects are distributed over larger surfaces (landslides, windthrow). The results of the former may be impressive, especially if considering duration of formative events, but one needs to realize that the slope section affected is only 1–10 m wide, rarely more than this. Adjacent surfaces may be left without any signs of surface remodelling. Landslides and windthrows affect

much larger areas, measured in hectares (tens of hectares), which is however still very little on the scale of the entire mountain range. Nonetheless, ‘hotspots’ of landsliding can be identified, e.g. in several parts of the Kamienne Mountains (Migoń *et al.*, 2017) where landslides of different types occur next to one another, forming large complexes of 30–50 ha. An analogous spatial clustering of slopes affected by strong wind can be recognized in the Karkonosze Mountains (Pawlik *et al.*, 2016). Considering geomorphic effects of windthrows it should be noted that landforms resultant from tree uprooting are short-lived and their dimensions are much smaller than of those resultant from landslides. However, effects on the regolith structure may be considerable and recent work on mountain soils suggests that poorly horizonated Cambisols, typical for forested slopes, provide pedological record of ongoing disturbance by surface and near-surface processes (Kabała *et al.*, 2013).

4.2 Extreme geomorphic events in time – triggering mechanisms

Triggering mechanisms of geomorphic events considered in this paper are exclusively meteorological and related to high precipitation, notwithstanding speculations that seismic factor may have contributed to the 1598 Bardo landslide (Ciężkowski and Koszela, 1988). However, to establish threshold values for debris flows and surface erosion is not easy because of insufficient spatial coverage of rain gauging stations. Available data allow to suggest that rainfall intensities above $20 \text{ mm} \cdot \text{hr}^{-1}$ are necessary to set the debris cover in motion but antecedent moisture is also an important factor as demonstrated by most debris flow events in the Karkonosze (Parzóch and Migoń, 2010) and the circumstances leading to the 2011 debris slide in the Śnieżnik Massif (Parzóch *et al.*, 2012).

Recurrence intervals of extreme geomorphic events should be considered at two spatial scales: (a) relevant to the entire Sudetes and (b) in respect to specific localities. Regarding the former, heavy rainfall with reported erosional effects on slopes somewhere in the Sudetes occurs every 3–5 years.

Debris flow/slide incidents are less frequent and highly irregular. The most recent ones occurred in 2006, 2009 (both in Karkonosze), 2010 (Jizerské hory) and 2011 (Śnieżnik Massif), with no significant events since. These were preceded by 1997 and 1994 events, but there was a much longer quiet interval before (up to 1974). Thus, 1–2 events per decade on average may be hypothesized, although they vary in intensity. In addition, the 2006 and 2009 events occurred above the timberline, so that the regionally applicable recurrence interval for debris flows on forested slopes is longer, approximately once in a decade. Strong winds exerting significant damage in forest stands and hence, altering slope geomorphic systems, occur approximately once every 30–40 years (Pawlik, 2012). The 2007 Kyrill storm was preceded by events of similar magnitude in 1930 and 1966, whereas the most recent, although more localized damage occurred in the Bystrzyckie Mountains and Śnieżnik Massif in 2015.

At the scale of specific localities the recurrence intervals are much longer, although it is important to distinguish between meteorological events and geomorphic events. Heavy rain with intensities capable of triggering debris flows in the Karkonosze occurs at least once per decade, but debris flows in the same locality are triggered with much lower frequency which is mainly due to sediment exhaustion. Again, the headwater part of the Łomniczka valley is a good example. Seven larger debris flows were triggered by heavy rain in September 1994 whereas only one followed the heavy rain episode in July 2009. However, scars and bare granite surfaces left by the 1994 flows are still visible and the source of material was clearly not yet replenished by subsequent weathering.

Any discussion about frequency of hillslope geomorphic events over longer timescales beyond the observation period, in the absence of geochronological data, is at best speculative. The only attempt was that by Pawlik *et al.* (2016) in respect to tree throw. They proposed that complete soil turnover due to uprooting may have occurred 2–6 times during the Holocene at wind exposed localities. Thus, it is not really possible to establish the representativeness of the last 150 years for the entire Holocene.

4.3 Implications for the present-day geomorphic systems

Although the observational basis is still scarce and significant gaps in our understanding of hillslope geomorphological system of the Sudetes remain, it is clear that the forest belt is not a dormant environment, moulded only by low magnitude processes, which has retained most of its pre-Holocene morphology. Sudden geomorphic events triggered by heavy rain or strong wind do occur, especially on slopes $>20^\circ$. In specific circumstances, provided by the combination of rain/wind intensity and suitable local topographic and geological conditions, such events are capable of accomplishing total forest destruction, complete regolith removal, incision down to bedrock and creating significant new landform assemblages over a few to a few tens of hectares. Landslides, even if infrequent, may reshape entire slopes.

The preceding discussion also showed that a combination of factors is necessary to generate an extreme geomorphic event in the forested environment of the Sudetes. Rain or wind are the necessary external triggers, but have to affect slopes which are sufficiently steep and covered by regolith that can be mobilized. Material availability is an important prerequisite, as testified by the fact that recurrence intervals of geomorphic events are longer than those of hydrometeorological events. In addition, human impact becomes a factor and it is proposed that linear erosion on forested slopes, leading to the origin of gullies under forest, would not be possible without surface disturbance and vegetation removal by people.

The challenge for the future is to set these observations in the broader temporal context of the Holocene. There were climatic and environmental fluctuations during the Holocene and it is not known how these may have impacted geomorphic systems. Sediment analysis from the Mały Staw lake in the Karkonosze suggests that an interval of significant erosion occurred around 8.2 ka, possibly linked with climate deterioration (Malkiewicz *et al.*, 2016). In the sandstone tableland of the Stołowe Mountains thick sandy covers are widespread on slopes, probably the effects of surface wash (Waroszewski *et al.*, 2015; Duszyński *et al.*, 2016).

Their presence implies less dense vegetation cover than today as processes of areal sand redistribution do not occur nowadays in forests with dense undergrowth. Scarce geochronological data and proxy soil data suggest mid-Holocene landslide activity in the Kamienne Mountains but it is not known whether they signify birth or reactivation (Kasprzak *et al.*, 2013). Even the status of the Little Ice Age is uncertain and whereas there are indicators that floods may have occurred with greater frequency (Kasprzak and Migoń, 2015), the behaviour of slopes remains an enigma.

5. Conclusions

Forested hillslopes of medium-altitude Central European mountains built of basement rocks such as the Sudetes should not be equated with the domain of geomorphic stability and periglacial inheritance. Although some places may have preserved most of their periglacial signatures, other show variable and repetitive activity and landform change. The region of Central Europe is exposed to extreme meteorological events and some of them are of sufficiently high magnitude to trigger sudden regolith displacements on steep slopes in the form of debris flows and landslides, linear erosion of cover deposits, or widespread forest calamities with geomorphological implications. The frequency of such events is nevertheless low which makes them difficult to predict in respect to both space and time. Likewise, as a consequence of sparse data base, to establish meaningful threshold values to initiate these processes is not straightforward. The example of the Sudetes shows that the combination of factors is normally necessary for an extreme geomorphic process to occur under forest. Local topographic and geological conditions are vital constraints. The frequency of extreme geomorphic events on the slopes of the Sudetes can only be established for the last 150 years or so. It is not certain whether this period can be considered representative for the Holocene and future research efforts should be focused on the geomorphic history of earlier time intervals of the Holocene.

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Assessment of landslide susceptibility for civil protection purposes by means of GIS and statistical analysis: lessons from the Province of Modena, Italy

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ABSTRACT

This paper is focused on the analysis of landslide susceptibility for civil protection purposes. A methodology was developed and applied to support measures aiming at landslide risk mitigation. It is based on GIS and the Weight of Evidence (WofE) method, which was preferred among several other statistical approaches because it is suitable for large areas, easy to interpret and simple to program. The latter feature is important for implementing a GIS tool aimed to facilitate Civil Protection in the updating of susceptibility maps. An application of the methodology was performed in a mountainous and hilly area of the Northern Apennines (Italy) located in the Province of Modena where landslides are a critical issue in terms of civil protection due to the recurrent damages to buildings, roads and infrastructures. According to the Region Emilia-Romagna Landslide Inventory Map (RER LIM), shallow slides and earth flows are by far the most widespread mass movement types. Hence, the susceptibility assessment concerned these two types of movements. The choice of the training set, based on active landslides, took into account possible limitations of the input data. The predisposing factors were lithology, slope, curvature, Slope Position Index, aspect, land use, distance from roads. The validation was conducted through the PRC and SRC curves, and direct checking (comparison with past occurrences, multi-temporal orthophotos and field surveys). The resulting models predicted the location of landslides in an acceptable manner. One map for each type of landslides was produced and afterwards they were combined in a single document to improve their intelligibility in a civil protection framework.

KEYWORDS

Landslide; susceptibility assessment; civil protection; GIS; Northern Apennines; Italy

1. Introduction

Prediction of landslide susceptibility and hazard for areas not currently subject to landsliding is fundamental for land planning and risk mitigation. At the same time, detecting the most susceptible areas to landslides is a challenging task since resources are becoming more and more scarce and exceptional rainfall events, which are likely to trigger landslides, are increasing (Borgatti and Soldati, 2010). Landslide susceptibility and hazard assessment is based on the assumption that hazardous phenomena that have occurred in the past can provide useful information for prediction of future occurrences (Soeters and van Westen, 1996). Many other authors agree on assuming that the same factors which triggered past landslides might cause future slope movements (Guzzetti *et al.*, 1999; Soldati *et al.*, 2009). Two basic methodologies are listed in relation to the analysis of the terrain conditions leading to slope instability (Soeters and van Westen, 1996): 1) direct mapping (experience-driven applied-geomorphic approach), through which earth scientists evaluate direct relationships between landslides and their geological and geomorphological settings by direct observations; 2) indirect mapping which consists of mapping a large number of parameters considered to potentially influence landsliding and subsequently (heuristically, statistically, or through physically-based modelling) analyzing their contribution with respect to the occurrence of slope instability phenomena, in order to identify the relationships between the two.

An important role is played by the scale of the analysis (International Association of Engineering Geology, 1976) and by the input data available (number, typology and quality), factor maps, but especially Landslide Inventory Map (LIM) quality (van Westen *et al.*, 2005; Guzzetti *et al.*, 2006; Galli *et al.*, 2008; Guzzetti *et al.*, 2012; Van Den Eeckhaut and Hervás, 2012; Chalkias *et al.*, 2014; Petschko *et al.*, 2014; Piacentini *et al.*, 2015; Hussin *et al.*, 2016). The methods of landslide susceptibility and hazard assessment are subdivided into heuristic, statistical and physically-based modelling approaches (Carrara *et al.*, 1995; Soeters and van Westen, 1996; Guzzetti *et al.*, 1999). In the heuristic approach the expert

opinion of scientists conducting the survey is used to assess the hazard. This approach combines the mapping of mass movements and their geomorphological setting as the main input factor for hazard determination. In the statistical approach the combination of factors which have led to landslides in the past are determined statistically, and quantitative predictions are made for areas currently free of landslides but where similar conditions exist. Finally, the physically-based modelling approach is applicable only when the geomorphic and geological conditions are fairly homogeneous over the entire study area and the landslide types are simple. It is based on physical models (slope stability and hydrologic models), and it is generally applicable in the case of large-scale hazard zoning.

1.1. Geographic and geomorphological settings

The study area is located in the Province of Modena (Italy) and it is approximately 1,300 km². It is intersected by the Northern Apennines and by the hills at the border of the mountain chain. The altitude ranges from 150 m to 2,165 m a.s.l. and the highest peak is Monte Cimone (Fig. 1).

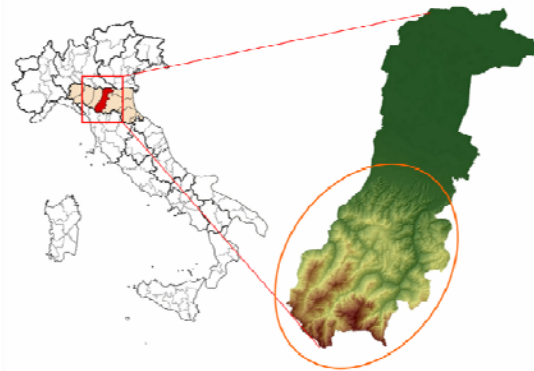


Figure 1 Location of the study area in Italy and in the Province of Modena

The main river basins are the Secchia, the Panaro and the Reno. Inside the study area there are 25 municipalities with a total population of 194,278 (Province of Modena, 2012). The physical features of the Modena Apennines landscape are the result of

geomorphological processes which have been active mainly from the Upper Pleistocene on different lithological types under changing climatic and geodynamic conditions in terms of recurrence, spatial distribution and intensity (Castaldini *et al.*, 2003; Siddiqui and Soldati, 2014).

In the study area there are erosional, structural, glacial and anthropogenic landforms. Badlands and landslides are widespread. Selective erosion, combined with geological structures, emphasize the contrast between calcarenitic or flysch rocks and ophiolitic outcrops with the gentle landscape dominated by the marly-clayey substratum. In the upper sector of the Modena Apennines, glacial landforms and moraines, dated to the Last Glacial Maximum, characterize the territory. Lastly, human activities, both quarrying and urbanization, have heavily re-shaped its natural morphological features.

1.2 Landslide inventory

Within the above framework, landslides are one of the most important geomorphic process that affects the area. According to the Region Emilia-Romagna Landslide Inventory Map (RER LIM), dated to 2006 with last updates in 2011, the total number of

landslides in the area is 7,865 (Fig. 2). The total surface affected by landslide is 316 km² corresponding to approximately 24.2% of the study area. In total 22% of the affected area is covered by active landslides, while the remaining 78% are considered as dormant.

Focusing on landslide types (both active and dormant), complex landslides occupy a large area (201 km²), followed by earth flows (60.41 km²); shallow landslides cover an area of 16.8 km² and DGSDs covers 16.4 km²; “non-classified mass movements” extend for 19.46 km²; the remaining 2 km² about are debris flows, rock falls and topples, as well as lateral spreads. The most frequent landslides are earth flows (2,723) and shallow landslides (2,812). The high number of large and periodically reactivated landslides depends primarily on geological causes, linked to the quality of rock masses and their state of physical weathering; the triggers are intense and/or prolonged precipitation events (Castaldini and Ghinai, 2007). The reactivation of large dormant landslides still represents a threat in terms of hydrogeological risk (Bertolini *et al.*, 2017).

LANDSLIDE (LS) TYPE	sq km (all LS)	Nr. of polygons (only active)
Slides (S)	16.8	1854
Complex landslides (CL)	201	360
Earth flows (EF)	60	1683
Debris flows (DF)	0.64	18
Not classified landslides (NC)	19.4	117
DGSDs	16.4	-
Rock falls (RF)	0.03	4
Lateral spreads (LSP)	2.23	-

TOT Nr. of Landslide: 7858
TOT Area of Landslide: 316.5 sq km
Landslide index: 24.2%
Active: 22% of total area of LS
Dormant: 78% of total area of LS

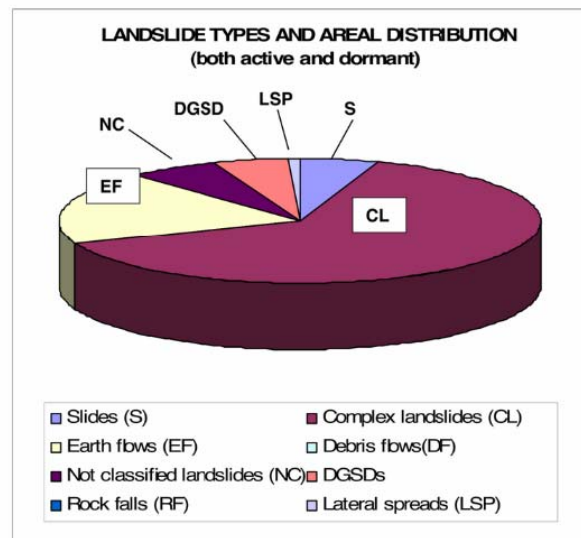


Figure 2 Landslide types and distribution in the study area (elaboration from RER LIM data). In terms of surface: S=5.31%; CL=63.51%; EF=18.96%; DF=0.2%; NC=6.13%; DGSDs=5.18%; RF=0.01%; LSP=0.7%

1.3 Main goals

This research is an attempt to assess susceptibility for different type of landslides in the Province of Modena (Italy) for civil protection purposes. It was conducted in the framework of a wider project, briefly described in the next paragraph, whose main purpose was to re-organize the geographic information system and data related to risks which affect the provincial territory. The principal goals of the research were: 1) investigate if certain slopes, considered as stable at the moment, could be prone to landsliding in the future; 2) create a "priority scale" of landslide-prone areas where the local Civil Protection could concentrate efforts to prevent and mitigate damages; 3) identify a simple but effective methodology to assess susceptibility in order to update the map in the future and use it as a WebGIS layer and tool. A previous landslide susceptibility analysis was carried out by Generali and Pizziolo (2013) in the study area, based on a model at the scale of Region Emilia-Romagna with some differences in goals, methodologies and input from what is discussed in the present paper.

1.4 The Risk Web-GIS

Since October 2011, the Civil Protection work of the Province of Modena is supported by a new Web-GIS (Fig.3) with advanced geoservices that are compliant with INSPIRE (2007/2/CEE) and OGC (Open Geospatial Consortium) (Nicolini *et al.*, 2012). Born as an evolution of the previous Data Collection System (named SRD), designed in 2001 by National Defence Department (DPCN) in Italy, and those of the Emilia-Romagna Region other than the Province of Modena, the new Web-GIS is intended to store and organize data necessary for assessing events and damage scenarios, during the phase of planning or when emergencies, linked to the hazardous phenomena which affect Province's territory (floods, landslides, earthquakes, industrial or other relevant incidents, forest fires), happen. The data stored in the geodatabase are mainly from the Province of Modena planning instruments (e.g. the main Province's plan, that is named PTCP 2009, emergency and other civil protection plans), but

also from other public and private sources, and they concern the entire jurisdiction of Civil Protection that is the whole provincial territory from the plain to the high Apennine mountains.

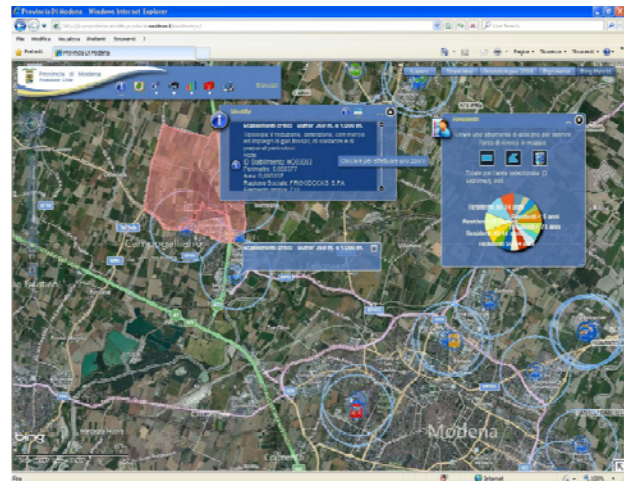


Figure 3 The Risk WebGIS of the Province of Modena Civil Protection and some of its advanced functionalities

The Risk WebGIS application, developed with ESRI standard FLEX programming language, is intended for the spreading of all the information managed by the new system (alphanumeric and geographic data; base and thematic layers; vectorial and raster data). Thanks to this web application, users can display and query thematic data, overlay them with base cartography (CTR – the regional technical map, ortophotos, satellite images etc.) and print their customized maps. Moreover, the WebGIS provides users with several decision support tools both for "simple" needs (e.g. how to get in the emergency area? where are the nearest civil protection structures and facilities?), and for performing advanced analysis: the Menu Census 2001 (Fig. 3) allow users to get spatial statistics without being specialists, such as information on resident population or on buildings' age of a customized area (defined by users drawing a polygon) involved or susceptible to be involved in an emergency. Other than the typical GIS tools for map browsing and querying (zoom, pan, identify etc.), the WebGIS offers different interesting functionalities, some of which are based on external

geoservices (e.g. those of Google Maps, like Street View, or Bing). While the server engine (and the geodatabase) is physically installed only on a centralized machine in Marzaglia (Modena), where the Unified Centre for Civil Protection of Modena is located, the data entry client (based on ArcExplorer build 1750, a software solution for browsing GIS data distributed for free by ESRI) is also installed on users' computers and available especially for the COCs (the operations centres for civil protection at a municipality level).

The first large-scale emergency during which the new system was successfully tested is the 2012 Emilia Earthquake which caused 27 fatalities and damaged approximately 40,000 buildings. The application comprised the following activities: georeferencing and daily updating of the 49 emergency shelters; mapping a further 30 suitable areas for hosting people in case of worsening; and mapping the distribution of approximately 350 interventions (urgent temporary works) necessary to ensure public safety (e.g. shoring, demolition of unsafe buildings, barriers etc.).

2. Landslide susceptibility assessment and mapping

2.1 Methods

In the present study, a statistical approach, the Weight of Evidence method (Bonham-Carter, 1994) was selected to perform indirect landslide susceptibility assessment. It was selected among several statistical methods as it is suitable for determining landslide susceptibility in large areas with complex geological and geomorphological settings (Piacentini *et al.*, 2012), it is easy to interpret, simple to program, and patterns with complex spatial geometry can be modelled with the same computational effort as those with simple geometry (Bonham-Carter *et al.*, 1989). Briefly, in this method positive and negative weights (W_i^+ and W_i^-) are assigned to each class of the input factor maps, to indicate if and how much its presence/absence is important for the occurrence of landslides. If the weight W_i^+ is positive, the presence of the factor (or of a specific classes of it) is

favourable for the occurrence of landslides whilst, if it is negative, the presence of the factor is not favourable for the occurrence of landslides. W_i^- is used to estimate the importance of the absence of the factor in relation with landslide phenomena. Thus, when positive, it means that the absence of the factor is favourable for the occurrence of landslides. The total/final weight (W_{map}) of each factor, in a multi-class map where the presence of one factor implies the absence of the other factors of the same map, is defined by the following formula:

$$W_{map} = W_i^+ + W_{mintotal} + W_i^- \quad (1)$$

where $W_{mintotal}$ is the total weight in a multiclass map.

In order to quantify the spatial association between a map class and the occurrence of landslide, the contrast factor C_w can be used (Bonham-Carter, 1994). It is the difference between W_i^+ and W_i^- . The further the contrast factor is from zero, the more the factor is a significant predictor for the analysis. A positive contrast indicates a positive spatial correlation and vice versa for a negative contrast.

2.2 Input data and sampling activity

Most of the data used for the research illustrated in this paper are from the Cartography Archive of the Region Emilia-Romagna (RER) and RER Geological Service (SGSS) and are primarily as follows:

- Landslide Inventory Map (2006, with last updates in 2011);
- Geological Map;
- Land Use Maps (2008 and 1976);
- Street Map 1:5,000 from the Province of Modena;
- Digital Terrain Model 5x5 m.

The top three are all at the scale 1:10,000. Considering the selected statistical approach and the research purposes (civil protection), only the most frequent types of landslides were considered, earth flows and slides (Cruden and Varnes, 1996), in the susceptibility analysis. The two types were modelled separately because their driving factors and failure mechanisms are different.

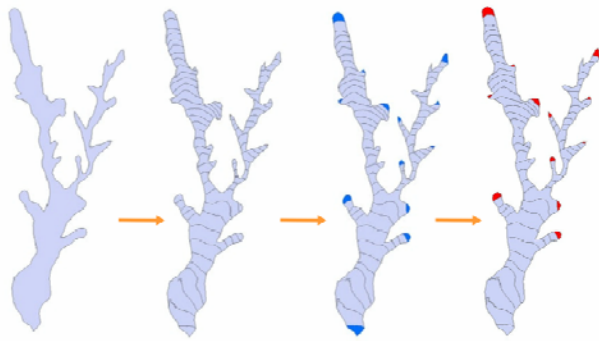


Figure 4 Schematic representation of the main steps utilized to extract the upper part of landslide polygons in ESRI ArcGIS 9.3.

As it is expected that susceptibility maps show the worst case scenario for mass movement initiation, one of the main problems encountered was that in the RER LIM scarps (depletion areas) are usually not mapped. However, the highest elevation points of the branches of each landslide polygon usually fall within the depletion area (Generali and Pizzolo, 2012). Therefore, the upper part of landslides polygons were used as training zones, assuming that they are most similar to scarps. They were extracted (Fig. 4) with a complex but semi-automatized procedure developed using ESRI ArcGIS 9.3.1 and three free extensions packages (Remove Small Polygons by Gonzalez, 2009; Find Adjacent Polygons by Buja, 2009; Topography Tools by Dilts, 2010 and Jenness Enterprise, 2006).

For both landslides types, the training sets were divided into two groups thanks to random selection as follows: the calibration set (80% of the sampling polygons) to compute the model itself and the validation set (20% of the sampling polygons) to estimate its predictive power. Only active landslides were included in the training sets (van Westen *et al.*, 2003; Poli and Sterlacchini, 2007). In the case of slides, rock slides were excluded from the analysis (the selection was based on the lithology map). The following analysis was conducted treating the two types of landslides separately as susceptibility assessment shows better results if one map for each types of movement, or movements comparable for materials and failure mechanisms, is computed (Zêzere, 2002; Fell *et al.*, 2008).

2.3 Factor maps

The utilized factor maps were prepared with ArcGIS 9.3.1 and its extensions for raster analysis (mainly Spatial Analyst) converting vector maps (lithology, land use and distance from roads; Fig. 5-a) in to 5x5 m cells raster maps and deriving geomorphic parameters (slope, aspect, curvature and Slope Position Index) maps from DTM 5x5 m (Fig. 5-b). The lithology map was derived from RER Geological Map 1:10,000 (11 classes). The 1976 map was employed for land use as it is the first digitally available one, assuming that the map represents land use at the date of the landslide activation or re-activation (assumption supported by the analysis of the RER Historic Archive data). The selection of the 13 classes were operated taking in account two issues: 1) the significance of each land use in respect with landslide phenomena; 2) the compliance with the 2008 land use map classes which is considered to be representative of the current situation. Distances from roads were obtained by buffering a vector map of State, Provincial and local roads (4 intervals empirically determined; Fig. 5-a). The 9 aspect classes are 45° each, while the 9 classes of the two slope steepness maps (different for the two types of considered landslides) were selected on the basis of a pre-analysis of maps with more than 70 classes, one degree spaced. The curvature map classes represent the 9 possible shapes that a hill slope unit can assume (Parsons, 1988) resulting from the combination of profile and forms (concave, convex and plain), represented in two maps derived from DTM in GIS environment and subsequently overlaid using ESRI Spatial Analyst Map Algebra operators. For the Slope Position Index map, the Slope Position Classification tool of ArcGIS extension Topography Tools (Jenness, 2006; Dilts, 2010) was used to compute the 6 classes. As it is a scale dependent factor, 4 different maps were produced using an equal number of circle radiuses for performing the Focal Statistic calculation (Neighborhood type) and the resulting maps were tested in susceptibility models taking into account the dimension of landslides (SIPI 10 and 20 m for slides, SIPI 50 and 100 m for earth flows).

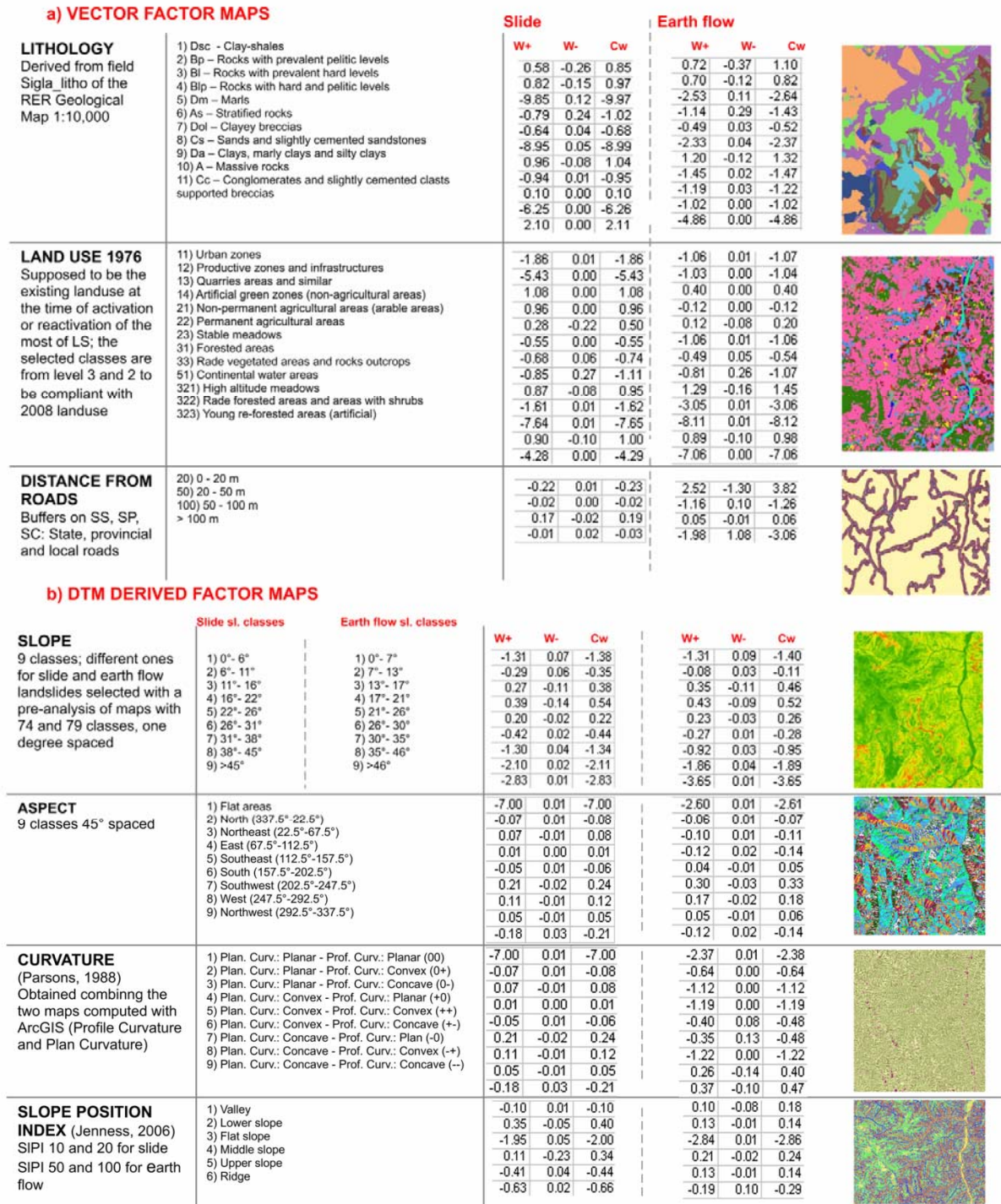


Figure 5 The whole set of factor maps introduced in landslide susceptibility assessment; a) shows vector factor maps; b) shows the DTM derived maps. The figure also reports the list of classes for each factor, the resultant weights and contrast factor (W+i, W-i and Cw) for each types of landslides. In Figure 5-a, it was preserved the acronyms used in RER Geological Map for the description of lithology classes.

2.4 Validation

Subsequently, the above factor maps were combined to obtain 18 scenarios (9 for each landslide types) and they were evaluated using Success Rate Curve (SRC) (Chung and Fabbri, 1999, 2003, 2008; van Westen *et al.* 2003; Sterlacchini *et al.*, 2011) and Prediction Rate Curve (PRC) (Chung and Fabbri, 1999, 2003, 2008; Sterlacchini *et al.*, 2011) methods. The first one, to evaluate the model fitting performance, is applied by plotting on the x axis the cumulative percentage of susceptible areas (from highest value to the lowest one) and on the y axis the cumulative percentage of landslides occurrences of the calibration set. The latter is a similar plot, but differs from the other as on the y axis the cumulative percentage of landslides occurrences of the validation set is presented. It evaluates the predictive power of the model. The steeper is the curve (SRC or PRC), the best is the result as a greater number of landslides fall into the classes of the map with the highest susceptibility. In order to compare different curves it is possible to use the AUC (Area Under the Curve), which is the extent of the chart area under the curve expressed in percentage. In this paper only PRC curves are shown and commented, as they are considered particularly interesting for the aim of the paper. Hence, in figures 6 and 7, PRC curve respectively for slides and earth flows, are plotted.

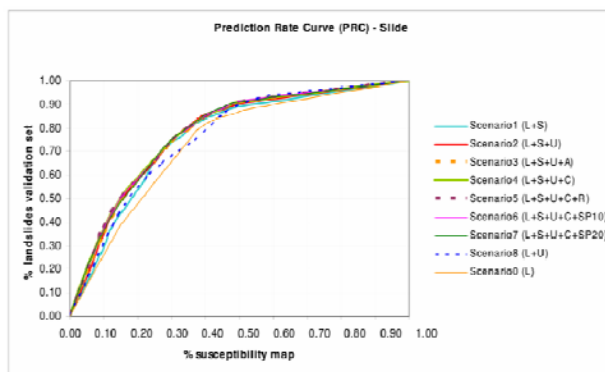


Figure 6 PRC Curve of the 9 scenarios computed for slides (L = lithology; S = slope; U = land use; A = aspect; C = curvature; R = distance from roads; SP10 = Slope Position Index (SIPI) 10 m; SP20 = SIPI 20 m)

They compare the 9 scenarios evaluated for each type of landslides. Analysing the plot in Fig. 6, PRC curve for slides, it can be noted that as the number of factors of the 9 scenarios increases, the curve becomes steeper.

At the same time, the AUC (Area Under the Curve) increases with the increasing of the number of factor maps from 0.74 (scenario 0) to 0.78 (scenarios from 2 to 7). From the curve in the Fig. 6, considering scenario 4, it can be said that 30% of the map predicts 75% of slides in the study area, which is a good result. Analysing the plot in Fig. 7, PRC curve for earth flows, it can be noted that the 9 scenarios have high value of AUC except for scenarios 0 and 5.

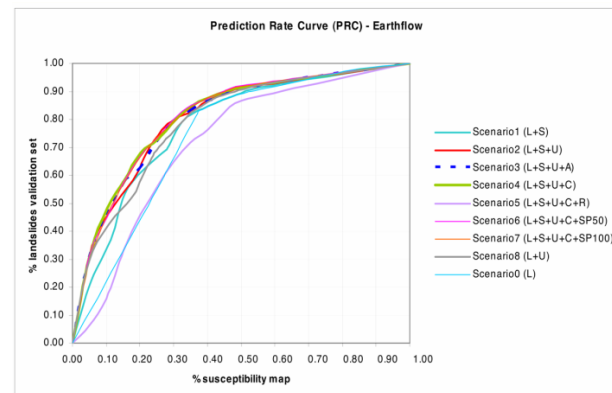


Figure 7 PRC Curve of the 9 scenarios computed for earth flows (L = lithology; S = slope; U = land use; A = aspect; C = curvature; R = distance from roads; SP50 = Slope Position Index (SIPI) 50 m; SP100 = SIPI 100 m)

This is to be expected for the first (one factor maps), but not for the latter (five factor maps). Scenario 5 differs from scenario 4 only for one factor (distance from roads), but the AUC of the first is only 0.72, while the AUC of the latter is 0.81. This means that introducing "distance from roads" the prediction rate worse significantly.

Considering scenario 4, it can be said that 30% of the map predicts 80% of earth flows in the study area, which is a very good result.

3. Application for civil protection purposes

3.1 Preparation of the map

Aiming to ensure a greater usability for civil protection purposes, the two susceptibility maps were integrated into a unique document and compared with the existing landslides (Fig. 9). The conditional Map Algebra expression in ESRI Spatial Analyst, utilized to perform the integration, was the following:

$$\text{Con}(\text{susc_map_ef} > \text{susc_map_es}, \text{susc_map_ef}, \text{susc_map_es}) \quad (3)$$

where *susc_map_ef* is the susceptibility map for earth flows and *susc_map_es* is the susceptibility map.

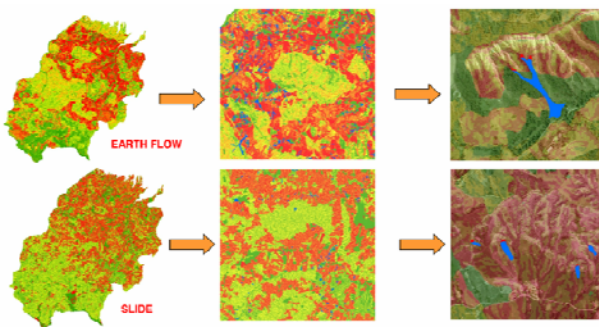


Figure 8 Susceptibility maps for the two types of landslide and a comparison with the existing landslides (red/blue polygons in the third image)

Briefly, it consists in assigning to each cell of the combined map the highest W_{maptot} value of the two original maps. In fact, it is often necessary to assess separately susceptibility for the different type of landslide affecting the area (i.e. for rock falls, small shallow landslides and deep-seated large landslides); these maps may be combined later onto one map (Fell *et al.*, 2008).

The susceptibility maps for each landslide type, computed as illustrated in the above paragraph, could be useful for skilled users, such as geologists and geomorphologists, while the combined map of equation (3) could be easier to understand for non-specialist users, such as in civil protection where users could be decision makers and disaster

managers, rather than technicians. The intelligibility of the map depends also on the adopted symbols, number of classes and colours.

To define class intervals is a hard task since it could strongly influence the interpretation of the map and consequently drive civil protection decisions. Anyway, it was considered that if the map is left as the GIS software automatically displays, or the number of assigned classes is too high, non-specialist users must interpret the map by themselves without having adequate knowledge on the real significance of the coloured pixels they are viewing. For this reason, two classification methodologies, among those which are available in ESRI ArcGIS, were experimented in order to define the map legend: Quantile and Natural Breaks (Jenks). A third, Equal interval methodology in which each class has an equal range of values, was dismissed a priori because it was considered unsuitable for representing the type of data discussed in this paper. In both cases, Quantile and Natural Breaks (Jenks) five susceptibility classes were generated (very low, low, medium, high and very high). Briefly, in the first method each class contains an equal number of features whilst in the latter the features are divided into classes whose boundaries are set where there are relatively big differences in the data values. In the current case, by using the Quantile methodology the ratio between negative and positive values of map cells' weights appeared more "equilibrate".

The differences between classes seemed emphasized locally. Using Natural Breaks (Jenks) method, a map was obtained in which cells with the value "medium susceptibility" and "high susceptibility" were predominant. As Natural Breaks (Jenks) is a data-specific classification, and suitable for representing unevenly distributed data, the related map was preferred and loaded in the Risk WebGIS of the Province of Modena Civil Protection.

3.2 Comparison with multi-temporal orthophotos and field data

In order to perform a direct checking of the output maps quality, they were compared with existing landslides in RER LIM (Fig. 8), orthophotos (AGEA 2008 and 2011) and field surveys (Fig. 10).

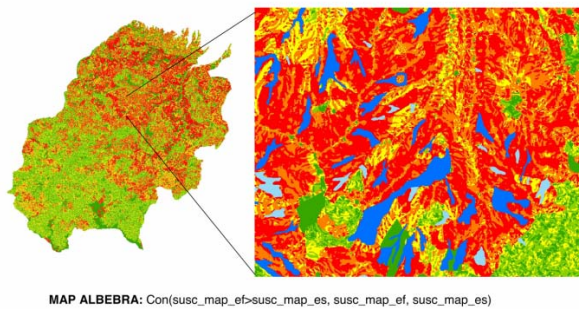


Figure 9 The combination of the two susceptibility maps (the existing landslides are in blue and cyan)

The latter were carried out in a sample area and provided good result as is shown in Fig. 10: landslide clues and warning signs (scarp retrogression, typical morphologies, sags in the road etc.) correspond to the areas of the map classified as medium to very high susceptibility. In addition, the comparison with the orthophotos provided a positive result in most cases for all the three susceptibility maps (earth flows, slides and combined). Very frequently where landslides from RER LIM are located, the maps' cells are classified as medium to very high susceptibility, even if in some cases they are classified as low susceptibility. The reasons may be different: 1) the susceptibility assessment reported in the present paper did not take into account all types of landslide; 2) the input data might have some lack of information; 3) after the landslide occurrence it might be reached a new equilibrium. In any case, it must be remembered that the three susceptibility maps represent the "initiation points", namely points or areas where new mass movements could initiate. Therefore, while comparing susceptibility maps with the existing landslides from RER LIM, rather than considering the landslide body, it must be verified what classes are assigned to the area of scarps and/or upstream of them. An interesting case is shown in Fig. 11 in which the orthophoto a) is the AGEA dated 2008 and b) is the AGEA dated 2011. The map in figures c) and d) is the combined susceptibility map of Fig. 11. The c) version is obtained with Natural Breaks (Jenks) method while the d) is made by means of Quantile method (see previous paragraph). The polygon with the blue outline is a

landslide reactivation. The movement is located in the Secchia Basin near the large and well-known landslide of Boschi di Valoria (Manzi *et al.*, 2004). It is mapped in the RER LIM and classified as active complex landslide. In the 2008 orthophoto (Fig. 11-a) the landslide appears to be dormant; only the scarp is visible. On the contrary, in the 2011 orthophoto its reactivation is conspicuous. The area of the reactivation is classified as "medium", "high" and "very high" susceptibility in both maps (Fig. 11-c and 11-d). In the Quantile version of the map (Fig. 11-d) there is a high compliance with the zone of the scarp. This example (not significant for the issue discussed in the previous paragraph about the symbolization methodology) highlights that the evaluation of the risk on an area like that of Fig. 11-a could be reviewed by Civil Protection during planning activities by examining the susceptibility map. This is even more important considering that landslide reactivations could damage buildings and infrastructures (Galve *et al.*, 2015; 2016) as in Fig. 5-b where a road is intersected by the landslide accumulation.

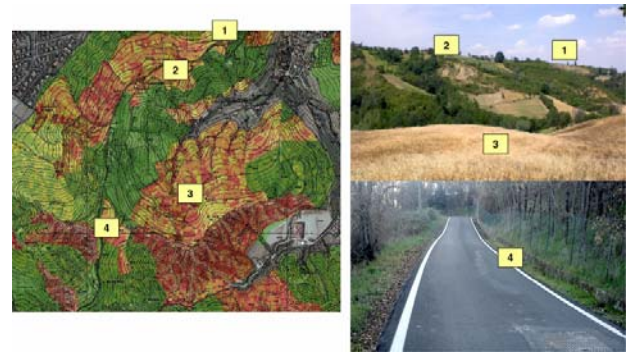


Figure 10 Direct checking of resultant susceptibility maps quality performed by means of field surveys in a sample area (Corlo Basin in the Municipality of Fiorano Modenese)

3.3 The updating issue

One of the main challenges in cartography is to maintain the data steadily updated. The availability of updated data is fundamental for civil protection purposes. For this reason, a simple but effective procedure was developed using Model Builder in ESRI ArcGIS 9.3.1. It is based on the following

assumption: the most part of landslide driving factors, used before for computing susceptibility maps, can be considered static except for land use which is surely subjected to a rapid evolution and therefore is dynamic. When a new land use map becomes available, it can be converted in raster and its classes uniformed with those of the 1976 land use map. After that it can be reclassified using weights calculated on 1976 land use map and added to the other weighted maps (slope, lithology and curvature) in order to obtain the new susceptibility map. Thanks to the Model Builder tool "Update SMap" (Fig. 12), even non-specialist users are able to perform these kind of operations for each landslide map (earth flows and slides), and subsequently the two updated maps could be combined into one using the conditional equation (3) in ESRI Spatial Analyst Map Algebra.

3.4 Discussion

The susceptibility analysis led to a better understanding of the most important factors for slope instability in the study area. It made available new susceptibility maps useful for civil protection purposes in Province of Modena that can be loaded as thematic layers in the Risk WebGIS, including the input factor maps (e.g. lithology, slope, aspect, curvature, slope position index and distance from roads). The final susceptibility map documents are good decision support tools suitable for the elaboration of events' scenarios in the framework of civil protection forecast and prevention programmes (Soldati *et al.*, 2014). When overlaid with elements at risk (such as buildings, roads and other infrastructures, population etc.), that is easy to be performed with the Risk WebGIS, Civil Protection can obtain damage scenarios useful for the provincial emergency plan on hydrogeological risk. The 1:10,000 map scale, consistent with those of the input data, makes them usable for wide area (supra-municipal) forecast and prevention purposes like provincial territory is. Other than the resultant susceptibility maps, the analysis itself highlighted

weak points and gaps of the existing inventory map that could be partly fixed by Civil Protection. In fact, the Modena Civil Protection collects data on landslide from municipalities, by means of the SRD (data collecting system), the module connected with the Risk WebGIS, and stores them in the geodatabase. Highlighted gaps could drive a revision of the data collection forms. About the updating issue, the tool implemented for updating susceptibility maps could be used also for a small part of the territory, when new data on land use are available partially, or to design landslide susceptibility scenarios assuming a variation of land use.

4. Conclusions

The present paper deals with the issue of risk forecasting in civil protection, which consists of activities aimed to study and detect what are the causes of hazardous events, namely landslides, as well as to identify areas particularly prone to mass movements for zoning them and plan measures to mitigate related risk. In the case of the Province of Modena, earth flows and slides happen frequently and are widespread, hence they generate critical situations for the population, damaging infrastructure, especially roads, and sometimes buildings. They often require the intervention of Civil Protection even when they are not extensive. Thus, a susceptibility assessment for these two types of landslides was performed and described in the present paper. Considering the above mentioned limitations due to input data, the resulting models predict an acceptable number of landslides. In both cases, earth flows and slides, the final susceptibility map is the sum of the following weighted factor maps: lithology, slope, land use and curvature. They resulted to be the most important factors which drive landslide phenomena in the study area. In order to take into account current situation, weights calculated by means of the 1976 land use map

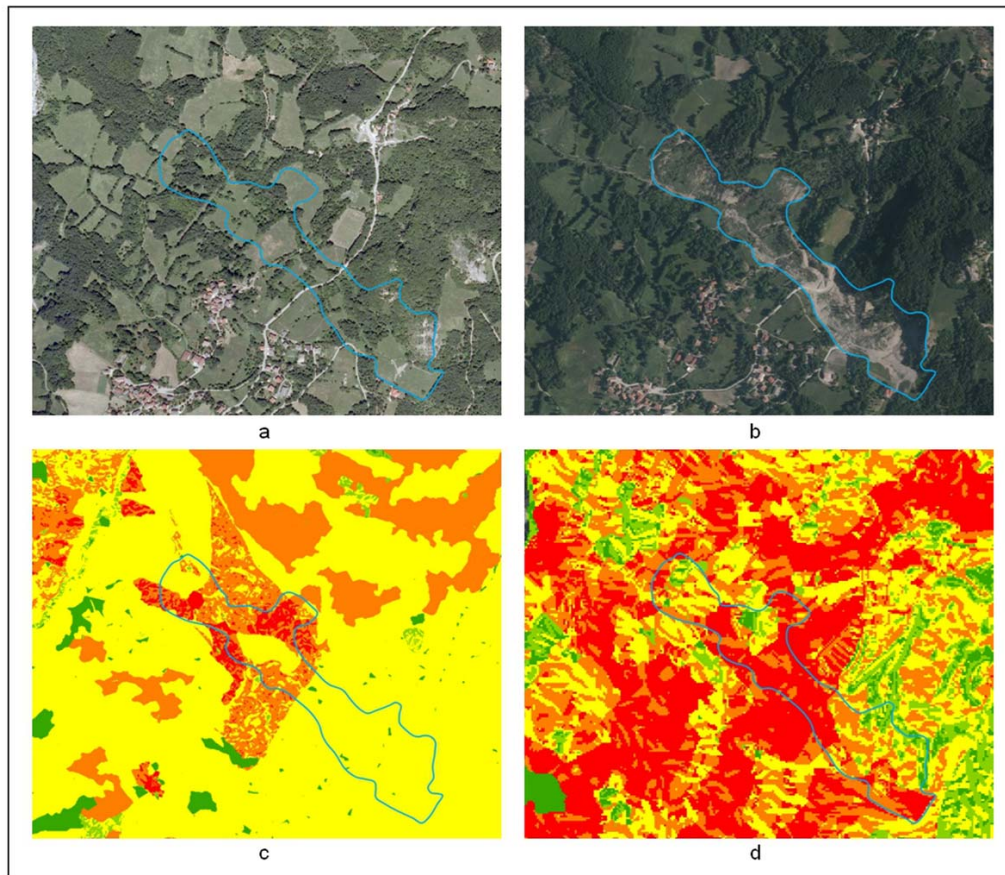


Figure 11 Orthophoto a) is AGEA 2008 and b) is AGEA 2011. The depicted map is the combination susceptibility map of Figure 9. The c) version is obtained with Natural Breaks (Jenks) symbology classification method whilst d) is made by means of Quantile method. The polygon with blue outline is a landslide reactivation, existing in RER LIM, the shape of which is clearly recognizable in 2011.

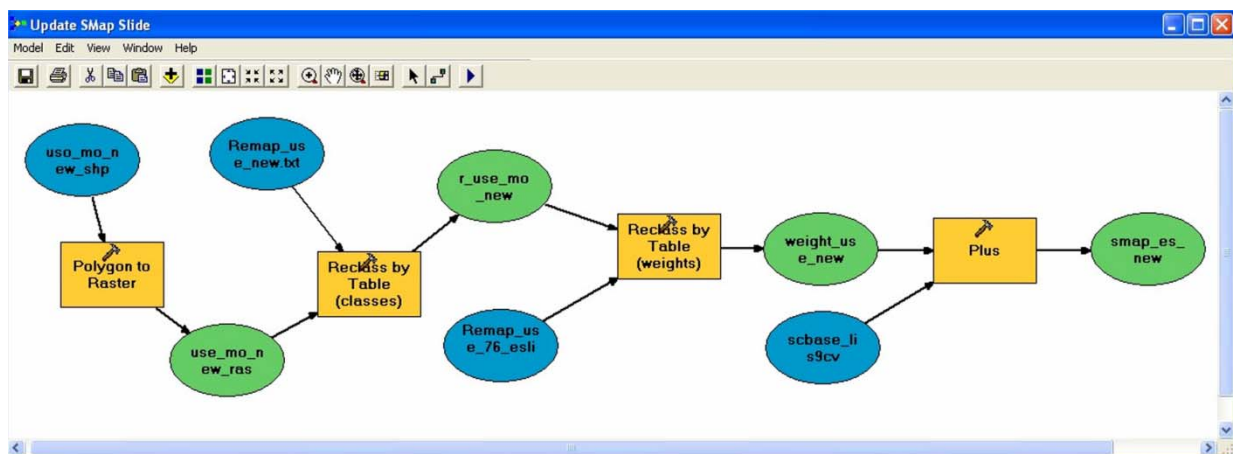


Figure 12 The Model Builder scheme of ESRI ArcGIS reporting operations needed to update the susceptibility maps. The tool designed for updating slide susceptibility map is shown in the figure; the one for earth flow map is similar.

(assumed to be the situation before the existing landslides occurred) were assigned to those of 2008. Therefore, two susceptibility maps were computed for as many types of landslides. These documents are useful for skilled users but difficult to be interpreted by non-specialists, such as Civil Protection users who were supplied with a third document resulted from the combination of the two maps. In order to increase the intelligibility of the map even more, two classification methods of ESRI ArcGIS were tested to symbolize the map: Quantile and Natural Breaks (Jenks). The range of weight values were grouped into only five legend classes. In fact, an excessive number of classes could confuse the user and lead to a wrong interpretation of the map information content. Both tests on the two classification methods led to good results, but the Natural Breaks (Jenks) method was preferred to continue the test that is still to be concluded. In fact, at this point the map was considered ready to be loaded in the Risk WebGIS of the Modena Province Civil Protection. The example of Fig. 11 demonstrates how the susceptibility maps can be useful for Civil Protection in order to include in their plans some landslide apparently dormant in certain period of time.

Another issue to be faced was the “updating question”, well known in cartography. Maps risk to age before users become familiar with them. Hence, some custom tools were developed for ESRI ArcGIS with Model Builder assuming that only land use is a dynamic factor. The procedure is simple enough to allow even users with little experience of GIS to update maps. Having worked on a wide study area (about 1300 km²), using a quite detailed DTM (5x5), and a statistical method easy to apply (Weight of Evidence) which has also allowed the development of an automated GIS procedure for updating the landslide susceptibility maps, makes what is illustrated in this paper an example for other Civil Protection organizations, other than Province of Modena one. In fact, if on the one hand Civil Protection needs detailed data, on the other hand at a supra-municipal level an overview of hazardous phenomena is required to perform planning activities. In addition, the actions undertaken to make the susceptibility maps more intelligible, issue

seldom investigated by those who assess landslide susceptibility, become fundamental in a context of civil protection.

In conclusion, the experience conducted in the framework of the research discussed in this paper is exportable to other civil protection contexts where the integrated planning among stakeholders (i.e. regions, provinces, municipalities etc.), the constant and dynamic updating of geographic information, as well as an efficient system to share them (namely WebGIS applications), is considered strategic for risk forecasting and preventing, and emergency management.

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Landslides and human interference in Darjiling Himalayas, India

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ABSTRACT

Landslides are among the nature's primarily ways of adjustment to slope stability. In Darjiling Himalayas the process has been intensified by human interference mainly through rapid deforestation, incorrect construction procedure and unplanned tapping of natural resources. The present paper aims at investigating the occurrence of landslides mainly due to human intervention. For analyzing the acuteness of the problem, important events of landslides over time, landslide susceptibility map using traditional check-list and investigation of the nature of human intervention for landslide occurrences have been carried out. From the study it is found that extreme rainfall events of consecutive days accumulating an amount of 1000 to 1200 mm, coupled with deep weathering in susceptible structure could trigger to 5 to 10 m-thick landslides. Being saturated with percolating rainwater, such slopes even with a rainfall 50 of mm/h would cause disastrous landslides. Common occurrence of landslides is found along the springs, where thick debris is removed along the slope, on top of the bedrock.. Generally deforested urbanized tracts, illegal coal mining sites, tea gardens, artillery roads connecting hills with the plains are the most susceptible areas to sliding.

KEYWORDS

Slope stability; deforestation; incorrect construction; structural elements; joints and shear plane

1. Introduction

Landslides and related phenomena are the most serious natural hazard in the Darjiling Himalayas which undermine the overall socio-economic development of the area. From the past records it

becomes apparent that the area has been suffering from landslide problems since 1899 and the situation has deteriorated further in recent time, particularly after India's independence (1947) and

the last three decades (since 1968) have witnessed the most damaging landslide cases.. The Darjiling Himalaya, elevated at 2000-3000 m asl, extends at the foreland of the Kanchenjunga massif and are exposed directly to the invasion of humid air masses from the Bay of Bengal. The rising mountains with ever increasing human interferences create favourable conditions for rapid runoff, landslides and floods. The damages after heavy rains are extremely large. Landslides are known to be among the worst disaster phenomena in the concerned area. Even a glance at landslide statistics gives some idea of the enormity of damage done and the ever present threat to lives and property (Starkel and Basu, 2000). So far as the history is concerned, sliding was a minor physical phenomenon a hundred and fifty years ago. Ever since the British occupation, the physical and cultural set up of this region has been seriously disturbed. Tea plantations, extensive deforestation, hazardous construction works, inadequate drainage, in other words – unscientific and unplanned usage of land has led to the establishment of a vicious cycle of denudation, vulnerable geological structure along with heavy and concentrated rainfall enhancing soil-erosion and landslides.

2. Location and physical background of the study area

The Darjiling Himalayas (Fig. 1) are located in the mountainous part of the Darjiling District above the 300m contour line and is bounded by latitudes 26°50'N to 27°13'05"N and longitudes 87°59'30"to 88°53'E, comprising of an area of 2417 km². They are including three hilly sub-divisions of Darjiling Sadar, Kalimpong and Kurseong and host a population of 790591 in 2011. In Darjiling Himalayas, landslides are long-time acknowledged as being the worst disaster phenomena which could inflict damages to human lives and properties.

The Darjiling Himalayas are separated from the foredeep of the Ganga-Brahmaputra plain by two active tectonic lines in the subduction zone of the Indian block (Fig. 2) and were built through a sequence of overthrusts pushed southwards and deepening to the north (Fig 3). Going southwards

from the north there are the medium resistant Darjiling gneisses, the Daling metamorphic rocks of varying resistance, from phyllites to quartzites, and the Damuda shales with coal beds. The Damudas are separated by the Main Boundary Fault from the narrow thrust of Siwalik built of Tertiary sandy molassic deposits. The Siwaliks are separated by the active Himalaya Front Tectonic Line from the subsiding Bengal plain (Fig. 3). Some fresh tectonic scarps and exposures with the Tertiary overthrusts over the alluvium deposits indicate that the movement continues. The uplift in the Eastern Himalaya is calculated to be of the order of 0.5 to 2.0 mm/yr (Starkel and Basu, 2000). The Darjiling Himalaya are rising directly over the piedmont plain called Terai composed by a system of alluvial fans. The edge of the hills is dissected with slopes inclined to 30-40° and at a distance of 2 km from the piedmont plain rise to 600m above it. The higher ridges are represented by hog backs, which are elevated to 1200 m a.s.l. at 6 km distance and to 2000 m a.s.l. at 12 km

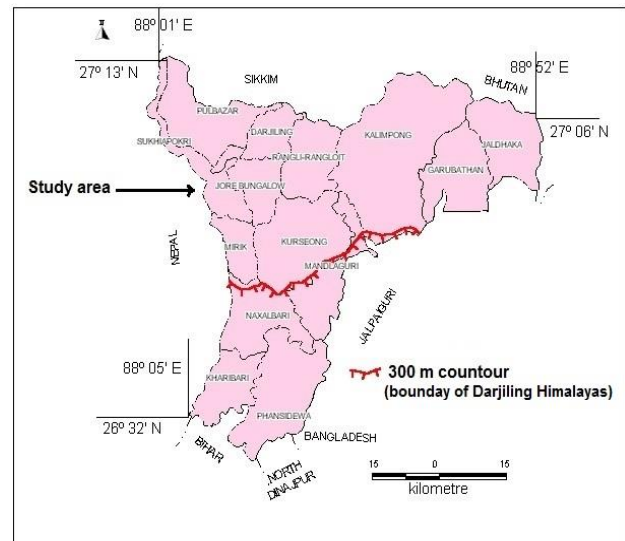


Figure 1 Location of the Darjiling Himalayas

In general young convex slopes with weakly developed concave basal part dominate the relief. Their steeper portions are inclined at 30-45° and are mainly rocky; the more gentle slopes inclined at 15-30° are covered by regolith. But such simple slope profiles are relatively rare.

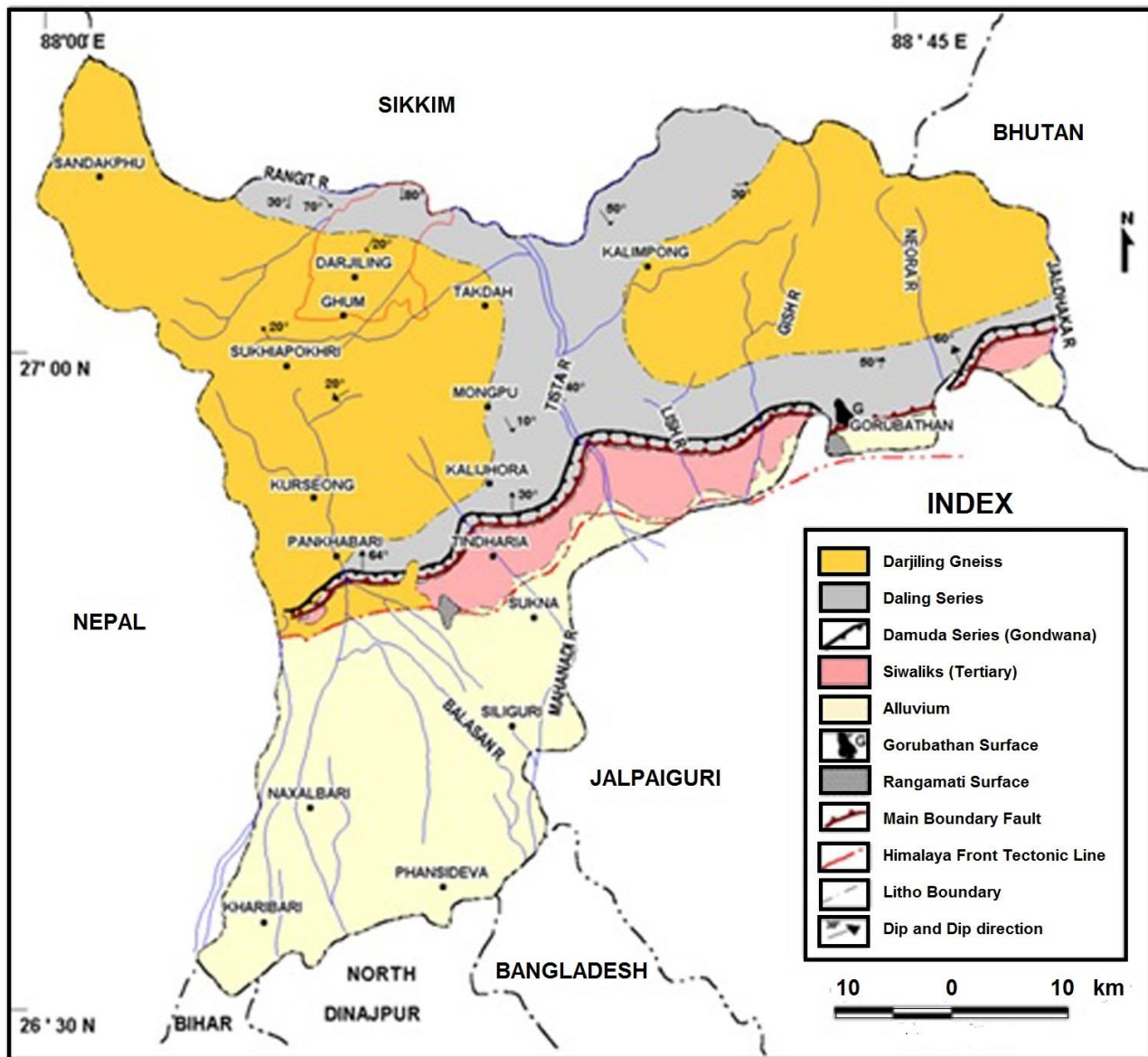


Figure 2 Geological Map of Darjiling District (modified after Ganssar, 1964)

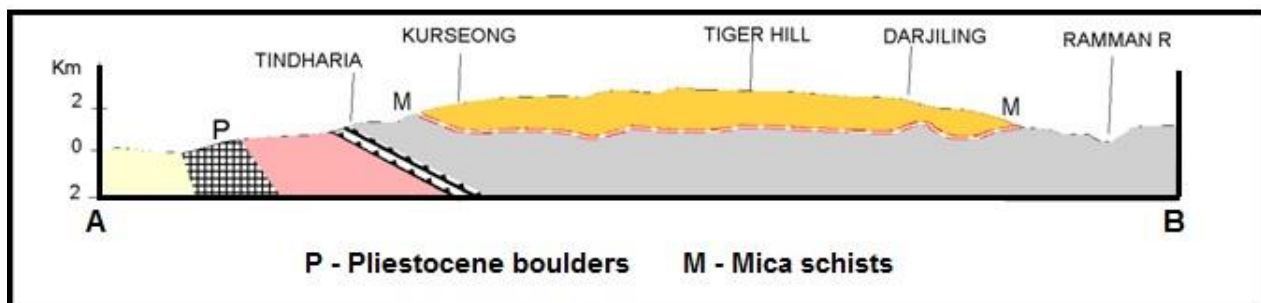


Figure 3 Cross section across the geological formations (modified after Ganssar, 1964)

In general young convex slopes with weakly developed concave basal part dominate the relief. Their steeper portions are inclined at 30-45° and are mainly rocky; the more gentle slopes inclined at 15-30° are covered by regolith. But such simple slope profiles are relatively rare. Very frequently on a single slope there are several scarps and flattening which are mainly structure-controlled and rarely reflect an older phase of planation (Froehlich, et al, 1989).

The major southern slope of the Himalaya lies at the margin of the high-pressure belt where seasonal migration of wind systems alters the weather and rainfall pattern. The summer monsoon starts in May and ends in September or early October. Beside seasonality, the second feature of climate in the Darjiling Himalayas is created by the orographic factor, causing the vertical zonation of temperature and other parameters and the decline of precipitation moving from the margin to the centre of the mountains (Froehlich, et al, 1987).

The annual precipitations fluctuate from 4000-6000 mm at mountain front and then decline to 2000 mm north of Darjiling. In Darjiling there is a distinct seasonal distribution of rains. It fluctuates from several mm in winter months up to 400-800 mm every month in summer. The number of days with rain in Darjiling is 124 (among them 102 from May to September).

The variable thickness of regolith and soils in the longitudinal slope profiles depends on the rate of weathering and intensity of mass movements connected with slope gradients. In many cases the thickest soil profiles are composed of *in situ* regolith and superimposed colluvial or proluvial deposits. The mountain slopes are covered with sandy-silty soils, usually 0.5 to 2.0 meter thick (on flat surfaces up to 4 meter). They change from red clay soil in the lowest elevation areas to grey brown forest soils in the higher elevations sectors. Soils are generally permeable but their thickness and physical parameters vary from place to place depending on the slope gradient, lithology of weathered bedrocks and land use.

3. Population growth in the Darjiling Hill District

Success of tea plantation, partition of Bengal, introduction of tourism and the resultant massive construction works (expansion of roads, construction of new urban structures etc.) ushered in more and more immigrants from the neighboring countries and thereby more than doubling the population of Darjiling Hill District (328785 persons) in 1951, while by 2011 the recorded population was of 790591 persons. The population density changed from 38 persons /km² in 1881 to 74 persons /km² in 1901 and 327 persons/km² in 2011 (Fig. 4).

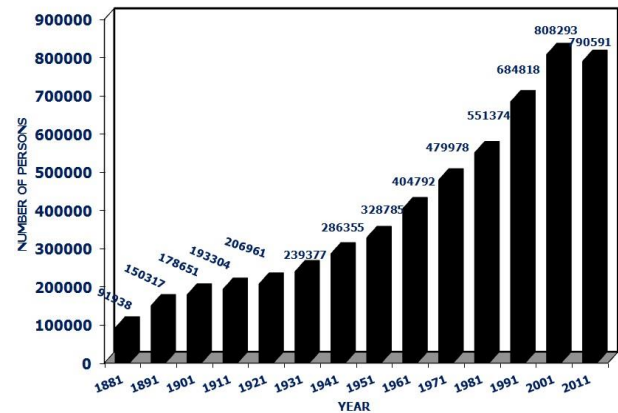


Figure 4 Decadal growth of population in Darjiling hill district

4. Materials and methods

The base map has been prepared from the Survey of India topographical sheets of 1:50,000 scale (Sheet nos. 78 A/4, 78A/8, 78 B/1, 78 B/5 and 78 B/6), Landslide spots have been plotted from the secondary data bases collected from the Geological survey of India, IRS P6- LISS III satellite image, Google Map images and from different published literatures. Field rectification of such slide spots has been done through extensive field survey with the help of handheld GPS.

Identification of landslide-prone areas has been performed with the help of a "Check-List" where each separate and discrete slope unit has been classified according to their stability rating. Rating

has been done according to a scale from stable to already failed, through several degrees of potential instability. Special attention has been paid to the old slides, which could become re-activated. The position and depth of different excavations, drainage diversion across the hills, loading of the upper/lower slopes, cutting of basal support, unscientific construction and land-use, deforestation, legacies from the past slope movement (landslide reactivations), relief unit, drainage characteristics, slope materials, etc. have been accounted for in the "Check-list". Data for such investigation have been collected from the direct field observation (82 sample sites) as well as from secondary sources, and a geomorphological map has been prepared for the landslide-prone areas.

Through the investigation of location and causative factors of such landslides it is found that rainfalls and earthquakes are the main triggering factors, but most of landslides have been taken place due to their preparation through human intervention. An analysis of landslide occurrences in different parts of Darjiling since its inception in 1899, reveals that the most common occurrence of landslides is found: *a.* along the springs which invariably cut across the roads, *b.* at illegal coal mining sites *c.* in tea gardens and *d.* in urban agglomerations. As such the present study has been restricted to those sites only. Therefore, the following case studies of individual landslides due to human intervention have been considered from different parts of the Darjiling Himalayas.

5. Result and discussion

5.1. Landslide events in Darjiling

From the available records it is found that disastrous landslips occurred during September 1899, January 1934, June 1950, October 1968, September 1980, September 1991, July 1993 and July 1998 (Fig. 5). Such landslides caused widespread damage to human lives properties, roads, railways and cutoff the town from the rest of the region. Details of all these slides except 1998 are shown in Table. 1. The causes and consequences of the 1998 landslides

have already been described along with the landslides related to the transportation routes heading to Darjiling by Basu, in 2000).

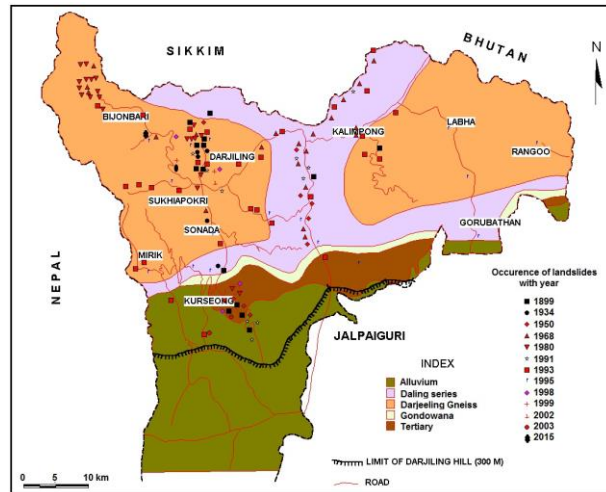


Figure 5 Distribution of landslides in different lithological formations

On July 8th, 2003 at about 3.30 a.m. a landslide occurred at Gayabari Bustee and four houses were destroyed and twelve lives were lost (especially due to the early hour). On July 7th, 2004 a series of devastating landslides crippled the tourist movement to Darjiling affecting the Hill Cart Road in several places. High rainfall amount coupled with rock falls damaged the road along the Jhora crossings. Cracks on roads favored the flowing water to seep underground and caused subsidence. During July 1-2, 2015 continuous rainfall for more than 72 hours amounting 350 mm caused severe debris slides in Gayabari and Tinling tea gardens and tolled 68 lives as well as the destruction of 16 houses.

5.2. Landslide susceptibility zonation

From the detailed check-list and according to an expert judgement approach, the following three susceptibility zones have been demarcated based on the susceptibility values (Fig. 6).

i) High landslide prone areas: the Tindharia-Pagalajhora, Pankhabari, Rimbik-Lodhama, along the river Tista, Bijanbari, in and around Darjiling, Kurseong, Mahanadi, Ghum, Sonada, Sukhiapokri

Table 1 Major events of landslips in Darjiling town and their effects

PERIOD	LOCATION	TYPE	CAUSATIVE FACTOR
January, 1897 23rd – 25th September, 1899	Tindharia Landslide Tumsong, Margaret Hope Landslides	Subsidence – induced Debris-slide	Rainfalls Heavy and concentrated rainfall (1065.5mm) increasing pore water pressure and gravitational pool on the loose materials
15th January, 1934	Sukhna and Tindharia Landslides	Subsidence – induced	A number of ground fissures developed due to Bihar-Nepal Earthquake
11th – 13th June, 1950	Kurseong Landslide	Debris slide along a stream	Heavy rainfall (834mm) with solifluction
11th – 13th June, 1950	Mirik and Gayabari Landslide	Rock fall	Heavy rainfall and gravitational pull on loose rocks
2nd – 5th October, 1968	Ambootia Landslide	Debris flow	A big debris tongue carved out a channel at least 30-60 m deep due to heavy rainfall (890mm.)
7th July, 1985	Pankhabari Landslide (4.00 km south of Kurseong)	Rock fall	Heavy rainfall and gravitational pull on loose materials
7th July, 1985	Pankhabari Landslide (4.20 km south of Kurseong)	Debris slide	Heavy rainfall, solifluction and gravitational pull on loose materials
8th July, 2003	Gayabari Landslide	Debris slide	A concentrated rainfall of over 300 mm during a period of over 48 hours
16th August, 2009	Gourisankar Landslide	Debris slide	Torrential rain for a period of more than 70 hours and flash flood
June 16, 2010	Paglajohra Landslide	Debris slide	Torrential rain of 122mm from 16 to 20 June, 2010
September, 2011	Tindharia Landslide	Debris fall	Earthquake (M_w 6.8)
June, 2012	Tindharia Landslide	Debris slide	Torrential rainfall
July 1-2, 2015	Gayabari and Tinling Slide	Debris slide	Torrential rainfall

sectors are included in this zone, which occupies about 32% of the Darjiling Himalayas hills.

ii) Moderately landslide prone areas: in this zone landslips occurred once or twice in last ten years. The lower hills and the North facing slopes are showing moderate to moderately-low susceptibility and covers about 30% of the study area.

iii) Low landslide prone areas: the ridges having almost flat slopes are less susceptible to landslides. Both the hill top and lower parts towards the southern part of the study areas belong to this category which covers about 37% of the whole area.

5.3 Human intervention on landslide events

5.3.1. Landslides along the transportation routes to Darjiling: Pagla Jhora

Occurrence of landslides in Darjiling Himalayas is mainly found along the springs, which cut across the Hill Cart road as well as other roads connecting the hills with the plains. The most vulnerable site is situated in between the Upper and the Lower Pagla Jhoras (Fig.8), extending about 8 km in length. Here, the road has subsided at a maximum depth of about 7-9 m. since 1979 (Basu, 2001).

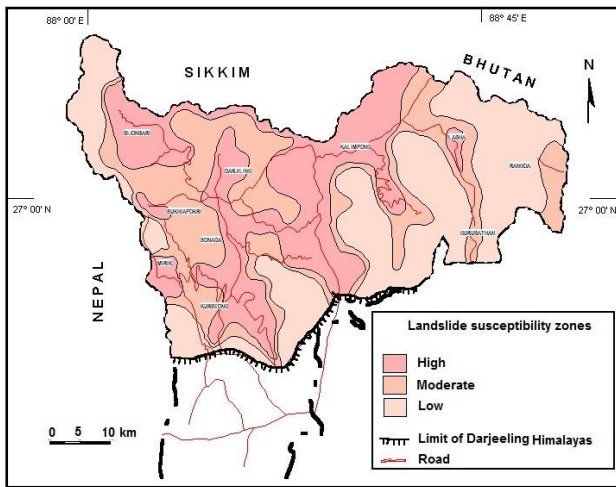


Figure 6 Landslide susceptibility zones of Darjeeling Himalayas

The Hill-Cart road always provides a space for deposition of materials of the overflowing mountains torrents. The slope-wash materials consist of large boulders as well as fine-grained silt. The narrow culverts below the roads are inadequate to cope with the exceptionally high discharge of the springs during rains. Moreover, smooth passage of the discharges of the springs are sometimes temporarily blocked by the presence of boulders below the culverts until the rising water levels flow along available depressions on the road benches to create a new course diverting the spring away from their earlier established paths, causing loss of basal support and ultimately creates landslides. The damage of the road bench in all cases has been proportional to the discharge of the spring. Where the discharge exceeds the carrying capacity of the spring, the road bench also acts as a drainage channel. Cracks characterizing the road, allow the water to percolate below and erode the softer veins of rocks like phyllites and schists and thereby causing further subsidence along the road.

The Pagla Jhora and its tributaries with their exceptional discharges during 5th to 7th July, 1998 (Bhattacharya, et.al., 1998) due to high rainfall amounts (300 – 600 mm) badly damaged the rail, cutting the road bridges from 37.5 to 45.5 km causing numerous landslides, due to bank undercut. The morphological configuration of the mentioned area is largely controlled by geological structure and the existing hydro-geomorphic process. Bedrock

slopes are 35° – 43° in inclination, uniform in pattern, partially stable and mostly free from sliding and slumping. The colluvial slope in the upper part consists of gigantic gneissic boulder of above 40 m in diameter. The size appears to be smaller (10-15 m in diameter) in the middle and lower parts. The slope form developed over such deposits is complex and exhibits a combination of convex-concave-irregular form with highly variable inclination (10° – 25°). Field evidences suggest that the active mass movements including slumping at Pagla Jhora is directly related to this colluvial nature of hill slope.

Overland flow feeding the uppermost niche, during heavy rains, transforms into concentrated sub-surface flow over the less permeable gneissic bedrock. The observed rills and gullies facilitate the piping and deep drainage towards the slump areas. Thus, the subsurface flow is connected with the continuous beds in the colluvial sequence and jointing of bedrock. It is probably much higher during heavy rains with superimposition of an overland flow and seepage pressure. The flattening of topography suggests a subsurface run-off towards SSE direction.

The high intensity of the processes as well as the relative heights and steep gradients are the limiting factors in the stabilization of the Pagla Jhora slumps (Fig. 7). At present the form reached a quasiunstable equilibrium. Each extreme rainfall (> 300 mm/day) causes substantial change in its morphology. The expanding incised valley and reactivated scarp along the upper section poses a danger to the Hill Cart Road, railway line and the existing settlements. There is every possibility of further sliding and slumping in this area until the slip surface reaches the underlying compact bedrock, 15 –30 m below the present surface (Sarkar, 2011).

The corrective measures that have so far followed in case of Pagla Jhora consist of: a) building up of a retaining wall made of boulders (irrespective of their hardness) at the affected area (Fig. 8) and covering the newly built-up wall with a weir net and b) construction of a number of weep-holes in the retaining walls to allow the rain water to flow out.

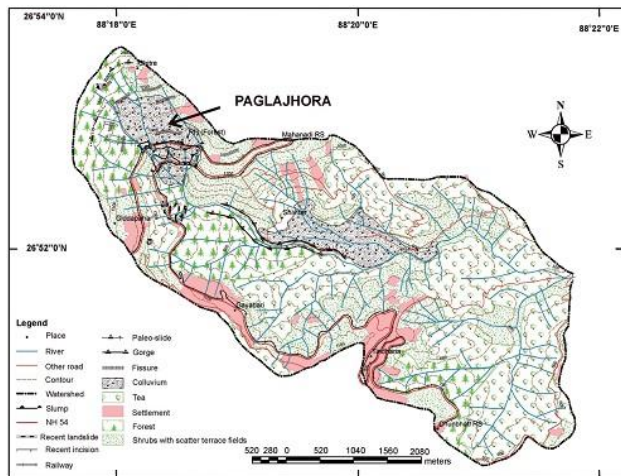


Figure 7 Pagla Jhora landslide in Shiv Khola slump basin (Sarkar, 2011)

The corrective measures that have so far followed in case of Pagla Jahora consist of: a) building up of a retaining wall made of boulders (irrespective of their hardness) at the affected area (Fig. 8) and covering the newly built-up wall with a weir net and b) construction of a number of weep-holes in the retaining walls to allow the rain water to flow out. With the onset of monsoon and the consequent washing away of the plaster coating of the revetment wall, it was created a passage for the rain water to percolate below which lead to the erosion of the softer veins of the boulders. If one boulder is thus reduced in size creating space for other boulders to roll down by gravity in order to occupy the empty space, the equilibrium of the newly built up revetment wall is thus lost (Fig.9). In such a competition among boulders to occupy the empty space, the wire-net will take too much load concentrated at a particular point,, creating a passage through which adjoining boulders will be let loose. Moreover, most of the weep- holes are choked with fine silt or clay after rains and as there is none to clean these, so the free passage of rain water through the retaining wall beeing thus not at all possible. Water is accumulating behind the wall, flows out along the sides of the wall creating deep gullies which ultimately contributeat dislodging the whole retaining wall. In between the upper and lower Pagla Jhora, on the existing road bench of Hill Cart Road, large wide-open arcuate cracks were visible during the landslide disaster of July, 1998

(Basu and De, 2003). Infiltration of surface waters into these cracks, has been visible in many places. Such infiltration increase the pore pressure within the soil on valley sides and was responsible for slope failures in these areas. The south- eastern slopes of Giddha Pahar at about 46 km from Siliguri shows a surfacial slope failure on the hill slope and subsidence zone towards the valley. These are indicative of the instability of the area and the possible presence of a slip zone below the road bench. A few of the above mentioned areas were affected by the landslide disaster on 13th July, 2003. Some old slides and subsidence zones (Fig.10) in and around Pagla Jhora were reactivated. A major portion of NH55 near Pagla Jhora at 14th Mile had again gone down 15 m on 8th July, 2004 due to torrential rains which lasted for almost a couple of days. The present condition of NH55 at Pagla Jhora has become so acute that it has been decided by the authority to divert the road along with the railway line for avoiding further disasters.

5.3.2. Illegal coal mining and the incidences of landslides and subsidence: Tindharia

Sir Joseph Hooker in 1854, while going to Darjiling, noticed several people burning coal near Pankhabari, for the first time. Mallet (1874) while preparing the geological map of Darjiling, identified a narrow band of coal bearing rocks extending between Pankhabari and Dalingkot, covering a length of 37 km. Coal exposures are not continuous everywhere. These are well exposed at Pankhabari, Tindharia, Kalijhora, Bagrakota, Dalingkote and in the valleys of Mahanadi and Tista (Ghosh, 1975; Ghosh, 1998). Due to its flakiness and crushed condition, the former British Government never felt interested in its natural state economic utilization. As such, since 1896 many private firms opened up collieries to extract coals from places like Bagrakota (1896- 1900, extracted about 7231 tonnes of coal), Chunkhola (1943 – 1961, collected 30000 tonnes of coal per year), East Bagrakota (1960 – 62, total production was 25700 – 37200 tonnes), Lethi Colliary (1961–62, total production 900-1200 tonnes) and Fagu Colliary (1962- 63 total production 2600 – 6600 tonnes).



Figure 8 Subsiding Hill-Cart road al Lower Pagla Jhora. The Toy train and the vehicular tracks are at different levels. The former boundary wall of the road is found at a lower level (Photo: S. R. Basu)



Figure 9 Building the retention wall along the Hill Cart road at Pagla Jhora without any weep hole (Photo: Author)

All these collieries were abandoned in 1964 due to labour-force legal troubles.

The modes of quarry operations in the coal mines mentioned above were introduced by a group of profiteering miners, without following scientific procedures. They punctured the entire slope face with diggings in order to obtain only a few tonnes of coal and did not treat the abandoned pits with any soil conservation method. This eventually led to the innumerable gully erosion formss during rains and disastrous slipping of quite friable and soft Gondwana sandstones and shales. Such conditions not only enhanced the critical conditions of stability of hill slopes, but also provided the tributaries with enormous loads which

in turn, have incapacitated the parent river like Lish, causing overflowing of water over the banks, affecting the nearby plains. The disastrous flood of 1968 and 2002 which damaged the Lish road bridge, may be regarded as a typical example in this regard. During non-monsoon months when the discharge of the river Lish remains low, it often gets polluted by the coal-wash water from the remaining mining sites at Chunkhola (Basu, 1998, Basu and Maiti, 2001).



Figure 10 Recurring subsidence of the Hill-Cart road at Pagla Jhora, where the tourist traffic to Darjiling has been badly affected (Photo: Author)

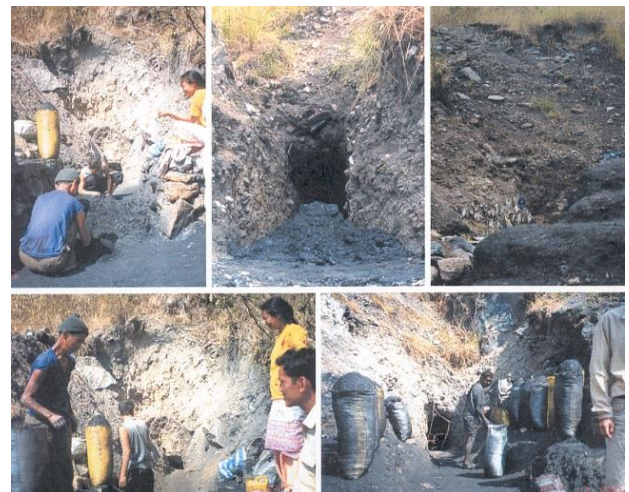


Figure 11 Illegal coal mining at Tindharia by making tunnels in the slope (Photo: S. Sarkar)

During recent observations in Chunkhola (10 km north of Bagrakot) it has been found out that

hundreds of people from adjoining area still visit the coal mine daily to collect coal. Part of this coal is used for cooking purpose but the rest is sold to the traders who ultimately sell it to the owners of brick-factories. In Tindharia area, on the way to Darjiling, local people have dug up long tunnels in the local beds of Damuda formation to collect coal illegally at night (Fig.11). Sometimes the roof of such tunnels collapsed injuring the workers. Such examples of landslides were studied in details in works such Basu and Sarkar, 1985, 1988). The Tindharia Cricket Colony, a densely settled area at Tindharia, on the way to Darjiling, has been severely affected by landslides (Fig. 13) induced by subsidence since 1966 (Bhattacharya, 1999) due to coal extraction by drilling tunnels and caves at the base of the Colony. The measured subsidence is about 2.5 m and due to this the base and the walls of the houses have been broken and tilted dangerously.

5.3.3. Landslides in tea gardens: Bannockburn Tea Garden and Kurseong Subdivision

Largely due to the pioneering zeal of the British Planters, the tea industry took firm roots in the district of Darjiling. Started as an experimental plantation in 1840, the tea industry was established as a commercial enterprise by 1856. In 1885 about 38499 acres came under tea cultivation accounting for an 82% increase in the cultivated area.

The industry's decline commenced in 1947 when the British Tea Companies suddenly diverted their investments to Africa. Darjiling happens to be the first victim of neglect. The British owners sold off the gardens to the native companies who were motivated towards profit maximization and did not pay any attention to the ecological conditions. This sheer negligence compounded by the unemployment problem, generated the sickness of Darjiling Tea Industry. In 1971, there were 140 operative gardens in the hilly area occupying 63000 acres of land and employing 69000persons. By 1991 the number of operative gardens had come down to 86. Even out of these nearly half of the gardens were either sick or uneconomic. Consequently unemployment problem in the hilly area has increased by leaps and bounds.

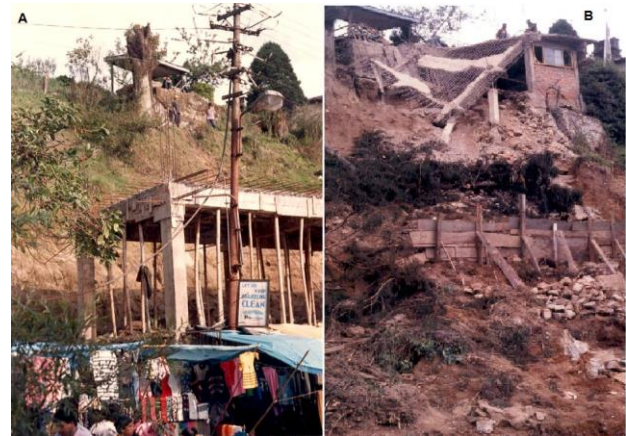


Figure 12 A. Construction of building very close to Bellevue hotel in Darjeeling and B. its ill effect endangering the lives and properties of the local inhabitants (Photo: Author)

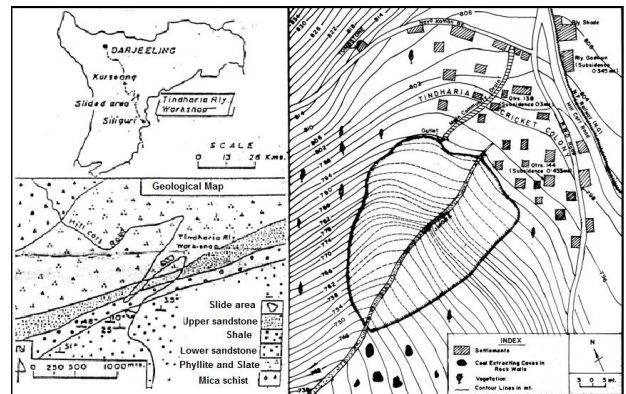


Figure 13 Tindharia Cricket Colony landslide (Basu and Sarkar, 1985)

Table 2 Age classification of plant population for the gardens in Darjiling.

Age of bushes	<10 yrs.	10-25 yrs.	26-50 yrs.	51-70 yrs.	71-100 yrs.	> 100 yrs.
Area (%)	3.4	8.0	7.5	21.9	34.6	24.6

Most of the gardens are very old in Darjiling (Table 2). This old age has consequently given rise to shrunken bushes which otherwise would have formed a thick hard canopy and protect the soil of being washed away by the splash of rain. The soil in the area is induced with chemical fertilizers, weedicides and pesticides. These have resulted in the acidic character of the soil and hence have

made it friable. The ill effect of deforestation for cultivation, grazing, lopping of leaf twigs for fodder and firewood extraction are also factors to reckon with.

Bannockburn Tea Garden

The garden at Bannockburn bounded by lat. 27°03'N and long 88°17'E (700-1800 m a.s.l.) belongs to the oldest category of gardens in Darjiling Himalayas. It is situated in the eastwards exposed valley side of the Rangnu creek. The long step-like slope (10° –15° steep) is dissected by tributary valleys up to 200 m deep and minor depression appeared as an effect of slides and shallow mudflows. The thickness of regolith deposits varies from seldom bare rocky fragments to 4 –10 m on the gentler parts. At least 60% of the whole area is occupied by terraced tea plantations, most of them exceeding 500 ha.. On steeper slope there are villages and small gardens. Patches of jungle occupied an area of at least 20% of the whole garden in 1968, while presently there are only poor remains of bushes used for fodder (Majumder, 2006).

The detailed surveys and measurement of rainfall, infiltration rate and run-off were carried out by Froehlich and Starkel, 1987 and Froehlich et al., in 1989. After the heavy rainfall in October 1968, the seepage pressure was so high, due to the high permeability of the substratum, that hundreds of shallow landslips, mudflows and debris flows occurred, which damaged 20-25 % of the tea gardens. Local downpours exceeding 200-300 mm have caused the reactivation of numerous slides on the steep slopes or the occurrence of new ones in 1983 and 1987.

Summarizing the aforesaid facts it may be said that in this garden the slides have been initiated since 1950 and reactivated in 1968 1980, 1983, 1987, and 1990 due to catastrophic rainfall. Maps showing the change in forest cover, landuse and landslide incidences have been detailed since 1931 up to 2001(Fig. 14).

Kurseong Subdivision

A total number of 32 tea gardens have been inventoried in the Kurseong Subdivision, most of which are free from any landslide event (Fig. 15).

Out of the 80 landslides in the whole study area, only 17 landslides are occurring in tea gardens, among which Ambootia and Gayabari landslides proved to be devastating.

The hill-slopes in and around Kurseong, Mirik and Gayabari were seriously affected by landslides due to heavy rainfall between October 2–5, 1968 (Starkel and Basu, 2000,). The severity of landslides in that year was so high that the whole hilly area was totally cut-off from the surroundings for about a week. Ambootia, the most dangerous and largest landslide in Darjiling Himalayas occurred in that year (Froehlich, et.al., 1991). Severe landsliding phenomena again occurred between September 3–4, 1980 and have been continuing till today. On July 8, 2003 at about 3.30 a.m. a (previously-mentioned) major landslide occurred at Gayabari Bustee, during which four hamlets were destroyed and twelve lives were lost. A concentrated rainfall of over 300 mm during a period of over 48 hours saturated the soil covering Damuda and Daling series and activated the debris slides (De, 2011). Moreover, recently the thick soil has been unscientifically utilized for the cultivation of ginger, whose harvesting during the monsoon season disturbs the cohesiveness of soil and aggravates soil erosion and shallow landsliding.

5.3.4. Landslides at urban agglomeration: Darjiling Town

Landslides could be considered perhaps the most rampant environmental hazards threatening the town of Darjiling.. Many times during or after the monsoon season, landslides create havoc in and around Darjiling township area. Numerous slides have occurred in the past and the intensity cause and severity level of the slides are being recorded since 1899. The records of recent landslide revealed clearly that the slides frequency is presently increasing year after year.

Up to the first half of the XXth century there were certain regulations for the commercialization of the hill slopes, but since India's independence, in a desperate attempt to acquire as much arable land as possible, extensive areas covered by forests were gradually encroached upon.

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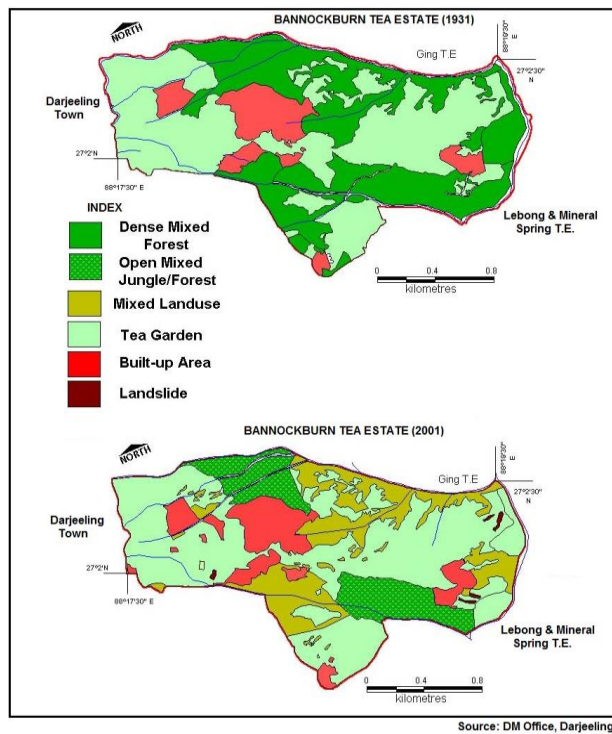


Figure 14 Changes in land-use/land-cover in Bannockburn Tea Estate

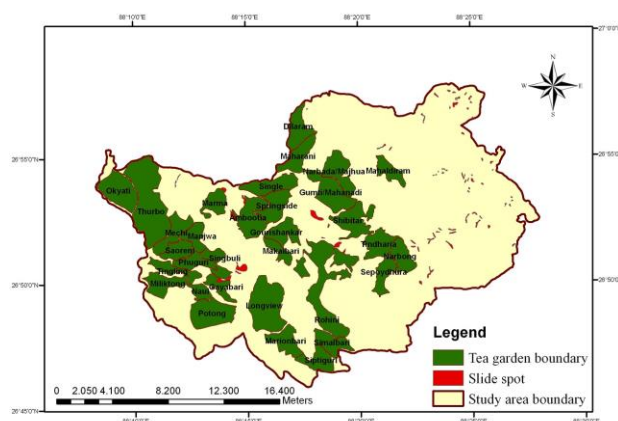


Figure 15 Distribution of landslides in different tea gardens of Kurseong subdivision

The ever-increasing number of people haphazardly settled in an every bit of land available. During the British period it was stated that forest on the upper part of the hills should not be brought under ordinary commercial forest management. But after independence, the demand for timber increased at an unprecedented rate and even the

upper layer of the forest was not spared. Even after a mass afforestation programme have been implemented, a big gap remains between felling and replanting. It has been estimated that 70% of the cooking energy needs of the people are being met by firewood. Thus, a reckless obliteration of forests along with unscientific use of slopes (especially in construction works coupled with geological, rainfall and slope characteristics) have changed the scenario completely. As a result, Darjiling, one of the most densely populated tourist centre in comparable environment exits on the verge of an environmental catastrophe as with just one concentrated shower of 50 mm/h would initiate numerous landslides endangering the lives and properties of the local inhabitants (Fig. 12). For better understating of landslide hazard in Darjiling town and following an expert-based approach, a landslide susceptibility zonation map including the corresponding landslide distribution has been prepared (Fig. 16)

6. Conclusion and suggestive measures

From the above study it becomes apparent that the nature of landslide varies in proportion in various localities in Darjiling Himalayas Hills. The high intensity of rainfall, extreme deforestation, vulnerable geological structures and overall human interference are the most important triggering, preparing and predisposing factors of such processes. The problems to be tackled immediately are summarized below:

- The protection of the whole Pagla Jhora valley would be extremely difficult not only for the high cost involved but also for the continuous down cutting and undermining of the slope from the base and the high delivery of coarse debris from the upper slopes during rains. So, while taking corrective measures, the authorities concerned will have to be very careful and follow a scientific method in preventing such slope failures. Moreover, the revetment walls and their surroundings should carefully be afforested preferably with local varieties of grass, bamboo or wild fern which can protect the slope better from the splashing of rains.

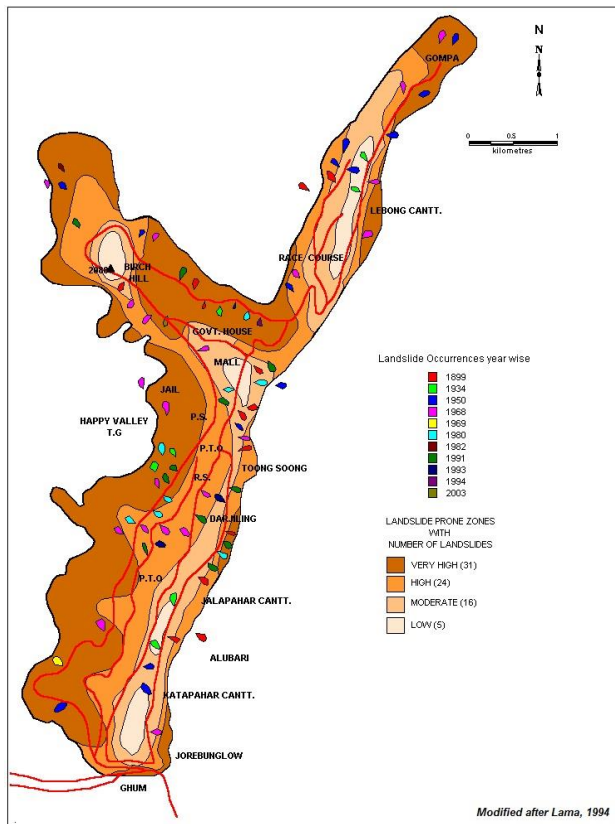


Figure 16 Landslide susceptibility zones along with the distribution of landslide occurrences

- The people of the localities should be provided with some alternate sources of energy through construction of Mini-Hydel Projects utilizing the voluminous discharge of the springs (e.g. Pagla Jhora), which can be an option to prevent them from cutting down more trees and digging out coal for fuel thus disturbing the natural slopes. Otherwise, allowing the springs to flow freely across the roads and causing soil erosion and subsidence, the protection of transportation routes to Darjiling (for both tourists as well as permanent settlers) will be endangered.

- In case of the Tea Gardens (e.g. Bannockburn) shrinkage of the old bushes is giving way to intense rainfall thus resulting in the formation of gullies, which have been considered to be the main causes of soil erosion and landslides since 1950. Catastrophic rainfall of 1968 reactivated almost all of the dormant mass movements. Later on many more spots were affected during the

intense rainfalls of 1983, showing that the cause of such menace remains to be the same.

- In view of the ever increasing problems of landslides in Darjiling Town, one must be aware of the possible dangers that the human is inviting due to its careless dealing with nature. It is true that one has to make room for the growing population and in this pursuit he has to utilize every piece of land available. But the precautions that have to be adopted should not be neglected. In the town, the revetments are not properly maintained, the weep-holes are choked and drains are dumped with garbage, restricting free drainage of water. Moreover, the present landuse system should properly be evaluated and the construction of high rise buildings should be controlled immediately. But above all it should be of extreme importance to develop awareness among the local people and the tourists, so that they perceive the existing ecological imbalances and take proper care to maintain an eco-friendly atmosphere in the said locality.

Acknowledgement

The author started this work with Late Prof. S. R. Basu. Due to his untimely demise the work remained incomplete for several years. The author gratefully acknowledges the contribution and motivation of Late Prof. S. R. Basu in completing this work.

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Combining landslide susceptibility maps and rainfall thresholds using a matrix approach

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ABSTRACT

On the regional scale, investigations on future landslide can broadly be distinguished in spatial or temporal analyses, i.e. landslide susceptibility or hazard maps, and landslide triggering rainfall thresholds. Even though both approaches have its uses e.g. in spatial planning, risk management and early warning, they also have limitations. Susceptibility and hazard maps do not contain information on when landslides will be triggered, while rainfall thresholds give no detailed indication on where a landslide might take place. The combination of spatial and temporal landslide research remains a complex issue and no ready-to-use methodology for combined spatio-temporal landslide analyses is presently available. In our study, we present a simple matrix approach to combine spatial and temporal landslide probabilities and highlight its application for a case study in the Wudu region, China. Landslide susceptibility mapping is based on a previous study involving logistic regression; the analysis of rainfall threshold was carried out applying the daily rainfall model. A 4x4 matrix was used to combine and reclassify the spatial and temporal landslide information. The results are then plotted on a map to highlight the susceptibility for rainfall events with varying likelihood of triggering landslides.

KEYWORDS

Landslides; susceptibility mapping; rainfall thresholds; matrix approach; China

1. Introduction

Landslides are an important geomorphological hazard and are responsible for significant damage to infrastructure as well as loss of lives. Petley (2012) reported an annual death toll of approximately 1600 due to non-seismic landslide events alone, the majority of these occurring in Asia. Yin *et al.* (2009) estimated an average of 700 to 900 landslide related fatalities per year for China. In particular large seismic shocks can result in substantial landslide activity. For the 2008 Wenchuan earthquake (magnitude M7.8), more than 20,000 landslide were reported and attributed to a third of the approximately 60,000 fatalities (Huang and Li, 2009). Consequently, the prediction of future landslides in space and time is crucial and should be fostered.

Landslide investigations generally concentrate on either the local scale, i.e. single slopes, or the regional scale, i.e. larger regions (Thiebes, 2012). While the former scale is a focus of engineering geology and related disciplines, the latter scale has intensively been worked on by geomorphologists and geographers. The basis of most regional scale landslide studies are landslide inventories, i.e. maps showing the location of landslides within the region. These can be used to compute landslide susceptibility maps depicting the spatial probability of slope failures using a wide range of approaches utilising Geographic Information Systems (GIS). The methodologies to estimate landslide susceptibility can broadly be divided into heuristic, statistic and deterministic approaches (Soeters and Van Westen, 1996; Van Westen *et al.*, 2006). Ordinary logistic regression is one of the methods that has been used extensively to map landslide susceptibility (e.g. Atkinson and Massari, 1998; Süzen and Doyuran, 2004; Akgün and Bulut, 2007; Greco *et al.*, 2007; Bai *et al.*, 2009, 2010b, 2012). Matrix approaches have also been used to produce regional scale landslide susceptibility maps (DeGraff and Romesburg, 1980; Fernández *et al.*, 1999, 2003; Irigaray *et al.*, 2007; De Graff *et al.*, 2012). A main shortcoming of susceptibility maps is the lack of information on the

temporal probability of landslides as well as on the magnitude of potential slope failures.

The regional scale analysis of the temporal probability of landslides strongly relies on the assessment of landslide triggering rainfall thresholds. This field of research has essentially been established by the works of Caine (1980) who put forward the first relationship between the intensity and duration of rainfall events and the triggering of landslides. Since then, many other researchers have established critical rainfall characteristics by the same methodology (Jakob *et al.*, 2006; Matsushi and Matsukura, 2007; Crosta and Frattini, 2008; Guzzetti *et al.*, 2008; Capparelli *et al.*, 2009; Cepeda *et al.*, 2010; Saito *et al.*, 2010). Other empirical thresholds have been determined based on antecedent rainfall (Sorriso-Valvo *et al.*, 1994), daily rainfall (Crozier, 1999; Glade, 2000) and event rainfall (Bell and Maud, 2000), cumulative event rainfall (Canuti *et al.*, 1985; Corominas and Moya, 1999), cumulative event rainfall and event duration (Innes, 1983; Wilson *et al.*, 1992; Zêzere and Rodriguez, 2002), and thresholds based on mean annual precipitation and normalised rainfall (Giannecchini, 2005; Sengupta *et al.*, 2009). Over the past years, a wide range of critical rainfall thresholds have been developed and an extensive overview is available on the website of the Italian Research Institution IRPI (rainfallthresholds.irpi.cnr.it). It should also be noted that regional scale landslide early warning systems, e.g. in Hong Kong (Yu *et al.*, 2004), Seattle (Chleborad *et al.*, 2008) and Italy (Rossi *et al.*, 2012), rely on rainfall thresholds for alerting civil protection and the general public.

At present, there is no general consensus on how landslide susceptibility maps and landslide triggering rainfall thresholds should be combined. However, a map combining both spatial and temporal landslide probabilities could aid spatial planning, civil protection agencies and the general public to deal with landslide hazards. In this paper, we present a straightforward matrix approach to combine a landslide susceptibility map and landslide triggering rainfall thresholds. To highlight our approach, we utilise a landslide susceptibility

map created using logistic regression (Bai *et al.*, 2013a) and rainfall thresholds established using the daily rainfall model (Bai *et al.*, 2013b). Our approach combines spatial and temporal landslide occurrence probabilities using a simple 4x4 matrix to create a combined map; however, the method could easily be modified to accommodate different numbers of combination classes. The study area of our investigations is the Wudu region in China's Gansu province, an area that is substantially affected by landslide and frequently suffers landslide losses.

2. Matrix approaches in landslide hazard and risk studies

Matrix approaches have been used for landslide susceptibility, hazard and risk studies in various research applications. Frequently, matrixes have been utilised to combine different aspects of landslide hazards with the aim to derive a new index value which can be used for further analysis or to aid decision-making on landslide risk management. Moreover, matrix approaches have been highlighted as a helpful tool to harmonise existing landslide hazard information available in different countries and territories. One such example was provided by the AdaptAlp project (2011) which aimed for a comparison, evaluation, harmonisation and the improvement of different methods of hazard mapping. Here, a matrix approach was proposed to combine spatial and temporal probabilities of landslide processes to receive a unified qualitative probability.

Matrix approaches have often been employed to determine a basic risk index by combining hazards and consequences. A hazard-consequence matrix approach was proposed by Chowdhury and Flentje (2003) to provide a qualitative estimation of landslide risks. The authors note that the hazard may thus be evaluated separately from the consequence based on site inspections. Moreover, consequences may be assessed separately for loss of life and economic losses. Kjekstad (2007) proposed a similar matrix approach to carry out preliminary landslide risk assessment in particular for developing countries. Therein, three hazard classes from low to high are combined with three

consequence classes. Consequence classes are based on a complex scoring system which takes into account e.g. the number of dwellings, the existence of critical infrastructure and life lines. The resulting risk index values range from one to five and aim to assist the prioritisation of high risk areas. Similar qualitative risk evaluations based on the combination of the likelihood of landslides and the potential consequences have been widely used by scientists (Ko Ko *et al.*, 2004a, 2004b) and practitioners and have been included in respective guidelines (Kohler *et al.*, 2004; Tonkin & Taylor Ltd, 2006).

Another field of applications for matrixes in landslide studies focuses on describing the hazard by combining the intensity of the processes with the occurrence probabilities. The most prominent matrix approach based on this concept was put forward by the Swiss Federal Office for the Environment (BUWAL) and combines the intensity and occurrence probability or recurrence intervals of hazard processes including rockfalls, landslides, and avalanches (Latelin, 1997; Bundesamt für Umwelt Wald und Landschaft, 1998). In the BUWAL framework for hazard assessments, class boundaries of intensities and occurrence probabilities are determined by quantitative values such as kinetic energy (rockfalls), pressure (avalanches), thickness of mobilised material (debris flows) and movement speed (landslides). However, to make the methodology more approachable by practitioners and to ease its use for the prioritisation of counter measures, intensity and recurrence intervals are rather included as qualitative classes (i.e. low, medium, high). The resulting hazard index values are then plotted on a map to aid spatial planning by restricting building activities to areas with low or medium hazard values (Raetzo H. *et al.*, 2002); for the latter certain building codes have to be respected. The BUWAL approach has also been used by other researchers, as well as regional administration dealing with landslides and other natural hazards (SafeLand Project, 2010; Paramount Project, 2012).

Additionally, matrixes have been employed to combine landslide susceptibility maps with information on the likelihood of their occurrence.

One such example was provided by researchers in France (Thiery *et al.*, 2006; Thiery, 2007). After estimating regional landslide susceptibility using a statistical bivariate weight of evidence approach, the occurrence probability was assessed using a deterministic landslide model calculating safety factors. The results were then combined to receive a new hazard index value which aimed to better describe the landslide hazard conditions in the region than the two input model results alone. In another study, Bell *et al.* (2014) used two different 4x4 matrix approach to combine landslide susceptibility classes with hydro-meteorological index values to receive warning classes to be included in the national scale early warning system for shallow landslides and debris flows in Norway. Their results showed that the combined warning classes improved warning procedures significantly.

Recently, matrix approaches have also been utilised in landslide studies using satellite-based InSAR (Interferometric Synthetic Aperture Radar), in particular for the updating of existing landslide inventories and hazard maps. Cigna *et al.* (2012) acquired information on the state of activity as well as on the intensity of landslide movements for a pre-existing inventory of slope movements based on the PSI approach (Permanent Scatterer Interferometry). The results are then combined in a matrix to yield updated information on the state of landslide activity (i.e. active, reactivated, stabilised, dormant). For newly detected slope movements, i.e. landslide not contained in the existing landslide inventories, the state of activity is derived based on a matrix combining historic PSI analyses results with more recent data. Another example of a matrix approach in landslide-focused InSAR research was presented by Lu *et al.* (2014). Here, an existing landslide inventory that included information on the intensity of the processes derived from geometrical properties of the slope movements was combined with InSAR-based measurements of the displacement. The resulting new intensity classes are then integrated in a risk assessment and an estimation of potential economic losses.

3. Study area

China is one of the countries with the world's most serious geological disasters and experiences high economic losses every year. For the period from 2006 to 2008, a total number of 154,748 geological disasters were recorded by the China Institute of Geo-Environment Monitoring of which 118,351 were landslide-related, thus accounting for approximately 76% (China Geological Survey Bureau of Statistics, 2008). The annual direct economic damage of landslides has been estimated to be approximately 10 billion RMB (approximately US-\$ 1.3 billion) in addition to 700 to 900 fatalities per year (Yin, 2009). These numbers strikingly underline the importance of spatial and temporal landslide predictions, hazard and risk analyses, and disaster prevention measures.

The study area of this research is the Wudu region in western China (Fig. 1). It covers an area of 4,683 km² and belongs to the prefecture-level city of Longnan in Gansu province. The Wudu region in Gansu province is a hot-spot of landslide activity (Scheidegger and Ai, 1987; Bai *et al.*, 2010a, 2012) and was severely affected by the 2008 Wenchuan earthquake which caused hundreds slope failures (Cui *et al.*, 2009; Chigira *et al.*, 2010; Bai *et al.*, 2013a). In addition, the earthquake deteriorated the area and made it more susceptible for future landslides (Jiao and Wang, 2010). Such secondary hazards are a major concern for local and regional decision-makers who require reliable information on current and future hazard conditions. The geological structure is dominated by the southern Qinling fold system. During the geologically recent Yenshan and Himalayan crustal movements, uplift and complex faulting of the region took place, resulting in widespread valley incision and undercutting of the slopes (Derbyshire *et al.*, 1999). Current uplift rates in the study area are high and enhance geomorphological activity (Chen *et al.*, 2006). The lithology of the study area consists of soft and erodible formations which are primarily marine metamorphic and carbonate rocks. Elevations in the study area range from 600 m to over 3500 m a.m.s.l.

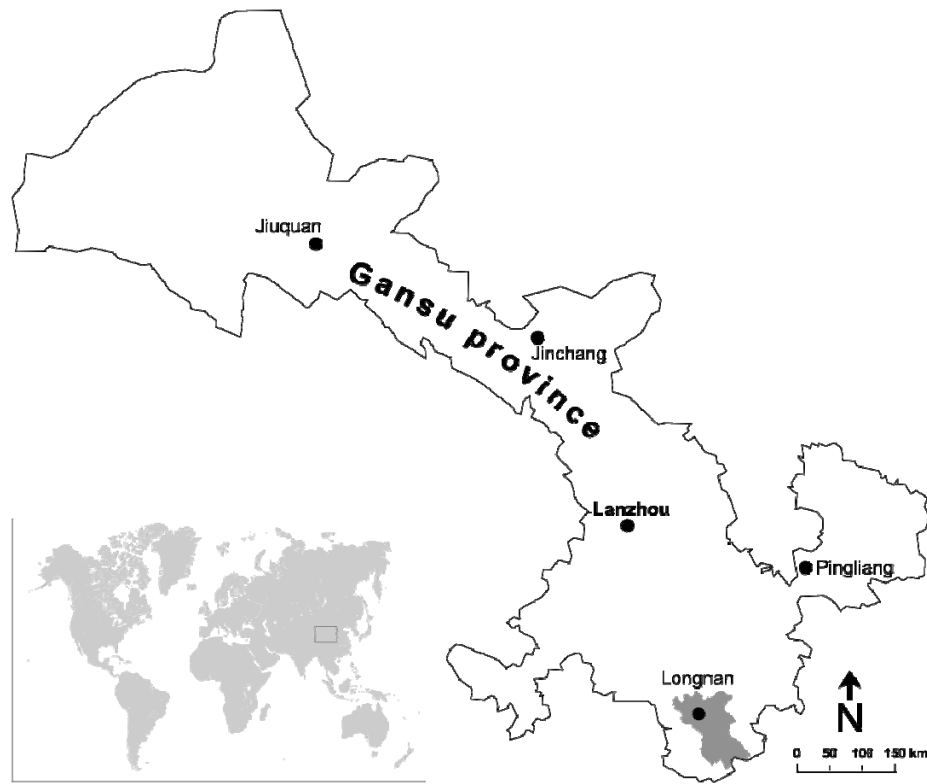


Figure 1 Location of the Wudu region (grey area) in southern Gansu province, China

The steep slopes of this rural region are often terraced and are used for agriculture. The Wudu region belongs to the drainage system of Bailongjiang river which is a tributary of the Yangtze (Changjiang) river. The area is influenced by warm and humid subtropical monsoon climate and experiences orographical effects due to the mountainous topography. Thus, climatic conditions vary strongly with elevation and topographical position. Regional governmental agencies use simple, empirical rule of thumb (Chen *et al.*, 2006) to roughly estimate the annual precipitation for different elevations; altitudes below 1500 m receive approximately 400 mm per year, while elevation between 1500 and 2000 m receive an annual rainfall of 500 to 600 mm, and elevation above 2000 m experience more than 600 mm of rainfall each year. The annual rainfall distribution shows a significant peak during summer (May to September), when approximately 80% of the annual rainfall is recorded. Rainfall events usually have durations of several days, but also short events with high intensity (up to 40 mm per hour) occur.

The combination of high relative relief, steep slopes and weak lithology, as well as the triggering influence of strong monsoonal rainfall and frequent earthquakes result in both large localised slope failures and widespread landslide occurrences. The Wudu region has long been known to be extremely prone to landslides and been rated as one of China's most severely landslide-affected regions (Scheidegger and Ai, 1987). According to the landslide classification by Cruden and Varnes (1996), the landslides in the Wudu region are mostly translational and rotational slides of loess and colluvial material which in some cases have a flow type run-out. Earthquakes and human activities (e.g. slope cutting and irrigation) have frequently triggered landslides but in particular rainstorm events have been reported to be of major importance for landslide triggering, with 95% of the landslides occurring in the rainy season from May to September and the more than half of all landslides occurring in August and September (Chen *et al.*, 2006). In addition, 60% of all recorded slope failures took place in years of annual rainfall above average.

Widespread landslide activity was particularly observed in the 1980s. In 1982, eight times more landslides than on average occurred as a consequence of heavy rainstorms in that year. Another significant event took place on August 3, 1984, when heavy rainfall caused more than 400 debris flows and 570 landslides which together affected approximately 9.3 million people and caused a direct economic loss of 265.26 million Yuan (approximately 30 million Euro) (Chen *et al.*,

2006). Over the last four decades at least 567 people were killed by landslides in the Wudu region (China Geological Survey Bureau of Statistics, 2008). One of the most recent destructive landslide events that was also reported in international news took place on August 8, 2010, in Zhouqu County, where a fast moving debris flow swept through the city destroying large areas and claimed at least 1287 lives (Yu *et al.*, 2010).

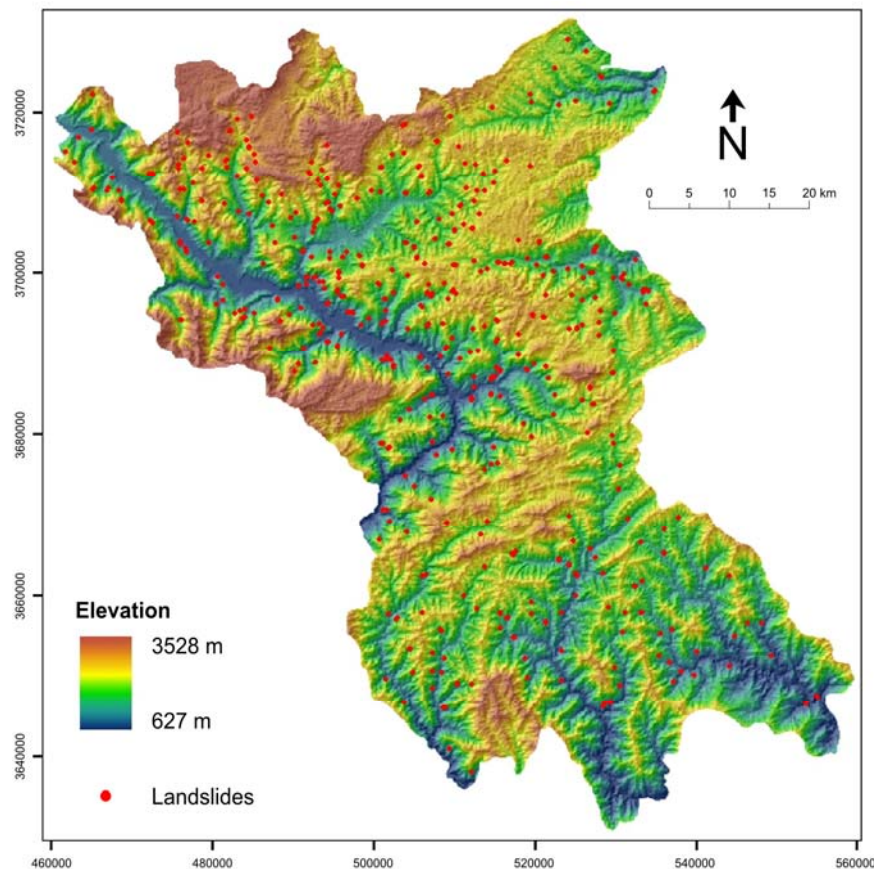


Figure 2 Distribution of rainfall-triggered landslides in the period from 1995 to 2003 in the Wudu region

4. Generation of input data

4.1 Historical rainfall-triggered landslide inventory

The 'Ministry of Land and Resources of the People's Republic of China' has been working on geo-hazard survey plans in counties seriously affected by geo-hazards since 1999. The 'Longnan First Station for

Landslide and Debris Flow Forecasting and Warning System of the Upper Reaches of the Yangtze River' was constructed in 1991. Both institutes provided information on landslide occurrences which were used to derive an inventory of rainfall-induced landslides between 1995 and 2003 for the Wudu region. The recorded attributes include spatial characteristics (location, length, width, volume), temporal information (day of failure), damage

information (people affected, damage caused) and additional information (e.g. landslide type and triggering conditions). For the period between 1995 and 2002, a total number of 217 rainfall-triggered landslides were recorded. In 2003 alone, 290 landslides and 360 debris flows triggered by seven rainfall events are listed. In total, 507 landslides are contained in the inventory (Fig. 2).

4.2 Landslide causative factors

Topographical information in the form of a digital elevation model (DTM) with a pixel size of 30×30 m

was created by digitising a 1:50,000 topographical map. Subsequently, all other spatial input data was set to the same pixel size independent of the scale of the original data source. The DTM was also used to derive topographical characteristics such as elevation, slope angle and aspect using ArcGIS tools. Rivers and roads were digitised manually from the topographical map. Information on lithology was available in the form of the geological map (1:200,000) which was reclassified (Chen *et al.*, 2006) to cluster eight lithological units which have similar physical-mechanical characteristics (Fig. 3).

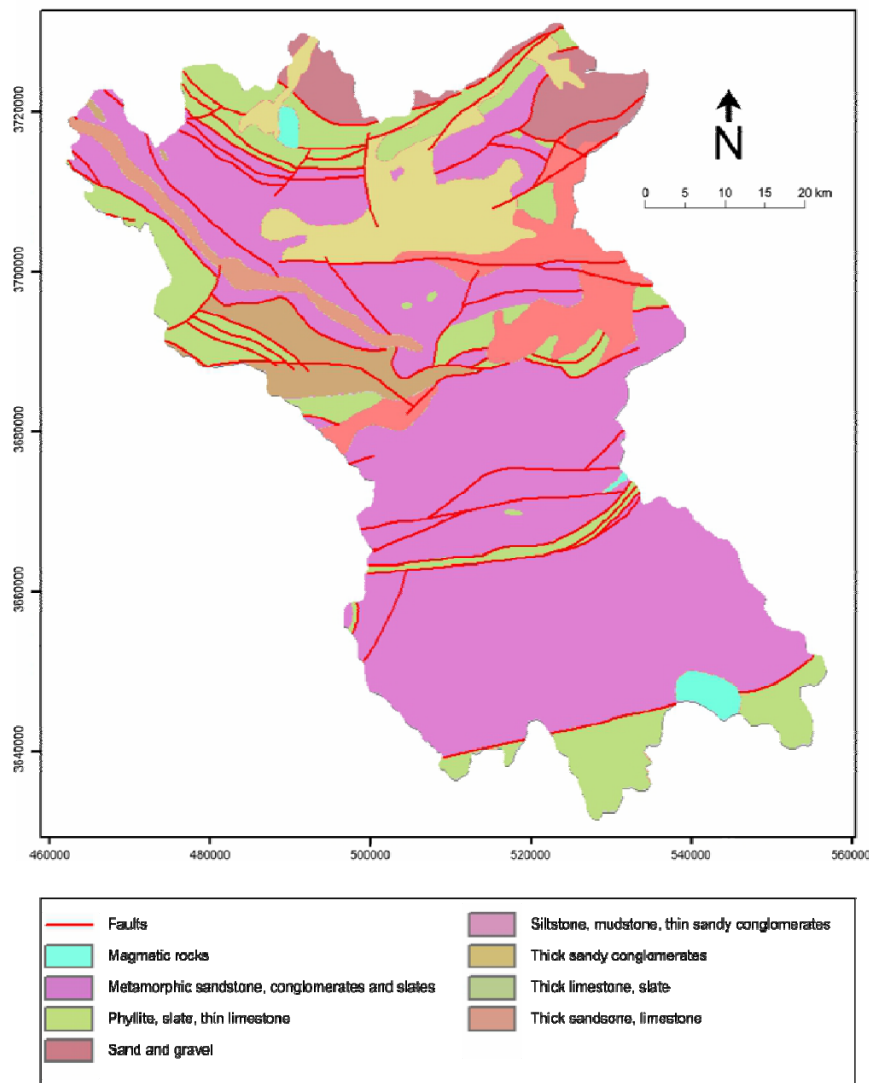


Figure 3 Lithological units and faults in the Wudu region (based on the 1:200,000 geology map) (modified after Bai *et al.* 2013b)

Land use types were mapped using pre-processed Landsat MSS, TM and ETM images (Liu *et al.*, 2003; Wu *et al.*, 2004). After geometrical correction and georeferencing of the images, the average location errors were found to be less than 50 m (about 2 pixels). The accuracy of the landuse interpretation was validated in the field by random checks and resulted in an accuracy of the land-use classification of 92.9% (Liu *et al.*, 2003). An annual average rainfall (1971-2009) map based on the data from 16 stations of which 9 are located within the study area were available to this study. The data from the respective stations were used for a spatial interpolation of annual precipitation using the kriging function (linear variogram model) in ArcGIS. Orographic effects of topography on rainfall distributions were not taken into account. In addition, daily rainfall measurements from five weather stations for the period from 1995 to 2003 were available and used to estimate the antecedent rainfall conditions of landslides in the study area.

5. Spatial-temporal landslide analyses

5.1 Spatial landslide analysis

In this study, the results of a logistic regression analysis of spatial landslide susceptibility were used (Bai *et al.*, 2013a). The algorithm of logistic regression applies a maximum likelihood estimation after a transformation of the dependent variable into a logic variable, which is representing the natural log of the odds of the dependent variable occurring or not. In this way, the logistic regression estimates the probability of a certain event occurring (Atkinson and Massari, 1998). In this study, the dependent variable is a binary variable representing the presence or absence of landslides. The logistic model can be expressed in its simplest form as:

$$P = \frac{1}{1 + e^{-z}} \quad (1)$$

where, P is the probability of an event (landslide) occurrence, which varies from 0 to 1 on an s-shaped curve; z is defined as the following equation (linear logistic model), and its value varies from $-\infty$ to $+\infty$:

$$z = \hat{\beta}_0 + \hat{\beta}_1 X_1 + \hat{\beta}_2 X_2 + \dots + \hat{\beta}_n X_n \quad (2)$$

Where $\hat{\beta}_0$ is the intercept of the model, n is the

number of independent variables, $\hat{\beta}_i$ ($i = 1, 2, 3, \dots, n$) is the slope coefficient of the model, and x_i ($i = 1, 2, 3, \dots, n$) is the independent variable. The linear model formed shows the relation of the dependent variable (presence of a landslide (1) or the absence (0) of a landslide) and the independent variables (pre-failure conditions) (Bai *et al.*, 2010b).

The landslide susceptibility mapping by the logistic regression model includes five main steps: (1) sampling of the data set; (2) splitting of the dataset by random selection into a calibration and validation sub-set; (3) multi-collinearity diagnosis by an analysis of the tolerance (TOL) and variance inflation factor (VIF); (4) application of logistic regression model; and (5) validation and evaluation of the model results by calculating the receiver-operating characteristics (AUROC).

For the landslide susceptibility analysis all 507 rainfall-triggered landslides were used. In total, 507 landslide and 507 non-landslide points were randomly selected. Input variables included topographical factors (elevation, slope angle, aspect), lithological classes, land use classes and spatially interpolated annual average precipitation (1971-2009). Categorized parameters such as lithology and land use were first transformed into a numerical variable (dummy variable) before they were included into the logistic regression model.

5.2 Temporal landslide analysis

In this study, the results of a landslide triggering rainfall threshold analysis were used (Bai *et al.*, 2013b). Critical rainfall conditions were determined by applying the antecedent daily rainfall model in combination with logistic regression to estimate landslide occurrence probabilities. This model is based on the research of Crozier and Eyles (1980), Crozier (1999), and Glade *et al.* (2000) and represents a conceptual approach to rainfall thresholds which are estimated based on soil

moisture conditions. A soil water status index is calculated based on the daily rainfall, and a decay factor which accounts for the loss of water due to evaporation and drainage from the soil over a period of days prior to a landslide event. The antecedent daily rainfall model was applied to the landslides triggered by the 2003 rainfall events in the Wudu region. From the available five meteorological stations, the highest daily precipitation records were assumed to be the triggering rainfall for the respective landslides. Due to missing local soil information, the decay constant k (representing the outflow of the regolith) was set to 0.84 and the r_n (maximum regional precipitation on the n^{th} day before 0) to 10 days. This value was chosen after initial analysis of rainfall data and is the same as in other studies (Crozier and Eyles, 1980; Aleotti, 2004). For the calculation of probability thresholds, days with landslide occurrences were treated as a binary variable. By a logistic regression, the correlation between the dependent variable (landslide occurrence) and the independent variables (antecedent daily rainfall r_a and daily rainfall at the day of slope failure r_d) was determined.

5.3 Combined spatio-temporal landslide analysis

In order to facilitate spatio-temporal landslide analyses, we adopted a simple matrix to combine the calculated spatial and temporal landslide probabilities. Thereto, the susceptibility map was classified into four equal interval classes, i.e. level 1 (very low susceptibility), level 2 (low susceptibility), level 3 (medium susceptibility) and level 4 (high susceptibility). Break points for the classes were chosen to be 0.25, 0.5 and 0.75. Similarly, the daily occurrence probabilities derived from both daily precipitation and antecedent rainfall were divided into four classes based on the daily landslide probability, i.e. level 1 (very low probability; <0.08), level 2 (low probability; $0.08-0.17$), level 3 (medium probability; $0.17-0.58$) and level 4 (high probability; >0.58). The combination matrix assigns a high index class to a high landslide susceptibility level and a high level of failure probability. In contrast, a low landslide susceptibility level and low landslide

occurrence probability level result in a low combined spatio-temporal index value. A very high spatial landslide probability combined with a low temporal probability results in the combined spatio-temporal class 2, and vice versa (Table 1). The combination of landslide susceptibility and occurrence probability was carried out with landslides that were not included in the previous determination of landslide occurrence probabilities and the respective rainfall thresholds. In total, 122 randomly selected landslides that have occurred prior to 2003 were used.

Table 1 Matrix used for combining landslide occurrence probability and susceptibility classes

Temporal probability	Spatial probability			
	Level 1	Level 2	Level 3	Level 4
Level 1	Class 1	Class 1	Class 1	Class 2
Level 2	Class 1	Class 2	Class 2	Class 3
Level 3	Class 1	Class 2	Class 3	Class 4
Level 4	Class 2	Class 3	Class 4	Class 4

6. Results

6.1 Susceptibility mapping

The application of the logistic regression model to estimate spatial landslide susceptibility resulted in a map (Fig. 4). High susceptibility classes can be found in the north-western part of the study area where the highest elevations and steepest slopes are present. The statistical analysis (Bai *et al.*, 2013a) of the influence of each variable showed that besides topographical aspects (primarily slope angle) lithological conditions control the spatial distribution of landslides. Herein, mudstone, siltstone and conglomerates are the most susceptible lithological units. In total, 46% of the rainfall triggered landslides are located in the highest susceptibility class, while 39% are within the class of medium landslide susceptibility. Analysis of the VIF and TOL showed values of less than 2 and more 0.4, respectively. The validation of the susceptibility map was carried out by analysing the prediction rate curves (Van Den Eeckhaut *et al.*,

2009). Results show prediction rates of 70.2% and 76% for landslides and non-landslides susceptibility class. The AUC (area under curve) value that

represents a quantitative measure of the model performance reached 0.782, thereby indicating a good model performance (Swets, 1988).

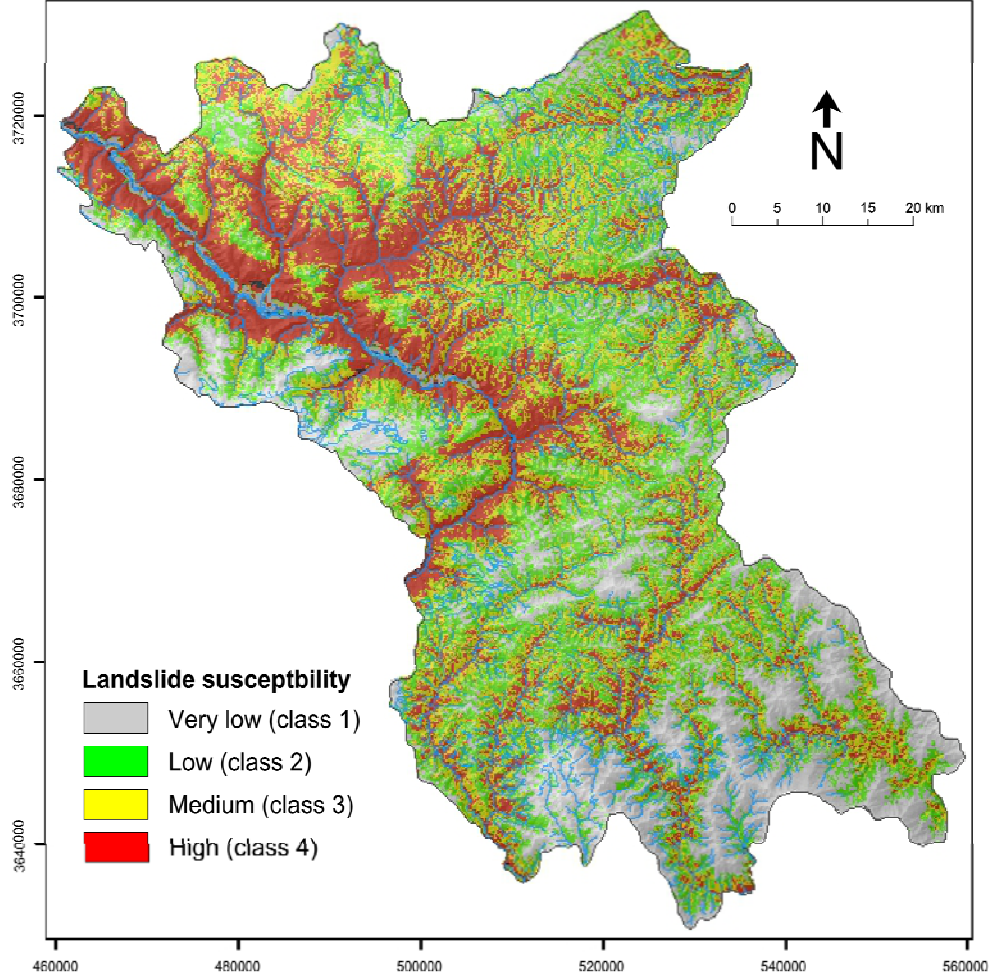


Figure 4 Landslide susceptibility map (modified after Bai *et al.* 2013a)

6.2 Landslide occurrence probability

The probability of failure as a consequence of daily and 10-day antecedent rainfall can be expressed by the following equation:

$$\log\left(\frac{p}{1-p}\right) = -5.26 + 0.22r_0 + 0.31r_a \quad (3)$$

where, p is the landslide occurrence probability at day 0 (i.e. the day of failure), r_0 the daily precipitation at day 0, and r_a the the antecedent daily precipitation for a specified period prior to day 0 (here 10 days). The respective equation demonstrates the triggering conditions for

landslides in the Wudu region based on the combination of 10-day antecedent precipitation and the daily rainfall (Fig. 5). In general, lower daily rainfall is required when higher antecedent rainfall conditions are present. After a certain threshold of antecedent rainfall the soil is so saturated, that no daily rainfall is required to cause landslides. Thus such an initiation is purely based on internal factors (such as positive pore water pressures) and not on external forces (such as additional precipitation). The results indicate, that a 10-day antecedent rainfall index of 20 mm is related to a 90% probability of landslides in the study area even

without any additional rainfall on the same day. The probability decreases to 50% and 10% with 17 mm and 13 mm, respectively. Similarly, an exceedance of a daily rainfall index value of 28 mm is related to a

90% probability of slope failures even without any antecedent rainfall. This probability decreases to 10% with a daily rainfall of 19 mm.

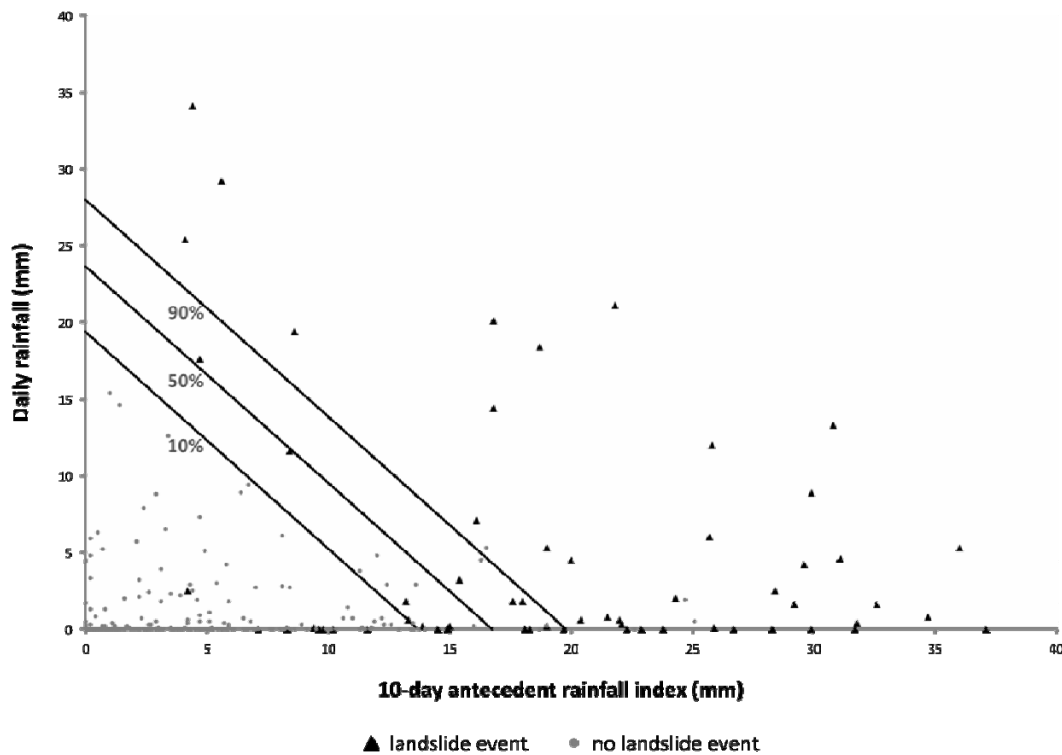


Figure 5 Rainfall thresholds for the Wudu region and related landslide occurrence probabilities (Bai *et al.* 2013b)

6.3 Spatio-temporal landslide analyses

A total of 122 landslides that have occurred between 1995 and 2002 were randomly selected for the creation of combined spatio-temporal landslide maps (Fig. 6) illustrating potential landslide scenarios for certain rainfall events. The daily rainfall model was applied to the selected landslides which relate to rainfall conditions that have a low, medium and high probability of causing slope failures; none fell into the category of very low occurrence probability (Fig. 6A). Figure 6B displays the spatio-temporal landslide map for rainfall conditions that have low probability of triggering landslides. Due to the re-classification using the matrix (Table 1), only very low, low and medium classes are present. This

map can be interpreted as the baseline susceptibility where areas are identified that might suffer landslides under frequently occurring rainfall conditions. Figure 6C is based on rainfall events with a medium probability to cause landslides. The spatial classification is the same as for the general susceptibility map (Fig. 4). Such rainfall conditions can be expected to occur regularly. The worst-case scenario is presented in Figure 6D. Under rainfall conditions that are related to a high probability of landslides, the susceptibility is much higher than in the previous maps. Large sections of the steep lower slopes in the study area have a high susceptibility and are thus likely to fail during extreme rainfall conditions.

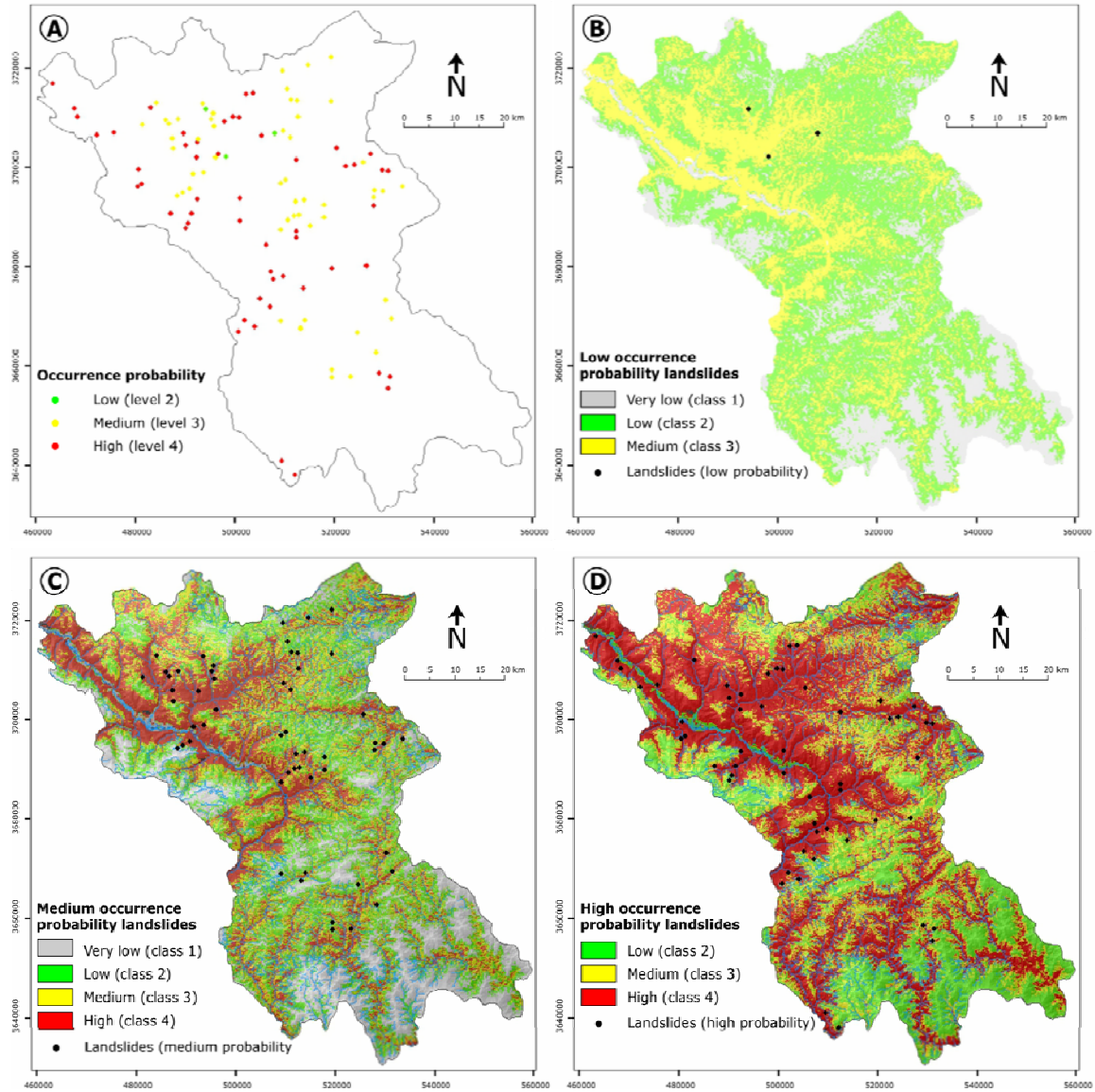


Figure 6 Position and occurrence probabilities of landslides (A); spatio-temporal landslide maps for landslides for low (B), medium (C) and high (D) occurrence probability

7. Discussion

This study presents the combination of spatial and temporal landslide probabilities using a matrix approach. The landslide susceptibility map and the temporal landslide occurrence probability were estimated by well established methodologies, i.e. logistic regression and the daily antecedent rainfall model. The susceptibility map highlights the extreme landslide proneness of the area with its

high and steep mountain slopes which consist of weak lithological units. The rainfall thresholds show that both daily and antecedent rainfall play an important role for landslide triggering, however, daily rainfall has a larger influence. In comparison to other study areas, it was found that rainfall thresholds are relatively low (see <http://rainfallthresholds.irpi.cnr.it/> for an extensive selection of rainfall thresholds); however, they are in good agreement with the conditions observed in the Wudu region.

The susceptibility map and rainfall thresholds could already be used to raise awareness among the general public as well as to support regional decision-makers on risk management and spatial planning. In general, temporal and spatial landslide probabilities are regarded as separate products; in this study, however, an innovative approach is proposed in which a matrix is used to combine the aforementioned landslide probabilities, and to assign a combined spatio-temporal index value to the land surface. The resulting map therefore combines information on the environmental factors predisposing the area to landslides, as well as information on the triggering rainfall conditions. We are convinced that the combined spatio-temporal landslide maps better highlight the hot-spots of potential landslide activity and represent an added value to the use of susceptibility maps or rainfall thresholds alone. A particular strength of the proposed method is the scenario building which can be thought of as a representation of the outcomes of specific rainfall events. For areas, which feature a medium probability of failure under frequently occurring rainfall conditions, even small rainfall events can be expected to lead to scattered slope failures. The worst-case scenario map that shows susceptibility conditions for extreme rainfall events can be used to estimate the outcomes of rare storms causing widespread slope failures. Such scenarios could help to improve the communication of regional stakeholders and the general public by raising awareness towards the landslide hazards.

To improve the results of the presented research, further investigations of landslide-triggering rainfall conditions should be carried out. Currently, the antecedent daily rainfall is calculated by a simple decay factor which simplifies the storage of water in soils. Internal characteristics of soils, such as permeability and saturated soil water content, as well as external factors such as evapotranspiration are not reflected. Moreover, only limited rainfall data was available to this study. Additional weather stations and complex simulations of rainfall distributions including orographic effects of topography would help to calculate more precise landslide-triggering rainfall thresholds. Moreover, additional data for the

calculation of spatial landslide probabilities, in particular digital elevation data of higher resolution than the current 30 m pixels, would be desirable and could drastically improve the results of susceptibility modelling. It also must be questioned in which extent the rainfall thresholds and the susceptibility maps are valid for the future given that they are only based on a short period for which data were available and due to the fact that the ongoing economic growth in Western China leads to massive human impacts, such as land use changes, increased population pressure and large scale construction of infrastructures.

Table 2 Three examples of possible matrixes for deriving spatio-temporal index values. (a) matrix assigning fewer low probability index values; (b) matrix assigning more low probability index values; (c) matrix introducing a fifth probability class to highlight hot-spots

(a) Temporal		Spatial probability			
probability		Level 1	Level 2	Level 3	Level 4
Level 1		Class 1	Class 1	Class 2	Class 2
Level 2		Class 1	Class 2	Class 2	Class 3
Level 3		Class 2	Class 2	Class 3	Class 4
Level 4		Class 2	Class 3	Class 4	Class 4

(b) Temporal		Spatial probability			
probability		Level 1	Level 2	Level 3	Level 4
Level 1		Class 1	Class 1	Class 1	Class 1
Level 2		Class 1	Class 2	Class 2	Class 2
Level 3		Class 1	Class 2	Class 3	Class 3
Level 4		Class 1	Class 2	Class 3	Class 4

(c) Temporal		Spatial probability			
probability		Level 1	Level 2	Level 3	Level 4
Level 1		Class 1	Class 1	Class 2	Class 2
Level 2		Class 1	Class 3	Class 3	Class 3
Level 3		Class 2	Class 3	Class 4	Class 4
Level 4		Class 2	Class 3	Class 4	Class 5

We think that a matrix approach is very useful for the combination of spatial and temporal landslide probabilities, however, it must be noted that it is of course extremely sensitive to the classification of the input data. Classifications for both, susceptibility maps and rainfall thresholds may greatly vary from one study to another and no single classification standard exists. Instead, the classification is generally defined based on the goal of the study or the requirements of the user group for which it is prepared. More complex classification could be appropriate for experienced spatial planners while the general public could probably benefit more from more simple map products. Some possible matrixes to be used in future studies are visualised in Tables 2.

8. Conclusions

This study presents an innovative approach to carry out a semi-quantitative analysis of spatio-temporal landslide probabilities in the Wudu study area in western China. Based on a database on landslide causative factors and an inventory of historic slope failures, a susceptibility map is calculated by a GIS-based logistic regression which ranks areas according to their likelihood to produce slope failures. In particular areas with mudstones, siltstone and conglomerates on slopes steeper than 20° feature a high probability of failure. Landslide occurrence probabilities in relation to daily and antecedent rainfall are estimated using the antecedent daily rainfall model. Rainfall thresholds are relatively low and a 90% probability of landslides is given with a daily rainfall of 28 mm. A simple yet innovative and adaptable matrix-based methodology is applied to combine the spatial and temporal probabilities of landslides and to produce combined spatio-temporal landslide maps. Therein, the combination of areas of high spatial and temporal probabilities result in high combined index values, while the combination of low spatial and temporal probabilities results in low combined index values. A high spatial landslide probability combined with a low temporal probability results in a medium combined index value, and vice versa. Still, other matrix classification could be used to

meet the requirements of the users. The maps produced aim to raise awareness towards landslides hazards and to support regional decision. It can be expected that other researchers will apply a similar methodology to combine temporal and spatial landslide probabilities which are currently mostly put forward separately.

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Transformation of different reaches of the Niida River (Japan) after extreme flood

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ABSTRACT

Extreme floods can have different effects on the river bottom relief depending on several factors. The geomorphological impact of the extreme flood occurring in the Niida River basin (Fukushima prefecture, Honshu inland, Japan) on the channels and river bottom of different reaches of the river is analyzed. High-resolution satellite images and field assessments were used for quantitative evaluation of river bottom transformation which mainly occurred in the lower reach of the Niida river. The lower reach of the Niida River was divided on three sub-zones according the channel gradient changes. Each sub-zones is correspond with the dominance of a certain type of channel (straight, meandering and wandering). It was found that bank erosion exceeded in- channel deposition in 1,7-2,7 times for all types of river channel in the low reach located within the coastal floodplain. However, floodplain sedimentation is the most active processes for the river sections with meandering and wandering types of the river channel. Floodplain sedimentation exceed bank-erosion in 2.2 times for river sections with the meandering type of channel and in 2.9 time for the river sections with wandering type of channel. It was found that bank erosion exceeded in- channel deposition in 1,7-2,7 times for all types of river channel in the low reach located within the coastal floodplain. However, floodplain sedimentation is the most active processes for the river sections with meandering and wandering types of the river channel. Floodplain sedimentation exceed bank-erosion in 2.2 times for river sections with the meandering type of channel and in 2.9 time for the river sections with wandering type of channel. The bank erosion exceeds floodplain deposition in 1,2 times only within the river sections with straight type of channel. Total sedimentation (in-channel + floodplain) in 2.6 times higher than bank erosion in the lower reach of the Niida River after extreme flood event with probability 4-5%.

KEYWORDS

Bank erosion; sedimentation; Niida river; valley bottom transformation

1. Introduction

Small mountainous rivers are characterized by high dynamics of river channel transformation due to high frequency of extreme floods. It is particularly true for small rivers of the sub-tropic and tropic landscape zones with high amount of annual precipitation exceeding 1000 mm per year. As a result, serious transformation of different river reaches occurs depending on water and sediment discharges and channel stability. Extreme flood events are very typical of small mountainous river basins in different parts of tropical and sub-tropical landscape zones (Marchi *et al.*, 2010; Borga *et al.*, 2014). They usually result in both intense erosion and sediment deposition on the river valley bottom (Costa, 1988; Gaume and Borga, 2008). Also, sedimentation rates considerably influence alluvial soil formation, depending on the sources of sediment. The consequences of extreme flood events are usually studied for the following calculations of stability of different constructions within the river valleys.

Geomorphic consequences of a flood can be evaluated based on the amount of sediment transported and also the amount of channel and floodplain morphological change caused by the flood (Wolman and Miller, 1960; Wolman and Gerson, 1978; Rădoane *et al.*, 2013). All this depends on flood strength, river bottom morphology, sediment composition, and reach connectivity (Hooke, 2003). In most cases it isn't possible to measure the amount of sediment transported during an extreme flood, because any measurement equipment would be damaged and destroyed. Therefore, it is only morphological analysis of the river channel and floodplain transformation after an event that can be used for quantification of geomorphic consequences.

Different methods and approaches are used for the evaluation of river channel and bottom transformation, including direct measurements of the river bottom morphology, application of aerial and satellite images interpretations (Zanoni *et al.*, 2008; Surian *et al.*, 2009; Lane *et al.*, 2003). Most detailed study can also be done using laser scanning (Kuo *et al.*, 2015). Large or extreme floods

may influence the river bottom morphology in different ways depending on the local features of the particular reach (Kochel, 1988; Eaton & Lapointe, 2001; Fuller, 2008; Thompson & Croke, 2013).

A detailed study of geomorphological impact of extreme flood on the morphology of different sections of the river valley bottom was undertaken in the Niida River basin (Fukushima Prefecture). An extreme flood event had occurred in the middle of September 2015, when 385–456 mm of precipitation fell during 6 days with maximum 200 mm/day in the end of the typhoon.

The objective of the study is evaluating the erosion/deposition processes and their spatial changes in different reaches of the Niida river, with particular attention to the low reach of the Niida River.

2. Study area

The study was conducted in the Niida River basin, which is one of several small river basins of the Fukushima Prefecture affected by serious radionuclide contamination after the FDNPP accident (Fig. 1). The total basin area is 265 km² and the elevation ranges from 0 to about 850 m ASL. The mean annual water discharges of the Niida River in the lower reach changes from the year to year depending from the amount of precipitation within the range 8–15 m³ sec⁻¹ (Fukushima..., 2007). Maximum water discharges (100–200 m³ sec⁻¹) are observed during typhoon season. The Niida basin is characterized by wet monsoon climate with highly variable total annual precipitation. According the meteorological observation the mean annual precipitation is 1900 mm at Haramachi station in the downstream reaches and 1700–1800 mm at Iitate and Tsushima stations located in the upper part of basin (JMA, 2016). Less than 5–7% of precipitation falls as snow. Extreme rains with precipitation sum >200 mm and >100 mm per event occur once every 5–7 years and every 1.5 years, respectively, according to meteorological observations. Several rains >50 mm fall each year, most frequently during

the monsoon season between June and September. Some heavy rains can, however, occur in April-May, when soil surface on cultivated fields is less protected by vegetation. Soils of steep slopes are shallow with high organic content. They are characterized by high permeability with intensive subsurface flow leading to tunnel erosion. Soils of the upland depressions and coastal lowlands are considerably transformed because of the agricultural activities. According to the erosion model calculation, despite the low topographic ranges and gradients, soil loss from cultivated fields is the main source of suspended sediment in small rivers of the coastal zones Fukushima Prefecture (Kitamura *et al.*, 2014).

Three main geomorphic regions have been selected within the Niida River basin (see Fig.1): 1) moderately dissected uplands, including low mountains and depressions, dominated by plutonic rocks (mostly Cretaceous granites and granodiorites); 2) severely dissected rangelands of the intensive faulting zone with a very complex geological structure consisting of patchwork of magmatic (both intrusive and effusive) and metamorphic (gneiss and schist) rocks; 3) coastal lowlands dominated by Tertiary to Quaternary

terrestrial and marine sedimentary rocks, with low topographic ranges and gradients.

The main orographic elements of uplands that occupy the upper (western most) part of the basin are low mountains and hills with relative elevation 200-350 m and moderate to steep slopes and wide flat-bottomed depressions occupied by main stream valleys. Hills are dissected by numerous gullies and small valleys with ephemeral and perennial streams and relatively short (100-200 m) slopes mostly covered by forest. This network is the main pathway for sediment transport from hills into main valleys in depressions. Limited areas of lower parts of hillslopes were artificially terraced to be used for cultivation. Most of depressions bottoms areas are used as paddy fields. Channels of main streams have high to moderate gradients and dominantly mixed gravel to coarse sand alluvium. Channels of the main streams and lower parts of their tributaries that drain depressions are mostly artificially canalized, with concrete embankments along straightened sections and systems of regulated flow gates on tributaries for paddy irrigation (Fig.2A). Both natural conditions (widened floodplains within depressions) and human impact (canalization, paddy fields) determine the potential for some fluvial sediment storage in this part of the basin.

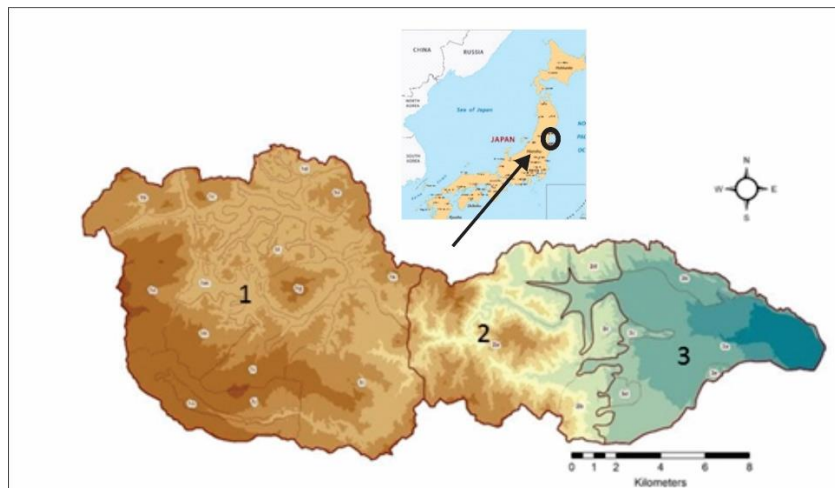


Figure 1 Geomorphic regions of the Niida River basin and location of Niida River basin within Japan (1-3 are the geomorphic regions).

Coastal lowlands are characterized by very flat topography with low ranges and gradients

except some peripheral residual hills. This area is mostly occupied by agriculture, settlements and

infrastructure. River channels have substantially lower gradients and are also artificially modified here by construction of low-level flow regulation dams and flood-protection levees on top of one or both channel banks. The most part of channel sections have also been artificially canalized by concrete banks (Fig.2C).

Different types of the river channels depending on the degree of anthropogenic impact can be distinguished in the Niida River basin. Artificially canalized channels with concrete embankments and levees are the dominant type for main rivers draining the basin headwaters upland depressions (Fig.2A). Constantly increasing volume of sediment deposited within a concrete channel effectively reduces the active cross-section area of a stream. As a result, the frequency of middle floodplain inundation increases considerably as compared with natural floodplain cross-sections. The second type of channels is mostly typical for the coastal lowlands of the Niida River basin. It is represented by significantly wider channels with flood-protection levees on one (if one bank is naturally steep) or two sides, as well as low-level dams used mostly for irrigation needs (Fig. 2C). Rangelands of the faulting zone occupy middle reaches of the main river and its tributaries in central part of the Niida River basin. The density of gully and small valley network is higher than that of the uplands. Slopes of that area have high to very high gradients.

Both small tributaries and main river channels in this area are characterized by very high gradients and composed mostly of cobbles and boulders with bedrock outcrops. Channels retain natural morphology without human interference. It can therefore be suggested that there is high hydrological and geomorphic connectivity between the catchment slopes, small tributaries and main river channels in this part of the basin.

Some valley reaches within uplands depression also have wider channels, but unconfined by levees or embankments (though there can be levees on one or both sides, but remote from the channel along the higher floodplain or low terrace level) and without low-level dams. Usually three levels of floodplain can be identified in such valley bottoms. In some cases, however it is difficult to distinguish low and middle floodplains. Natural step-and-pool channels dominated by cobble-boulder alluvium and bedrock is the third type of river channel dominant within the rangelands area (Fig.2B). The gradient of such channels is much higher than those of all other types, and very often floodplain is totally absent. Sometimes fragments of high or very young low floodplain can be identified. River reaches with bedrock channels are characterized by extremely limited amount of floodplain sediment deposition except for certain specific locations such as young point bar surface.



Figure 2 Views of the Niida river channels in the different geomorphic regions: A - upper reach, depression in uplands; B - middle reach, severely dissected rangelands; C - lower reach, coastal lowland

3. Material and methods

An extreme flood with 4-5% annual exceedance probability occurred from 6 to 11 September 2015 as a result of Tropical Storm Etau (Golosov *et al.*, 2016). During a 6 days-period, 456 mm of precipitation fell in the upper reach of Niida River (according to JMA data for Iitate meteorological station) which is about one fourth of the annual norm. Maximum rainfall with 200 mm precipitation was observed on the last day. All measurement equipment was destroyed, so actual maximum water discharges unknown. Preliminary assessment of water discharge for the some cross-sections in the low reach was evaluated based on heights under floodplain of objects dangling on trees. It is more likely that maximum water discharge during this extreme event was about $220\text{--}250\text{ m}^3\text{ sec}^{-1}$. During the flood of September 2015, water flows washed out the unsupported sections of stream banks. Also, some landslides occurred, mainly on very steep slopes.

The geomorphological impact of the extreme flood was identified in all reaches of the Niida River basins during the field survey. The most considerable changes were seen within the lower reach in the coastal lowland of the Niida River. So, the most detailed study was done for this reach which is located between the foothills and ocean coast. To assess the geomorphic impacts of the floods on the Niida channel and floodplain, high

resolution satellite images of a 14-km-long lower reach of the Niida were taken from Google Earth on 1 June 2015 and 12 November 2015, which were made before and after extreme flooding. Images were orthorectified and georeferenced using ERSI ArcGIS in geodatabase format. Channel changes were identified from the photography and verified using field visits at selected sites. By on-screen digitizing a series of metric polygons were generated for the entire 14-km reach, identifying wetted channel, bars, active channel (wetted channel and bars combined) and areas of inundation (proximal to the channel) and bank erosion. Proximal inundation is defined as that adjacent to the channel, identifiable by thick drapes of sediment over the floodplain overlaying previously vegetated or partly vegetated section of floodplain. Distal inundation is that further away from the channel with shallow layer of fresh fine sediment were not taken into consideration, because it was difficult to identify them on the satellite image.

Then the lower reach of the Niida River was divided into 21 sections according morphology of channels (Fig.3). There are few river channel type classifications used in the scientific literature. In Russian geomorphology three main morphological types of the river channel are usually selected: straight, braided and meandering (Leopold & Wolman, 1957; Alabyan & Chalov, 1998).

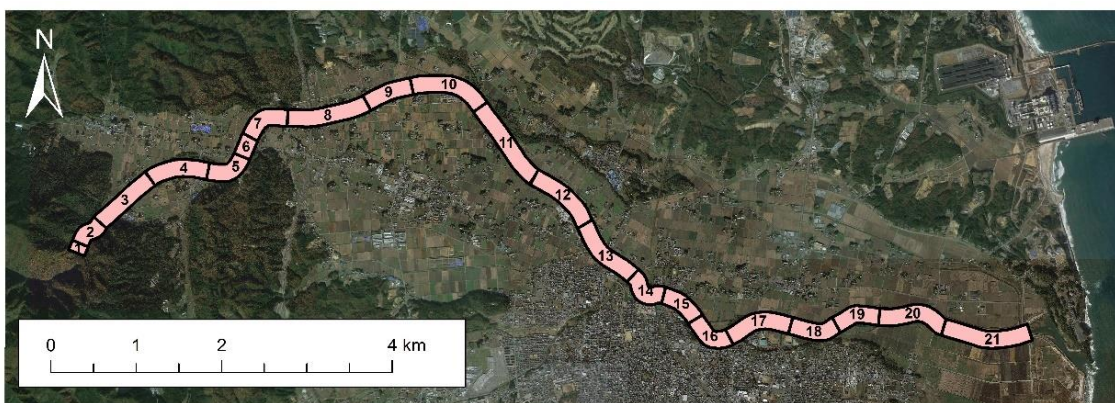


Figure 3 Location of the studied sections of the lower reach of the Niida River

However, classification of the river channels suggested by Schumm (1985) is more appropriated

for the Niida River, because it is included intermediate types of the river channels. One of

them is wandering type of river channel. Wandering rivers have a morphology that is intermediate between braiding and meandering with multiple channels separated by islands. So, river channels within each section were described using both Schumm and Leopold & Wolman classification. On the next stage the entire 14-km reach was divided into three sub-zones depending on the bed-slope gradients according to the classification suggested by Chalov (1996): sub-zone 1 (semi-mountainous); sub-zone 2 (semi-mountainous – plain) and sub-zone 3 (plain).

Areas of bank erosion and in-channel deposition was determined for each section (Table 1, Fig.4). Also, area of fresh sedimentation on floodplain was evaluated based on overlapping of vegetation by sediments. Field verification of the results of satellite image interpretation was undertaken along several profiles for typical sections belonging to each type of the channel (Fig.4). The correctness of identification of the boundaries of different areas was within ± 2 m. In addition, direct measurements of sedimentation for the extreme event was done along the same profiles, using a metal stick and tape-measure.

Depth of fresh sediments can be easily identified on the grassed floodplain section. However, it did not seem possible to perform reasonably correct measurement of fresh sediment depth within the bars unprotected by vegetation. So, we took the decision to analyze only the spatial changes of the river valley bottom without using volumetric measurements because of very high differences in correctness of spatial measurements and depth evaluation.

Evaluation of the geomorphological impact of the extreme flood on the river channels and floodplains in the two other geomorphological zones of the Niida River basin (see Fig.1) was based on the semi-quantitative assessment of the modification of typical fragments of the river valley bottoms. Sedimentation rates on the different floodplain level was measured using a metal stick or small pits (in case of extremely high deposition) and tape-measure. It wasn't possible to use satellite image interpretation for evaluation of the channel modification because of two reasons. Firstly, in the most cases the bank erosion and in-channel deposition rates don't exceed 1 m. Secondly, very often the river banks were covered by trees.

Table 1 Mean areas of the Niida river valley bottom affected by bank erosion, in-channel deposition and intensive overbank sedimentation within individual sections

River section	Type of channel	E_b^*	D_{ch}	D_f	Length (L), m	Wavelength (l), m	(L/l)	Average height, m a.s.l.
<i>semi-mountainous sub-zone (average slope 8‰)</i>								
1	straight	524	93	2323	122	122	1,00	65
2	meandering	1075	153	6499	360	341	1,06	60
3	straight	5917	696	2715	780	780	1,00	55
4	wandering (braided)	9897	488	15691	702	684	1,03	48
5	meandering wandering	4655	4133	12227	508	431	1,18	45
6	(braided)	3331	120	5924	248	248	1,00	43
7	meandering	11002	2892	14244	592	502	1,18	38
8	straight	8542	407	2856	956	945	1,01	35
<i>transit from semi-mountainous to plain sub-zone (average slope 4‰)</i>								
9	straight	4954	1248	9911	577	565	1,02	30
10	meandering wandering	10315	3517	22359	906	851	1,06	25
11	(braided)	10691	2290	19523	1041	1041	1,00	20

12	meandering	8429	772	23427	859	808	1,06	18
13	meandering	8757	6237	22424	866	824	1,05	16
14	meandering	3976	1370	1378	500	427	1,17	13
<i>plain sub-zone (average slope 3‰)</i>								
15	wandering (braided)	452	11152	15647	483	466	1,04	12
16	meandering	4872	1351	10269	520	449	1,16	10
17	wandering (braided)	4241	3583	12968	776	722	1,07	8
18	wandering (braided)	4202	1367	18960	589	542	1,09	6
19	meandering	2601	324	8507	540	513	1,05	4
20	wandering (braided)	5667	3611	23935	839	764	1,10	2
21	straight	3232	369	644	1041	1011	1,03	1

*E_b - bank erosion, m²; D_{ch} - in channel deposition, m²; D_f - floodplain sedimentation, m²

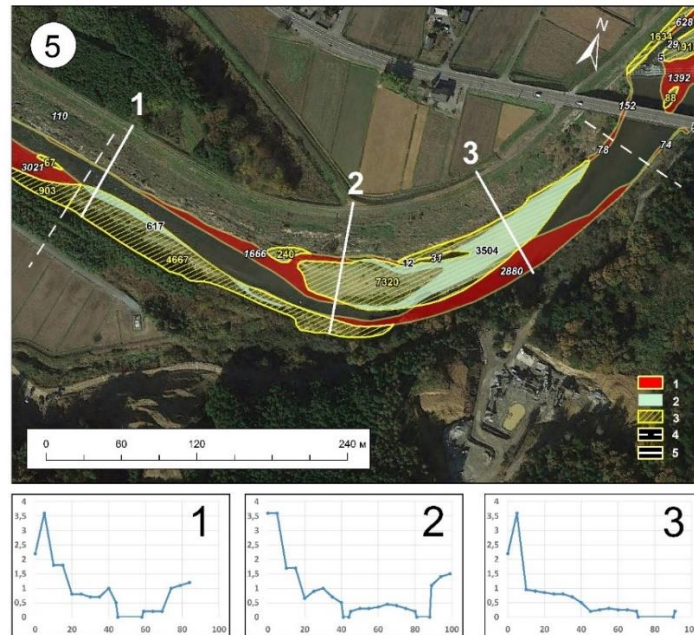


Figure 4 Section 5, sub-zone 1 of the lower reach of the Niida River. Legend: 1- areas of erosion; 2 - areas of in channel deposition; 3 - areas of floodplain sedimentation; 4 – boundary of section; 5 - field cross-section profile locations. Below – cross-section profiles, constructed based on the field measurements.

4. Results and discussion

The proportion of different type channel changes along the lower reach of the Niida river according to decreasing of the river bed gradients towards the river mouth (Table 2). In the upper-most sub-zone with the highest mean river bed gradient the straight channel dominated. In the sub-zone two the proportion of meandering channel is as high as 66%. In the sub-zone 3, located near the river

mouth and partly affected in the lowest section by tidal regime the braided channel type became the most extended. It should be reminded that several low-level dams are located along the entire lower reach of the Niida River (see as an example, view of such dam in right high corner of Figure 3). It is undoubtedly influenced the river bed gradient, and it is another reason of the presence of wandering (braided) type channels in sub-zones 1 and 2.

Table 2 Distribution of channel types in different sub-zones of the lower reach of the Niida River

Type of channel	Length, m and proportion of different channel types			
	Sub-zone 1	Sub-zone 2	Sub-zone 3	Total
Straight	1868/44%	577/12%	1041/22%	3486/25%
Meandering	1460/34%	3131/66%	1060/22%	5651/41%
Wandering (Braided)	950/22%	1041/22%	2687/56%	4678/34%
Total	4268/100%	4749/100%	4778	13795

The width of the valley bottom of the Niida River is relatively stable along the lower reach, changing within the range 90-110 m (Fig.4). So, the it is possible to use the length of type of channel for calculation of specific area of the different erosion-depositional processes (Table 3), which actually characterized the proportion of erosion and

sedimentation within the different parts of the river valley bottom, including the river channel and floodplain. The river section with straight type of channel is characterized by almost zero budget with extremely low in-channel deposition and the lowest bank erosion and floodplain sedimentation (Table 3).

Table 3 Specific area of bank erosion, in channel deposition and floodplain sedimentation for the sections of lower reach of the Niida river with different channel types.

Type of channel	Specific area of bank erosion, m ² /m	Specific area of in -channel deposition, m ² /m	Specific area of floodplain sedimentation, m ² /m
Straight	6.6	0.8	5.3
Meandering	9.9	3.7	21.5
Wandering (Braided)	8.2	4.8	24.0
Total	8.5	3.3	18.3

While both sections with meandering and wandering (braided) types of channels are characterized by high floodplain sedimentation during the extreme flood, the bank erosion exceeds the in-channel deposition by 1.7-2.7 times.

The proportion of areas with bank erosion and different types of sedimentation change differently for the different types of river channel in direction from foothills to the river mouth (Table 4). In the case of wandering (braided) channels, the proportion of deposition is increasing from sub-zone 1 to sub-zone 3. The bank erosion exceeds the total sedimentation in the case of straight channel. The highest proportion of sedimentation is

observed for the meandering channels with extremely large deposition in sub-section 3 (Table 4).

However, the highest bank erosion is observed for the meandering rivers. It is important to underline that areas of bank erosion exceed the area with in-channel deposition for all types of channel and for all sub-zones, excluding only meandering channel in sub-zone 3. It is fair to assume that river channel incision and intensive floodplain sedimentation were the dominant processes in the lower reach of the Niida River during the extreme flood. Extremely high energy of the stream has been confirmed by intensive bank erosion even in sub-zone 3 (Fig. 5).

Table 4 Mean areas of the lower reach of the Niida river valley bottom affected by bank erosion, in-channel deposition and intensive overbank sedimentation

Type of channel	E_b^*	D_{ch}	D_f	Proportion $D_{ch} + D_f / E_b$
Sub-zone 1 (semi-mountainous) **				
Meandering	16 732	7 178	32 970	2.4
Wandering				1.8
(Braided)	13 228	608	21 615	
Straight	14 983	1 196	7 894	0.6
Sub-total	44 943	8 982	62 479	1.6
Sub-zone 2 (transit from semi-mountainous to plain sub-zone)				
Meandering	31447	11896	69588	2.6
Wandering				
(Braided)	10691	2290	19523	2.0
Straight	4954	1248	9911	2.2
Sub-total	47122	15434	99022	2.4
Sub-zone 3 (plain sub-zone)				
Meandering	14562	19713	71510	6.2
Wandering				2.7
(Braided)	7473	1675	18776	
Straight	3232	369	644	0.3
Sub-total	25267	21757	90930	4.5
Total	113822	46173	252331	2.6

* E_b - bank erosion, m^2 ; D_{ch} - in-channel deposition, m^2 ; D_f - floodplain sedimentation, m^2

** sub-zone of the river valley bottom of the lower reach were separated according to the decrease of the river-bed gradient towards the mouth.

It was established that bank erosion is particularly high in sub-zone 1 because of high energy of the flow after the exit of the Niida river from the mountains to the coastal plain, in particular, in the river reaches with straight type of channel. Generally, erosion dominated over in-channel deposition for all sub-zones of the lower reach of the Niida River except meandering channel type at section 3. However, the meandering type of channel is characterized by the relationship of relative equilibrium between erosion and in-channel deposition even at section 1 with the most active valley bottom transformation, including overbank sedimentation.

The wandering (braided) type of the river channel is characterized by different modification of the river valley bottom depending on the river channel gradient. Active erosion was identified for the wandering (braided) channel at the sub-zone 1, section 6 (Fig.6), while intensive in-channel

deposition was observed at the sub-zone 3, section 15 (Fig.7).

Results of the field survey were used for understanding of the effect of extreme flood on river channels and floodplains in other reaches of the Niida river. The transformation of upper reaches of the Niida River within intermountain depressions depends on the type of the channel. High sedimentation on the floodplain in the range 10-15 cm (one order of magnitude higher than the mean annual) is typical for the artificially canalized channels with concrete embankments and levees, which are the dominant type for main rivers draining the basin headwaters upland depressions. However, sedimentation rates in only 1-3 cm was established after extreme flood for the uppermost section of the artificially canalized channels. Some valley reaches within uplands depression have wider channels, but unconfined by levees or embankments (though there can be levees on one or both sides, but remote from the channel along

the higher floodplain or low terrace level). Here in some sections within the floodplain there was extremely high deposition of sand and pebble material with an average depth of 30-40 cm and a total weight of 400-500 tons. Usually extremely high sedimentation was associated with very active bank erosion upstream of such sections.



A



B

Figure 5 Section 18 (sub-zone 3) of the lower reach of the Niida River before (A) and after (B) extreme flood. Legend: 1 – eroded part of the bank of the Niida River protected by concrete embankments; river channel position before extreme flood, 01.06.2015; 3 – river channel position after extreme flood, 12.11.2015. As can be seen the road on the right bank is completely washed out

As a result, it is possible to subdivide different parts of the Niida River basin schematically represented by the respective longitudinal profile reaches according to the main processes influencing sediment redistribution (Fig. 8).

Hills within the basin headwaters uplands are one of the dominant sediment sources during extreme events. Based on the monitoring results (Ueda *et al.*, 2013), it is fair to suggest that bank and, possibly, small stream bed erosion are the main sources of sediments, with mass movement processes (creep, shallow landslides) being the secondary sources. It is very likely that sheet and rill erosion occur under the forest during extreme flood.



Figure 6 The bank erosion (1), in channel deposition (2) and floodplain sedimentation (3) zones appeared after extreme flood at the section 1 (sub-zone 1, semi-mountainous sub-reach) within the wandering (braiding) type of the Niida River channel



Figure 7 The bank erosion (1), in channel deposition (2) and floodplain sedimentation (3) zones formed after extreme flood at the section 3 (plain sub-reach) within the wandering (braided) type of the Niida River channel.

According to the monitoring data, overland flow on forested hillslopes is formed only during

extremely heavy rainstorms or locally at spots unprotected by litter and understory vegetation (Miyata *et al.*, 2009). Runoff coefficient decreases with increase of slope catchment area and was found to be less than 0.05 on 20 m along forested slope (Gomi *et al.*, 2008). Serious soil loss in subtropical forested catchment (Honshu Island) with total annual precipitation about 3500 mm is observed only during extreme rainstorms with precipitation sum >300 mm per event according to the field monitoring (Fukuyama *et al.*, 2005). Such rains are very unusual for the river basins of the northeastern part of the Honshu Island with annual precipitation of 1200–1800 mm only.

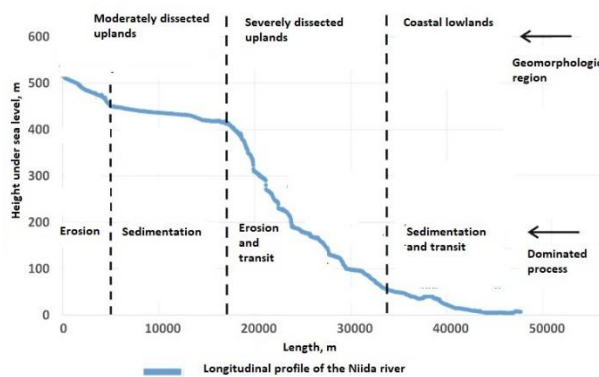


Figure 8 Longitudinal profile of the Niida river

Small streams are the main transportation pathways delivering sediments from the steep forested hillslope areas. For example, results of monitoring of water and sediment discharge in small stream catchment of the Japanese Alps demonstrate that maximum sediment amounts are transported during snowmelt period when highest water discharges are observed (Iida *et al.*, 2012).

A considerable part of sediments becomes temporarily redeposited immediately after a sharp decline of the river channel gradients where the stream valleys from hills enter the upland depressions. Such areas can be considered as intermittent storage, as sediment were remobilized by bank and bed erosion during extreme flood. Contemporary denudation rates for the faulting zone rangelands of the Niida River basin is $434 \text{ t km}^{-2} \text{ yr}^{-1}$ as estimated from sediment storage in Takanakura Reservoir for 1975–2013 period (based

on monitoring data), which even exceeds denudation rate for small catchments of Japanese Alps. Completely forested territory of the rangelands is also dominated by sediment production from small stream bank and bed erosion.

5. Conclusions

The detailed assessment of geomorphological impact of the extreme flood in the Niida River basin allows concluding that different exogenic processes (landslides, scree, bank erosion etc.) were the main sediment sources for the river sediment discharge. Maximum channel deformations were observed within the lower reach of the Niida River located on the coastal plain because of extremely high energy of the stream with maximum water and sediment discharges. Morphological type of channel in the lower reach of the Niida river considerably influence on the intensity of erosion and sedimentation processes and on the proportion between them. The most intense transformation of the river channel was observed within the river section with meandering type of channel following by the section of the river with wandering (braided) type of channel. The highest areas of bank erosion (36431 m^2) and floodplain sedimentation (79499 m^2) are observed for meandering channels, located in the sub-zone 2, while the highest area of in-channel deposition (19713 m^2) is established for the meandering channel in sub-section 3. The section of the river with straight type of channel was characterized by a relatively low river bottom transformation. It was found that bank erosion exceeded in-channel deposition in 1.7–2.7 times for all types of river channel in the low reach located within the coastal floodplain. However, floodplain sedimentation is the most active processes for the river sections with meandering and wandering types of the river channel. Floodplain sedimentation exceed bank-erosion in 2.2 times for river sections with the meandering type of channel and in 2.9 time for the river sections with wandering type of channel. The bank erosion exceeds floodplain deposition in 1.2 times only within the river sections with straight type of channel. Total sedimentation

(in-channel + floodplain) in 2.6 times higher than bank erosion in the lower reach of the Niida River after extreme flood event 4-5% probability. However, sedimentation rates on the floodplain of the upper reaches of the Niida River were also one order of magnitude higher than the mean annual rates. The middle reach of the Niida River is an area of active bank and bottom erosion, because of highest river bed gradient. It is also a transit area for the sediment transported by the stream from the upper reach.

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Natural and anthropogenic agents in the present geomorphological dynamics of the Torrent Corlo mountain catchment (Northern Apennines, Italy)

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ABSTRACT

The morphological changes affecting a small mountain catchment in the territory of Modena (Italy) have been taken into account. In particular, based on detailed field surveys and analysis of remote sensing imagery, an assessment was made on the natural and anthropogenic agents which have modelled this basin in the past 80 years. For several decades, the Torrent Corlo catchment was subject to intense exploitation of clay raw materials in order to supply a flourishing ceramic tile industry. As a result, a strong, negative impact has affected the landscape and, in some areas, the geomorphological evolution due to man's activities greatly surpasses the changes ascribable to natural processes, such as landslides or stream channel processes. Since 2008, all quarrying activities have ceased and the local public administration has started a project of reclamation of the abandoned clay pits, although it will not be possible to restore completely the original, natural features of this catchment. A comparison is made with the sub-catchment Rio delle Vigne valley, which has been spared from anthropogenic changes and has been affected only by natural gravity-induced processes, which have produced some twelve landslides. The final products of this research are the implementation of the first geomorphological map of the T. Corlo mountain catchment and an updated version of the hydrological hazard map, in which active and dormant landslides are much more numerous than those mapped in any other previous geological map (s.l.). These documents can be utilized for any intervention by public boards aiming at recuperating and improving this intensely exploited area.

KEYWORDS

Morphogenetic agents; gravitational processes; quarrying activities; geomorphological evolution; Northern Apennines; Italy

1. Introduction

The rapid urban and industrial development, which has affected large portions of northern Italy since the mid-1950s, has also caused heavy impacts on the territory, sometimes increasing geological instability processes in areas already predisposed to these. This is the case of the study area, which is characterised by the presence of silty-clayey rock types, naturally subject to intense erosion and slope movements. At the same time, these raw materials are particularly suitable for the production of ceramic tiles. Therefore, they were heavily dug out from large clay pits for a long time, without considering the consequences on the landscape and the environment. This research was carried out in order to identify landforms created by past and present morphogenetic processes in the small Torrent Corlo mountain catchment (Northern Apennines, Italy) and to quarrying activities carried out for several decades in the same area. The data collected were finally represented in a detailed geomorphological map, with the purpose of providing a starting document for the public authorities in charge of defining and undertaking upgrading and stabilisation measures.

2. Site description

The mountain catchment of the T. Corlo is located in the western sector of the Modena Apennine foothills, in the Municipality of Fiorano Modenese, which is part of the industrial district of Sassuolo-Fiorano-Maranello, where hundreds of factories were built, starting from the early 1950s, for the production of ceramic tiles (Fig. 1).

The T. Corlo is a small watercourse that runs across the Modena Apennine hills for about 3 km; it reaches the Modena Plain at Fiorano and, some 3 km downstream, flows into the Fossa di Spezzano stream, which belongs to the River Secchia catchment.

The T. Corlo catchment has a sub-continental temperate climate with average precipitation of about 700-800 mm/year and average temperature of 12-13 °C (Fazzini, 2007). The study area stretches over 175 ha with altitudes ranging between 125 m and 310 m approx.

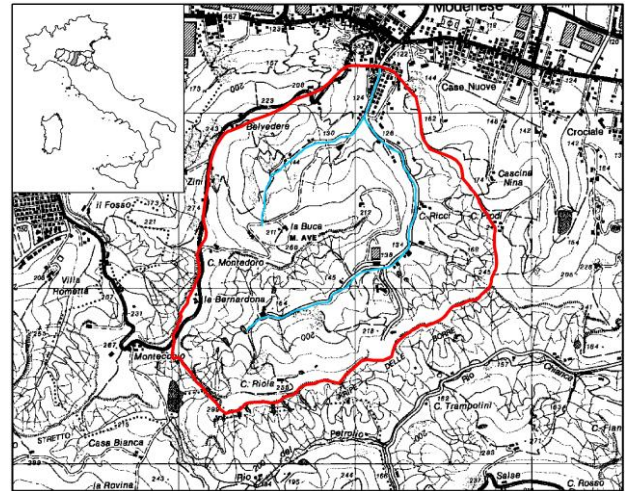


Figure 1 Geographic setting of the Torrent Corlo mountain catchment. Shaded area in inset is the Province of Modena.

2.1. Geological and geomorphological setting

From the geological viewpoint, the area is located in the Modena Apennine margin, where marine silty-clayey rock types of the Plio-Pleistocene “Argille Azzurre” Formation crop out (Gasperi *et al.*, 2005). They are marly clays, grey and blueish-grey clayey and silty marls, cropping out in medium to thin layers, with joints hardly visible owing to bioturbation. Locally, discontinuous, thin, laminated layers of fine biocalcarenes and yellowish siltites are found (Gasperi *et al.*, 2005; Regione Emilia-Romagna, 2017). In the study area there are sand intercalations exposed in medium-sized strata, particularly visible in the upper part of the left hand-side slope of the T. Corlo valley (Fig. 2). The general setting of the strata shows a NW-SE strike, with a 15° to 40° NE dip (Fig. 3). On the right hand-side of the T. Corlo valley, these rock types are affected by a WSW-ENE trending fault. In the lowest part of the T. Corlo catchment, fine alluvial deposits are exposed, which belong to the Modena Unit sediments dating from the 6th century CE. This Unit comprises gravel deposits turning to alluvial terrace sand and silt deposits (cf. Gasperi *et al.*, 2005, Regione Emilia-Romagna, 2017).



Figure 2 Argille Azzurre Formation (FAA) cropping out on the left-hand slope of the T. Corlo upper valley. In the top part of the cliff, ochre coloured sand layers are visible.

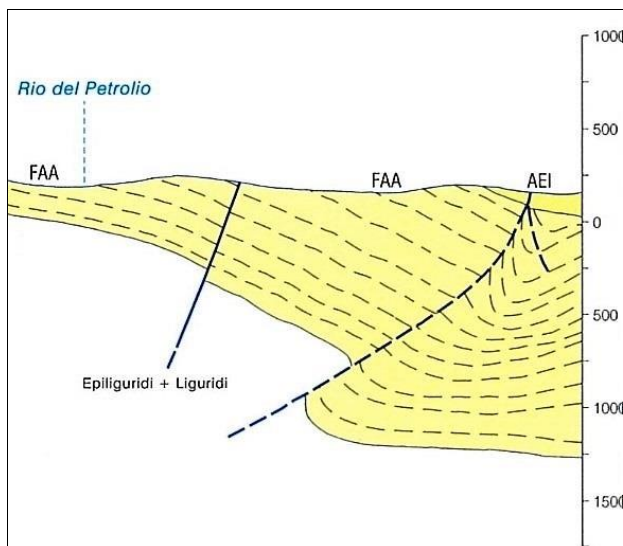


Figure 3 Geological section of the eastern sector of the study area. Legend. FAA: Argille Azzurre Formation (Lower Pliocene - Lower Pleistocene); AEI: Emilia-Romagna lower synthem of the Middle Pleistocene (after Gasperi *et al.*, 2005). In stratigraphy a "synthem" is a chronostratigraphic unit that defines an unconformity-bounded regional body of sediments and represents a cycle of sedimentation in response to changes in relative sea level or tectonics.

The geomorphological features of the study area are controlled by the widespread presence of clay. The main landforms are related to gravitational, running-water erosional processes, and anthropogenic activities. The most evident natural morphological features to be observed on the

slopes of this mountain catchment, as well as in the surrounding areas, are badland landforms locally named "calanchi". Indeed, badlands are one of the most spectacular erosion landforms of the Po Plain side of the Apennines. Typically, they are composed of silty-clayey rock types and are characterised by a very fine drainage network and short, steep slopes with narrow interfluvies. Various small to average-sized earth slides and earth flows are found in the area. Surface deposits are mostly made up of very fine materials sedimented by the T. Corlo on the valley floor and by rill-wash at the foot of the slopes. The main anthropogenic landforms consist of abandoned clay pits on the slopes of the mid-sector of the valley, which produced the raw material for the ceramic tile industry.

3. Materials and methods

The research here presented was carried out according to the traditional methods used in geomorphology and included the following steps:

i) A retrospective study was carried out based on bibliographic sources, research on historical maps, reports from technicians of the Municipality of Fiorano Modenese and accounts of the local population, in order to gain data on the spatial and temporal distribution of historical slope movements and anthropogenic activities. This task provided information about: 1) types of landslides, 2) origin of landslides (conditioning and triggering factors), with special attention on the role played by human activity on the generation/reactivation of slope movements, 3) reactivation frequency of particular landslides, 4) excavation and termination phases of quarrying activities.

ii) A multi-temporal analysis of aerial photographs and satellite images was carried out, with special attention given to erosional and gravitational phenomena. To achieve this aim, traditional stereoscopic and digital photogrammetry techniques were utilized. The documents considered in this study are listed in Table 1. The available digital data were overlaid and compared using GIS software, also by means of 3D elaborations in order to better appreciate morphological features. The study of landforms, represented in a sequence of

images corresponding to different years, allowed the evolution of the study area to be reconstructed.

iii) Field survey and related mapping was carried out at a 1:5,000 scale, with particular attention to the cartographic representation of instability phenomena and to the morphological features of the study area. The implementation of the geomorphological map followed the scheme and legend of Italian mapping methodology (Gruppo di lavoro per la cartografia geomorfologica, 1994) and was updated on the basis of recent geomorphological maps (e.g. Castaldini *et al.*, 2009; Panizza *et al.*, 2011; Bruschi *et al.*, 2012). According to the legend of this map, landforms and associated deposits are depicted by using different coloured symbols, according to the geomorphological processes responsible for their development, whereas their state of activity is marked by means of colour shades (cf. Dramis and Bisci, 1998; Dramis *et al.*, 2011; Panizza *et al.*, 2011). This 1:5,000 scale geomorphological map, constructed using GIS technology, provides a useful comprehensive basis as well as an original document for the area and an organic framework of past and present morphogenesis.

Table 1 Cartographic documents examined. IGM: Italian Military Geographic Institute; GAI: Aerial Italian Group; CTR: Regional Technical Maps (CTR) of Emilia-Romagna Region; RER: Emilia-Romagna Region; GN: Geoportale Nazionale website; AGEA: Agenzia per le Erogazioni in Agricoltura; GE: Google Earth website; B/W: black & white; C: colour.

Type of document	Date	Scale / Resolution	Note
IGM map	1935	1:25,000	B/W
GAI aerial photos	1954	1:33,000	B/W
RER aerial photos	1973	1:15,000	B/W
CTR map	1977	1:10,000	B/W
Volo Italia: aerial photos	1988	1:70,000	B/W
GN website	1994	1:2,000	
Volo Italia	2000	1:1,000	C
GN ortho-photos			
CTR map	2005	1:10,000	C
Volo Italia	2006	1:1,000	C
GN ortho-photos			
AGEA ortho-photos	2008	0.5 m	C
GN website	2012	1:1,000	C
GE website	2014	0.5 m	C
	2016		
	2017		

iv) Starting from the data collected in previous research phases, an updated version of the Province-Coordinated Territorial Plan (or simply PTCP Hydrological Hazard Maps of Provincia di Modena, 2009) was produced. The PTCP Hydrological Hazard Maps are thematic synthesis maps classifying the unstable zones as active or dormant landslides or as potentially subject to landsliding. They also outline critical areas in relation to hydrological instability, to which guidelines, regulations and directives are applied (see Table 2).

As highlighted by Castaldini *et al.* (2012b), the geological instability processes identified in many areas of the Modena Apennines do not correspond in several cases to those mapped by the Hydrological Hazard Maps. The main differences concern the presence, location and/or state of activity of slope instability phenomena.

It is important to stress how the contents of the PTCP Hydrological Hazard Maps (Provincia di Modena, 2009) have direct and constraining effects on the territorial planning of local boards. A peculiar situation for the Modena Province is that the PTCP Hydrological Hazard Maps represent the only reference plan for municipal urban planning with respect to hydrological safety regulations.

Table 2 Legend of the PTCP Hydrological Hazard Map (modified after Provincia di Modena, 2009).

ZONE	CATEGORY	ELEMENTS CONSIDERED
1	Areas affected by active landslides	Landslides which are currently active or that have been reactivated in the last 30 years (rock falls are also included).
2	Areas affected by dormant landslides	Landslides that have not shown signs of activity in the last 30 years and that could be reactivated by their original causes; among these, there are block slides, lateral spreads and Deep-seated Gravitational Slope Deformations.
3	Potentially unstable areas	Quaternary deposits affected by evident superficial morphogenetic processes such as creep, solifluction etc.; alluvial fans; areas affected by relevant processes due to running water (erosion, floods etc.); naturally stabilized or relict landslides.

In their territorial-planning phase, Municipalities can adopt all data contained in the PTCP Hydrological Hazard Maps without any change, but

they can also improve and update them by means of detailed investigations.

4. Geomorphological map

The geomorphological map (Plate 1) shows the geological and structural elements, hydrography, anthropogenic landforms, fluvial and slope landforms due to running water and gravity-induced slope landforms.

An important aspect concerns the “concept of activity”, which should be applied in defining the dynamics of geomorphic processes (and related landforms and deposits) in general, and slope instability phenomena, in particular.

It is of paramount importance in applied geomorphology to distinguish “active”, “dormant” or “non-active” processes. As definitions of these terms vary, we must define precisely how they are used. Since a geomorphological map was the base document for updating the PTCP Hydrological Hazard Map (see chapter 5), running water and gravity-induced landforms and deposits have been distinguished as “active” and “dormant”, according to the definition given by Provincia di Modena (2009) (see Table 2).

As previously stated, only marine silty-clayey rock types of the Plio-Pleistocene “Argille Azzurre” Formation crop out in the mountain catchment of the T. Corlo. The T. Corlo and its unnamed left tributary, which flows along the Vigne valley (meaning valley of the vineyards) (Fig. 4), are the main watercourses of the area. For simplicity's sake, the name of “Rio delle Vigne” was given to this small stream.

The T. Corlo and its tributary Rio delle Vigne are very small watercourses, with an intermittent regime, and in the summer they are practically devoid of water. In particular, in several stretches of its course the T. Corlo was artificially covered and therefore flows underground (Fig. 5).

Nine small to medium-sized artificial ponds make up other hydrographic elements. The biggest water bodies are located in the T. Corlo mid-valley; they are four ponds, some 100 m long and 10 m wide (Fig. 6) excavated around 2010; they appear in the AGEA 2011 ortho-photos but not in the 2008

ones. They resulted from abandoned quarries within the framework of the Riola Valley S.A. Project for the landscape and environmental reclamation of the T. Riola valley (ASQ-Consultinggroup, 2008). Since these water bodies were not mapped on the CTR maps (Regional Technical Maps of Emilia-Romagna Region), the Geomorphological Map (Plate 1) also provides an updating of the previous map.



Figure 4 Rio delle Vigne valley. In the background the Modena alluvial plain.

Other anthropogenic hydrographic landforms are the emergence and submersion points of the T. Corlo (Fig. 5).

In any case, the most evident and heavily impacting anthropogenic landforms are all related to quarrying activities, which dominate the middle T. Corlo valley (Plate 1), whereas the adjacent Vigne valley was spared. These man-made landforms (e.g. excavation, transport or deposit areas) have been classified as “abandoned” and “reclaimed” quarrying areas and edges of anthropogenic scarps. They still show their artificial origin.

Thanks to the presence of a clay formation, very suitable for ceramic tile production, and considering the proximity to the plain where industrial plants are located, quarrying activities were carried out in the T. Riola valley since the early 1900s (cf. Ronconi 2000; ASQ-Consultinggroup, 2008; Castaldini *et al.* 2012a, 2012c).

The reclaimed clay pits are mainly found on the valley floor, where the structures making up the Riola Valley Horse Riding Centre are located (Fig. 7).

The abandoned clay pits are found on both right and left slopes, sometimes reaching the crests.



Figure 5 Submersion point of T. Corlo south of the village of Fiorano Modenese.



Figure 6 Artificial pond on the right hand-side of the T. Corlo mid-valley, which was produced from an abandoned clay pit. In the background, the badlands.

Artificial scarps are found nearly everywhere within the various quarrying areas, both abandoned and reclaimed. When these scarps still show a typical aspect related to quarrying activities they have been represented as anthropogenic landforms. On the other hand, when rill-wash or gravity-induced processes have considerably modified their appearance they have been represented as modelled by other morphogenetic agents.

Landforms and deposits due to superficial running waters are rather widespread in the T. Corlo

catchment. They are: badlands, edges of scarps remodelled by water, concentrated runoff gullies, fluvial, colluvial and lacustrine deposits.



Figure 7 Panoramic view of Mt. Ave southern slope, which was heavily affected by quarrying. The clay pit area was reclaimed and the structures of the Riola Valley Horse Riding Circle were built on it. Notice the remodelling of the pit scarp by runoff waters. In the background the Modena alluvial plain.

In particular, typical examples of badlands can be observed in the T. Corlo upper and mid-valley. They are one of the most spectacular erosion landforms which affect the clayey soils of the Apennine northern margin. They are characterised by a high-density hydrographic network in which the single stream channels are separated by thin, blade-like crests. Runoff waters tend to have a thinning effect on the crests, also with the fundamental contribution of earth flows and earth slides, which have their crowns in the upper parts of the slopes. At present badland evolution affects many areas, owing also to the landslides which cause a rapid retrogression of the badlands' heads. Consequently, landslides from the crests that separate badlands located on contiguous slopes fill up the runoff channels with their deposits (Fig. 8). Generally speaking, the situation represented in the Geomorphological Map is merely indicative since it is practically impossible to map in detail all the landslide deposits which fill up the badlands' stream channels.



Figure 8 Example of badlands' head retrogression owing to slope movements. The ochre-coloured sandy tongues correspond to landslide deposits.

In this map the badlands have been distinguished as active or dormant, according to the activity of rill-wash erosion or landslide processes. Active badlands cover a much larger area than inactive badlands. The edges of active badlands, represented on the basis of the most recent remote sensing imagery, are in several points farther back than the edges shown in the CTR map. This fact bears witness to the intense activity of morphogenetic processes occurring in the past decades.

Among the landforms created by surface running waters, there are numerous runoff gullies cut along the main stream channels. Deposits of the main watercourses (with texture ranging from sand to clay) have been distinguished (where thicker than 1 m) from colluvial deposits resulting from rill-wash down slopes (with texture from silt to clay), and from lacustrine deposits (clay). The alluvial deposits of the main watercourses have been mapped as dormant from the Rio Corlo – Rio delle Vigne confluence as far as the valley's mouth.

Colluvial deposits have limited extent and are widespread only in the lower portions of some slopes. In particular, at the foot of anthropogenic scarps, NW of the Riola Valley Horse Riding Centre, there are accumulations in progress of both colluvial and small earth flow deposits.

Finally, in the upper T. Corlo valley, there are lacustrine deposits related to old artificial water

basins. These impoundments were built when quarrying activity was at its peak, in order to mitigate the effects of running water and safeguard service roads leading to the clay pits. In particular, in the valley SW of Corlo, lacustrine deposits are found on five levelled-out altitudes, between 175 m and 210 m circa. They have created a particular step-like longitudinal profile.

Gravity-induced slope landforms and deposits are common in both the T. Corlo valley and the Rio delle Vigne valley and are in great part due to earth flows, earth slides and soil slips (cf. Cruden & Varnes, 1996), which are the typical landslides affecting silty-clayey rock types (Fig. 9).



Figure 9 Active soil slip in the lower stretch of the T. Corlo valley.

The Geomorphological Map attached to this paper reports many more landslides than those shown on previous geological maps (cf. Gasperi *et al.*, 1989, 2005; Regione Emilia-Romagna, 2017). In particular, many landslides have been identified in badland areas in the catchment's southern portion. They are active earth flows and earth slides, which have caused the retrocession of badlands' scarps and deposit their materials in the small valleys. In the northern portion of the study area, there are various active and dormant landslides, which affect the slopes of the lower T. Corlo valley and, in particular, the Rio delle Vigne valley. Several of these landslides were triggered or reactivated in late March-early April 2013 because of heavy precipitation occurring in the winter months. Their chronology was determined on the basis of field

surveys carried out in different periods of the year and on local accounts.

The Geomorphological Map also shows the areas affected by solifluction, since this superficial morphogenetic process is considered to be among the causes of potentially unstable areas. Solifluction is typical of the finest soils and in the study area is found on several slopes where vegetation is absent. This research showed that in very recent years there has been an increase of morphogenetic processes, which have remodelled the badlands and caused previously undetected slope movements.

5. Updated Hydrological Hazard Map

As previously stated, in their territorial-planning phase, Municipalities and local boards can adopt without any change all data contained in the PTCP Hydrological Hazard Maps (Provincia di Modena, 2009) for assessing the geological instability situation of their territory. Nevertheless, they can also improve them through detailed investigations since Hydrological Hazard Maps represent a constantly evolving territory and consequently require constant updating.

The presence in the study area of mainly clayey rock types, which are easily erodible with a high capacity of absorption of precipitation and running water, makes the entire area particularly susceptible to instability, as shown by the numerous slope movements identified and mapped in the Geomorphological Map (Plate 1).

Notwithstanding this, the instability situation in the T. Corlo mountain catchment represented in the PTCP Hydrological Hazard Maps of Provincia di Modena (2009) is certainly underestimated (Fig. 10).

Therefore, since this study was financed by the Municipality of Fiorano Modenese, the updating of the PTCP Hydrological Hazard Map of the study area was implemented based on data collected and detailed field investigations carried out in the previous research steps (Fig. 11).

The updating of the PTCP Hydrological Hazard Maps implemented in this study (Fig. 11) shows a considerably different situation than the one shown by Provincia di Modena (2009) (Fig. 10). The great differences between the two maps, as pinpointed by

Castaldini *et al.* (2012b) in other areas of the Modena Apennines, are ascribable to the following causes:

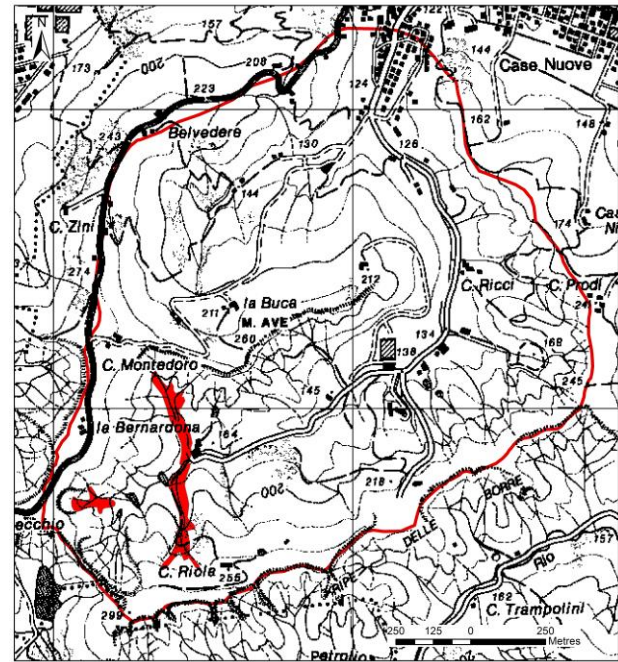


Figure 10 PTCP Hydrological Hazard Map (Provincia di Modena, 2009) of the T. Corlo mountain catchment. For the legend, see Table 2.

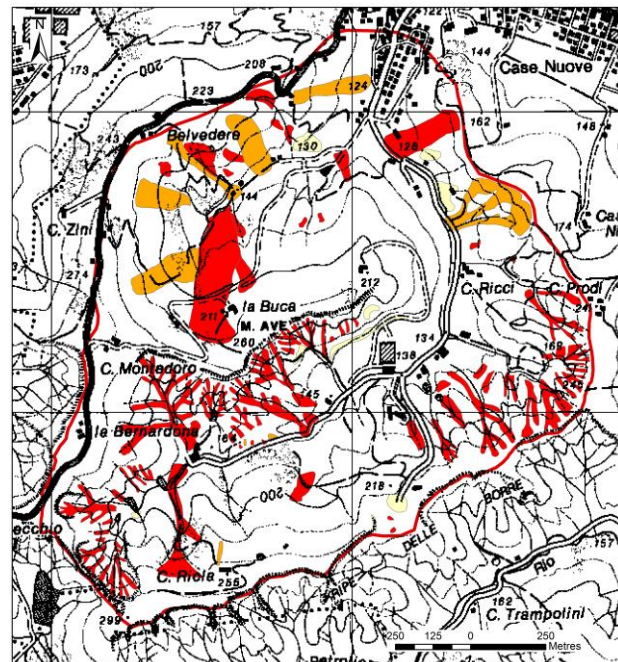


Figure 11 Our updated version (2017) of the PTCP Hydrological Hazard Map of the T. Corlo mountain catchment. For the legend, see Table 2.

a) The PTCP Hydrological Hazard Maps are derived from the instability inventory of the Emilia-Romagna Region, which are in turn derived from the Regional Geological Cartography. In the latter, the morphogenetic processes and deposits have been given a secondary importance compared with lithology and tectonic-structural elements.

b) The updating of the instability inventory of the Emilia-Romagna Region has been carried out by means of 'occasional and patchy' studies, while the slope instability phenomena regularly occurring during the rainy seasons show that the Apennine territory is characterized by intense and active geomorphological dynamics. Therefore, thorough and periodic investigations should be necessary in order to update the slope instability situation.

Another determinative factor concerns the detail of investigations. Our Hydrological Hazard Map is derived from an updated Geomorphological Map (Plate 1) surveyed in detail, in which geomorphic processes and superficial deposits were given their proper importance.

Since several landslides were activated in the March-April 2013 period, because of a long rainy period, they could not be represented in the 2009 Hydrological Hazard Map. In fact, the 2009 PTCP Hydrological Hazard Map shows only some of the active landslides in the T. Corlo upper valley (Fig. 10). Instead, our Hydrological Hazard Map (Fig. 11) shows landslides occurring both in the T. Corlo valley and in the Rio delle Vigne valley. It shows that the areas affected by active landslides are much more widespread than the areas affected by dormant landslides. The landslides of Rio delle Vigne valley (both active and dormant) affect a wider surface than the landslides of the T. Corlo valley (Fig. 12). The causes of this can be ascribed to two factors: i) The intense remodelling of the T. Corlo valley due to quarrying activities (which will be discussed in the next chapter); therefore, the slopes could not have evolved according to natural patterns. ii) The presence of badlands in the T. Corlo valley alone; their evolution has taken place owing to both running waters and landslides, which cause a rapid retrogression of their heads and fill up the stream channels with long and narrow clay deposits.



Figure 12 Upper Rio delle Vigne valley: eastern branch of the landslide which affected the road.

As for hydrological hazard, it can be observed that in the lowermost stretch of the T. Corlo valley, an area affected by an active landslide was mapped on the right side of the valley. In the past, this slope movement caused sliding of the stream's right bank. In the upper part of the valley two active landslides have been mapped which threaten some abandoned buildings. They originated on opposite slopes and have been classified as earth flows. In any case, the numerous active landslides occurring within the badlands' stream channels do not cause particular problems.

In the Rio delle Vigne valley some houses are located at the foot of dormant landslides, which so far have not caused instability problems. The large active landslide in the valley's upper part, which according to local inhabitants is periodically reactivated following intense precipitation, affects only superficial deposits and a stretch of the road (Fig. 12).

In the Hydrological Hazard Map implemented in this research, some "potentially unstable areas" have been represented by applying the legend of Table 2. Similarly, also some areas affected by solifluction and active colluvial deposits have been represented, although they are not particularly significant from the hydrological hazard point of view.

6. Geomorphological evolution

The study of the geomorphological evolution of the landscape of the T. Corlo mountain catchment,

which is characterised by uniform geo-lithological and climatic features all over its area, was based on numerous field surveys, the examination of topographic maps and multiscale and multitemporal remote sensing images, which are listed in Table 2.

Significant morphogenetic processes have not been identified in the Rio delle Vigne valley. Only small soil slips occurring on both sides of the valley's lower stretch can be reported. As previously stated, they were triggered following a high precipitation period in April-May 2013. These small-sized neoformation instability phenomena confirm that precipitation is one of the main triggering causes of landslides in the Northern Apennines (cf. Bertolini *et al.*, 2001; Tellini, 2013).

On the contrary, in the T. Corlo valley the main morphogenetic agent was mankind, who exerted intense quarrying activities, thus causing considerable and irreversible landscape changes. The latter have been only partially mitigated thanks to the reclamation measures which have been implemented in the past ten years.

Clay excavation began in the T. Corlo valley in an improvised, makeshift way in the 1930s (ASQ-ConsultinGroup, 2008). Anyhow, in the 1950s, the landscape of the T. Corlo valley still looked quite "natural", showing just three small clay pits in the middle sector. Quarrying was concentrated in the slope's lower portion on the left hydrographic side of the T. Corlo. In the 1970s, clay excavation activity was much more extensive, affecting also the right hydrographic side of the valley as well as upstream and downstream areas. Various artificial ponds and large levelled-out areas were present. These had been constructed in order to mitigate rill-wash erosion and safeguard dirt service roads leading to the clay pits. In addition, the lowest part of the valley had been developed, following the intense expansion of the village of Fiorano Modenese. In the 1990s, the clay exploitation areas on the left slope were abandoned whereas on the right slope clay exploitation activities were further expanded uphill with new excavation fronts, which in one place removed a stretch of the watershed with the conterminous T. Chianca valley. Quarrying activities for the ceramic tile industry ceased completely in

2008 (ASQ-ConsultinGroup, 2008). To date, man-made changes are clearly visible all over the T. Corlo valley, which appears to be characterised by levelled-out surfaces and slopes with artificial morphological profiles typical of excavation areas. Nevertheless, at present the remodelling of excavation fronts resulting from concentrated rill wash processes can be observed in various points. In some cases, the action of water running freely down slopes previously affected by artificial shaping tends to give them a more natural aspect. Sediments have filled some of the artificial ponds. Furthermore, in the upper portion of the slopes natural badlands can still be observed. In these areas rill wash water tends to narrow the interfluvies, owing also to the fundamental contribution of superficial earth slides and earth flows. Present-day evolution of badlands takes place in many areas also because of small slope movements, which cause the rapid retrogression of the badlands' heads and the deposition of clay sediments along the stream channels.

7. Final remarks

A detailed study was carried out on the geomorphological evolution and the instability processes affecting the T. Corlo mountain catchment, which comprises the main T. Corlo valley and the tributary Rio delle Vigne valley.

The cartographic documents produced in this research – a Geomorphological Map (Plate 1) and a Hydrological Hazard Map – were elaborated by means of a GIS software programme, using as a base map the most recent topographic map, updated to the mid-2000s, of Carta Tecnica Regionale (CTR) of Emilia-Romagna Region.

The T. Corlo mountain catchment is an exemplary study case in which two conterminous small valleys with the same geo-lithological and climatic characteristics have undergone quite different morphological evolutions.

The Rio delle Vigne valley has been affected only by natural gravity-induced processes, which have produced some twelve landslides, half of which have been classified as active (according to the definition shown in Table 2), although they have not

had any particular influence on the valley's morphology.

In the T. Corlo valley, on the other hand, excavation activities have drastically changed the landscape characteristics. In particular, clay excavation began in an improvised, makeshift way in the 1930s. By the 1960s, excavation was carried out in a more organized, industrial way. Soon after the cessation of quarrying activities in 2008, the whole area previously affected by the presence of several clay pits was the object of a project of landscape and environmental reclamation and upgrading, which included the implementation of a horse riding centre and some small ponds for recreational purposes.

Finally, a detailed assessment is made of the fundamental role played by excavation activity as a morphogenetic agent of the T. Corlo valley as well as its impact on the natural evolution of the landscape. This study case confirms once more that anthropogenic activity is a very rapid morphogenetic agent with a high impact on the landscape. Not even a project of landscape and environmental reclamation will be able to put right the man-made changes completely and reconstruct the original landscape of the T. Corlo valley.

As for the instability of the whole mountain catchment of T. Corlo, the landslides identified in this study and shown on the Geomorphological Map (Plate 1) are much more numerous than those reported in the more or less recent geological maps (e.g., Gasperi *et al.*, 1989, 2005; Regione Emilia-Romagna, 2017).

Consequently, the areas affected by active landslides and those affected by dormant landslides shown in our updated version of the PTCP Hydrological Hazard Map (Fig. 11) are much more numerous than those mapped in the PTCP Hydrological Hazard Map of Provincia di Modena (2009) (Fig. 10).

Since the PTCP Hazard Maps are the only reference documents for municipal urban planning with respect to hydrological safety regulations, they should be used just as "base documents", as pointed out by Castaldini *et al.* (2012b). Indeed, they

require more in-depth investigations at a local scale to be fully reliable. This can be accomplished only by means of accurate geomorphological mapping, at least for the areas that are going to be developed. As asserted also by Farabollini & Pambianchi (2011), accurate geomorphological mapping is of paramount importance for territorial planning. Updated geomorphological maps should represent not only the evolution of artificial features but also the elements of the physical landscape (such as watercourses, scarps etc.) which might have changed since the official topographic base maps were elaborated.

In addition, professional geologists could carry out detailed geomorphological mapping in the executive phases of a reclamation project in accordance with standard procedures set up in collaboration with the public authorities, especially when private purchasers play a major role. This could be a feasible solution, also in terms of economic balance, in order to achieve progressively more accurate hydrological hazard mapping, without putting heavy economic burdens on public authorities.

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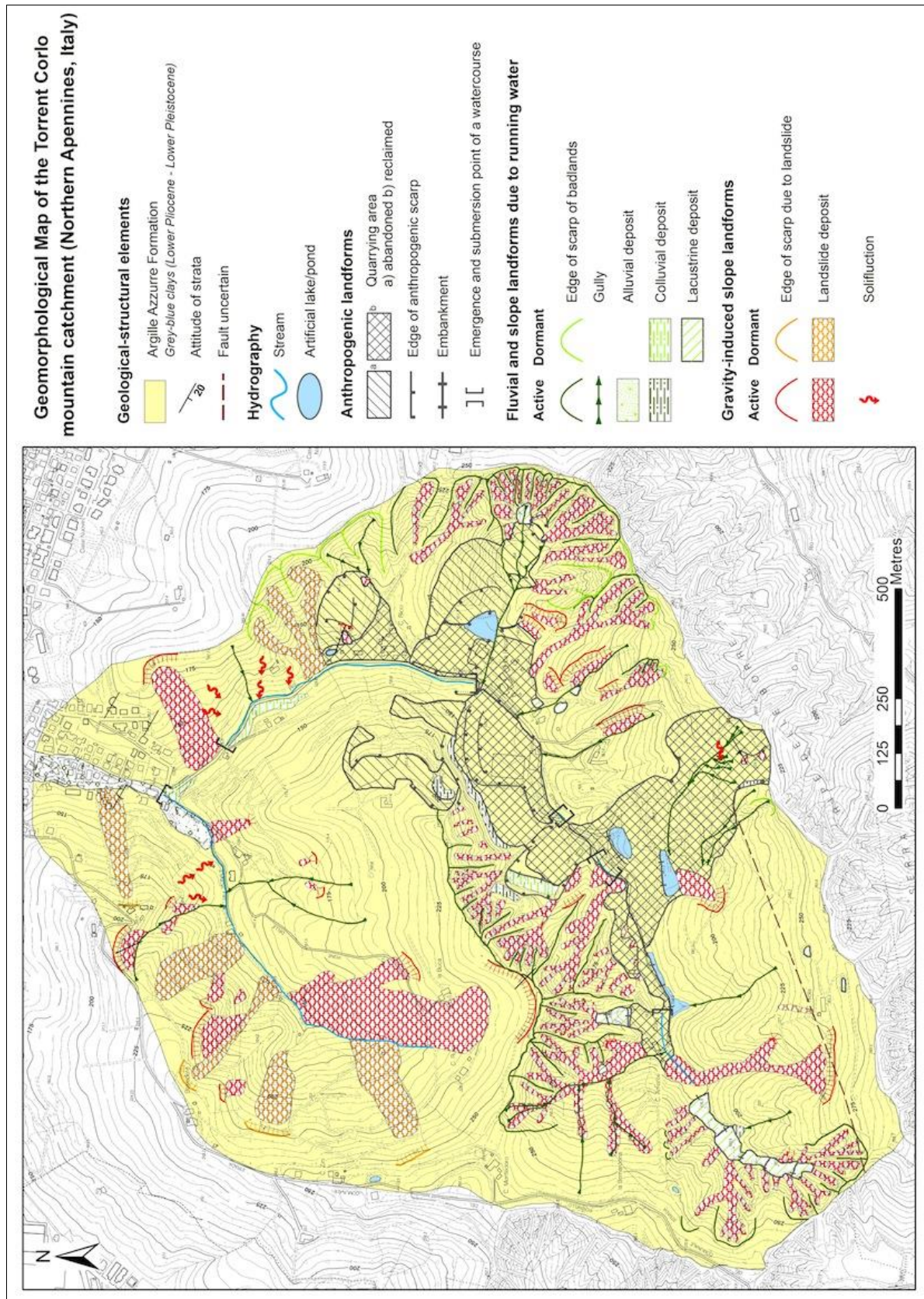


Plate 1 Geomorphological map.

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Landslide reactivation susceptibility modeling in Iași Municipality

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ABSTRACT

Iași Municipality as other urban areas around the world has a long history of landslide activity which needs to be studied considering the urban sprawl. We performed a first landslide susceptibility modeling for Iași Municipality based on the AHP method using weights given by expert judgements regarding the influence of preparatory and conditional landslides factors (slope, ruggedness, lithology, historic landslide density and hydrogeology) and weights given by the historic landslide density over the factors. The landslide inventory was performed based on LiDAR data and aerial imagery using the geomorphological mapping of landslide elements. Using the landslide probability density function we have shown that the landslide inventory is valid and we have selected 411 landslides considered recent to be used for the validation. The resulted susceptibility show that the most susceptible to landslide reactivations are the hillslopes of cuesta hills with relict and old landslides, especially at the main scarp. Recent landslides are mainly scarp slumps or landslide body translational reactivations. The validation showed that almost 70% of recent landslides are located on high susceptibility areas. Future work to improve the susceptibility and extend it to hazard modeling is needed considering the long history of landslide reactivations from Iași Municipality and the slow evolution of old landslides like in Țicău neighborhoods.

KEYWORDS

Urban landslides; landslide inventory; landslide susceptibility; Analytical Hierarchy Process; Iași Municipality

1. Introduction

Landslides are geomorphologic processes (Cruden, 1991) characterized by the gravitational induced displacement of the earth/debris toward the base of slope through several mechanisms: fall, flow, sliding,

toppling or spread (Cruden and Varnes, 1996; Hungr *et al.*, 2014). These natural phenomena are activated by several triggering factors such as heavy rainfalls, earthquakes, volcanic eruptions, snow melting on

slopes where preparatory (slope, geology) and conditional factors cause the instability. Also, the anthropic impact represents an important factor which leads to the (re)activation of landslides. Nowadays, due to the continuous expansion of the territory and infrastructure development, human activities meant to improve living conditions are having sometimes the opposite effect because the problem of landslides (Brabb, 1991) has not been treated with necessary importance. Thus, works undertaken for roads and railways development, land use changes, deforestations, mines and quarries exploitation, agriculture terraces construction lead to landslide occurrence through/ by incising the slope base, or by favoring the natural triggers.

To reduce the potential damage and economic losses (Schuster and Fleming, 1986; Kjekstad and Highland, 2009) in urban development and land use planning (Leighton, 1976; Záruba and Mencl, 1982; Alexander, 1986; Alexander, 1989; Alexander, 2005; Petley, 2009) a good support to provide information about landslides is given by landslide susceptibility maps. Susceptibility is the first stage in the process of hazard and risk evaluation (Crozier and Glade, 2005), through which is modeled the relative spatial probability for the occurrence of landslides in a given area (Carrara 1983; Guzzetti, 2006), considering previous information about landslides and their control factors (Carrara and Merenda, 1976; DeGraff, 1978; Kirschbaum *et al.*, 2010; Klose, 2015). To extend the susceptibility into landslide hazard the temporal probability needs to be taken into account (Varnes *et al.*, 1984; Guzzetti *et al.*, 1999; Corominas *et al.*, 2014).

To calculate the landslide susceptibility have been developed different methods, based on geomorphologic analyses and direct field observations as qualitative methods (Amadesi and Vianello, 1978; Aleotti and Chowdhury, 1999; van Westen *et al.*, 2003), or which are relying on statistical models, probabilistic and deterministic approaches considered as quantitative methods (Carrara, 1983; Carrara *et al.*, 1991; Ercanoglu, 2005). However, it cannot be said precisely which method is better, each one having their own advantages and disadvantages, for this reason recent studies attempts to combine these methods in order to

obtain more precise information (Rossi *et al.*, 2009). Another mandatory issue in susceptibility modeling is choosing the appropriate "mapping unit" and the appropriate method of sampling for statistical model fitting (Hussin *et al.*, 2016), which allows the exploitation of ground conditions of the terrain (Guzzetti *et al.*, 1999). For this reason, the selected approach is suitable only for study cases having specific environmental factors, the same methodology cannot be exploited in other regions as the result might not have the same reliability (Van Den Eeckhaut *et al.*, 2009).

Considering the previous landslide reactivations which affected Iași city hillslopes (Macarovici, 1942; Băcăuanu, 1970; Martiniuc and Băcăuanu, 1982; Niculiță *et al.*, 2017; Necula *et al.*, 2017) multiple times during the last two centuries, landslide susceptibility modeling becomes an important tool to prevent future hazards related to the reactivations of old Holocene to Medieval Age landslides (Niculiță *et al.*, 2016). The susceptibility map becomes a necessity for the urban development which can significantly reduce the economic costs and the damages to community (Leighton, 1976; Záruba and Mencl, 1982; Varnes *et al.*, 1984; Alexander, 1986; Alexander 1989; Petley, 2009).

For this case study, the landslide susceptibility modeling has been realized using a probabilistic approach which is taking into account the environmental factors of the study area based on the Analytic Hierarchy Process (AHP). This method was chosen because although a landslide inventory was created, the landslide morphology was altered by human intervention (Barbu *et al.*, 1987) and therefore cannot be used to train a more sophisticated statistical model. Also the landslide inventory is a geomorphological one and not a multi-temporal one, containing different age and magnitude landslides, the recent events that affected the city being mainly reactivations of old landslides.

1.1 Study area

Iași Municipality (91.5 km²) is located in the southern part of the Jijia Hills, at the contact with the Central Moldavian Plateau (Fig. 1). In the Jijia

Hills the monoclinic geological structure (Brânzilă, 1999; Ionesi, 1994), the relative resistance of claystones and mudstones intercalated with sands and the homoclinal shifting of the Bahlui River and its tributaries toward south generated the development of cuesta landforms: the asymmetric hills and the structural valleys (Băcăuanu, 1968; Ioniță, 2000; Niculiță, 2011). The lithology (Fig. 2 and 3) is predominantly composed from claystones and mudstones with sandy intercalations (Brânzilă, 1999; Ionesi *et al.*, 2005; Dill *et al.*, 2011) which are comprised in two formations of Bessarabian age: Cryptomactra Clays Formation (outcropping under 125-150 m a.s.l.) and Bârnova-Muntele Formation (230 m thick formation outcropping over 125-150 m a.s.l.). The cuesta hills North and South of Bahlui River have the planar and gentle sloping dip hillslopes covered by fluvial deposits (gravels and clays 2 to 5 m thick) and loess (5 to 25 m thick) (Martiniuc and Băcăuanu, 1959; Martiniuc and Băcăuanu, 1966; Schram *et al.*, 1977) and do not have altitudes going beyond 220 m a.s.l. (Rediu Hill, Copou Hill, Șorogari Hill, Galata Hill, Cetățuia Hill). Toward south, above the 200 m altitudinal boundary, in the Central Moldavian Plateau the presence of a caprock geological structure imposed the detachment of an escarpment which represents the Eastern part of the Iași Escarpment (Băcăuanu, 1968; Băcăuanu *et al.*, 1980, Ungureanu, 1993) where the ridges altitudes are between 365 and 407 m a.s.l. (Repedea and Păun Hills). The caprock is represented by the Repedea Formation, composed from calcarenites, oolitic calcarenites and quartz arenites intercalated with sands and claystones (Jeanrenaud and Saraiman, 1995; Brânzilă, 1999; Ionesi *et al.*, 2005; Dill *et al.*, 2011) which outcrops predominantly in the Repedea Hill. Over the Bessarabian rocks, a 40 m thick Kersonian suite starts transgressively composed mainly from sands (Balta-Păun Formation) and outcrops in the Păun Hill.

1.2 Landslide factors

In North-Eastern Romanian lowland, respectively in the Moldavian Plateau, relict and old landslides (Upper Pleistocene to Holocene age) appear on almost all cuesta scarps and steep hillslopes (Niculiță and Mărgărint, 2014; Niculiță *et al.*, 2016;

Mărgărint and Niculiță, 2017). Because of the dry climate (Pánek, 2015; Niculiță *et al.*, 2017) the landslide morphology and deposits were smoothed by erosion and are very susceptible to landslide reactivations. Recent landslides which still have all the landslide morphologic elements not affected by erosion triggered under the current dry climatic conditions after the Medieval times (Niculiță *et al.*, 2016).

The morphostructure, morphometry and the topography of the study area are favorable preconditioning factors to landslides development, especially for the steep cuesta escarpments (Mărgărint and Niculiță, 2017). The slope relation with the geological structure/rock stratification (Meentemeyer and Moody, 2000; Cruden and Eaton, 1987) on cuesta escarpments is anaclinal, with subdued relation (slope angle lower than the dip angle and the slope cuts perpendicular the bedding planes). The majority of the North, North-East and North-West facing hillslopes enter in this category. On Southern, South-Eastern and South-Western cuesta dip slopes the geological structure/rock stratification relation is cataclinal, the slopes being underdip (slope angle lower than the dip and the slope cuts along the bedding plane). Eastern and Western hillslopes are ortoclinal, the slopes cutting the bedding planes laterally. This morphostructure, combined with the presence of springs and aquifers at the base of the fluvial and loess/sandstone and limestone caprocks and along sand layers intercalated in the claystones and mudstones, is responsible for the great extension of the landslides along the steep hillslopes. The majority of landslides are soil/earth planar/translational slides (type 12 from Hungr *et al.*, 2014 extension of Cruden and Varnes, 1996 classification) developed on the steep slopes under the influence of river incision and lateral migration toward the hillslopes base. On old landslide scarps rotational soil/earth slumps are frequent (type 11). Old landslide deposits with a mixture of clays, silts and sands have flowslides and earthflows (type 20 and 26). On the western and northern hillslopes of Repedea and Păun Hills also compound slides appear (type 14) as multiple retrogressive compound slides due to the retrogressive evolution of the hillslopes under the influence of river incision (Niculiță *et al.*, 2016). Very often complex landslides appear on the steep

hillslopes as a combination of multiple mechanisms and the overlay/amalgamation (Marc and Hovius, 2015; Samia *et al.*, 2017) of different age events, generating continuous landslides which cover the hillslope on lengths of up to 2-3 km (the Eastern hillslope of Copou Hill, both Western and Eastern hillslopes of Șorogari Hill, and the Western hillslope of Aroneanu Hill).

Almost all steep hillslopes (Fig. 4) from Iași Municipality area are covered by such complex landslides, that is why landslide reactivations are quite frequent (Samia *et al.*, 2017) especially during spring time or summer time under heavy rainfall

(Mărgărint and Niculiță, 2017; Niculiță *et al.*, 2017). During the last two centuries, the magnitude of reactivations decreased also because remedial measures were carried out (Consiliul Județean Iași, 2012; Necula *et al.*, 2017): passive mechanic infrastructure, drainages and protection forests. Despite the remedial measures such areas are in a slow moving state (like the case of North-Eastern hillslope of Copou Hill where there is a velocity of the slow moving landslide of up to 1.8 cm/year - Necula *et al.*, 2017).

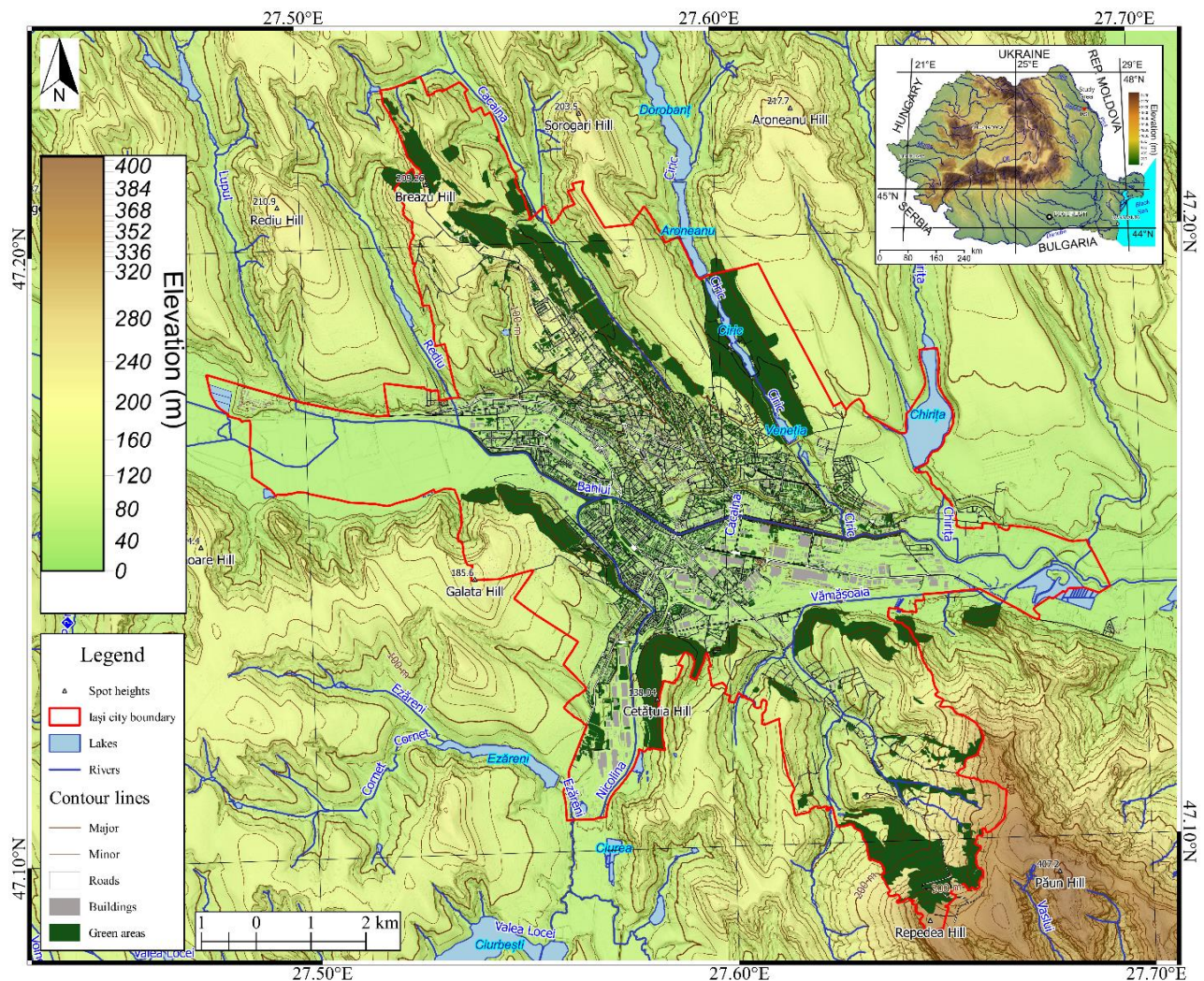


Figure 1 Geographical background of Iași Municipality.

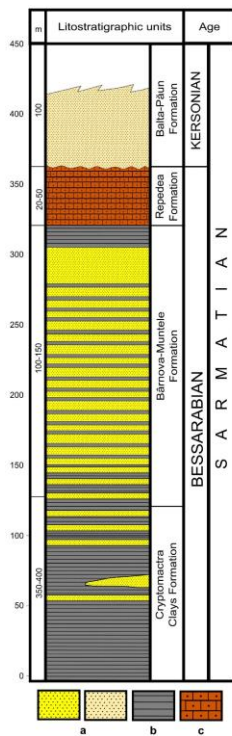


Figure 2 Lithostratigraphic column of the Bessarabian and Kersonian in Repedea Hill (compiled after Brânzilă, 1999; Ionesi *et al.*, 2005): a – sands, b – claystones and mudstones, c – limestones.

Although the area has a dry climate, maximum 24 hour rainfall amount can go beyond 100 mm (Mărgărint and Niculiță, 2017; Niculiță *et al.*, 2017). Historical rain trends also show a very humid period during the 70' and 80' which might repeat after a 30/40 year cycle (Niculiță *et al.*, 2017). Areas with reactivations are known for Iași Municipality in the following locations: the Copou Hill north-eastern hillslope (1932-1933, 1940-1942, 1969-1970, 1984; 2017), for Șorogari Hill western hillslope (1969-1970), for Galata Hill northern hillslope (1979), Cârlig Hill western hillslope (1981), for Cetățuia (1980) and for Bucium area (1973) as reported by various authors (Macarovici, 1942; Băcăuanu, 1970; Martiniuc and Băcăuanu 1982; Schram *et al.*, 1977). In recent times (after the 90') landslide reactivations were reported in Munteni Neighborhood, Cimitirul Evreiesc, Grădina Botanică, Șapte Oameni Street, Aleea Sadoveanu, Cetățuia (Consiliul Județean Iași, 2012). Although there are remedial measures

applied to the most active areas of landslide reactivations constructed especially before the 90' the failure to maintain them makes it difficult to estimate which is the level of protection which these measures assure for the future rainy periods.

2. Materials and methods

2.1. Materials

The historical map sources (1:20 000, 1:5 000, 1:2 000 topographic maps from the 1920-1960 period), Google satellite imagery archive (2003-2017), aerial imagery (1956-1964, 1971-1984, 2005, 2008) and a 0.5 m spatial resolution LiDAR DEM acquired in 2012 were used for the creation of a geomorphological landslide inventory (Carrara *et al.*, 2003; Guzzetti, 2006; Guzzetti *et al.*, 2012). Texture data from the aerial imagery and the LiDAR shading were supplemented by the use of the elevation derivatives (slope, curvature) and contours for the landslide delineation (Fig. 4) and typology assignation (Fig. 3).

For the susceptibility modeling environmental factors we have used the following layers aggregated to 5 m rasters (Fig. 5 and Fig. 6):

- Slope (Fig. 6a): computed from the LiDAR DEM at 5 m resolution using the algorithm of Wood (1996; 2009) in SAGA GIS (Conrad *et al.*, 2015) using a kernel window of 3 by 3 pixels;
- Ruggedness (Fig. 6b): computed with the algorithm described by Riley *et al.*, (1999) using a 5x5 pixels kernel window in SAGA GIS (Conrad *et al.*, 2015); this parameter is a measure of both vertical and horizontal dissection of landforms and better describe the fluvial dissection compared with drainage density where the source of drainage data can be biased (Mark, 1983; Niculiță, 2012);
- Geology (Fig. 3): compiled after the 1:200 000 Geological Map of Romania, Saulea *et al.*, 1966, completed with maps and information from Martiniuc and Băcăuanu, 1959, Martiniuc and Băcăuanu, 1966, Schram *et al.*, 1977, Brânzilă, 1999, Ionesi *et al.*, 2005 and slightly reshaped to match the LiDAR DEM resolution and features;

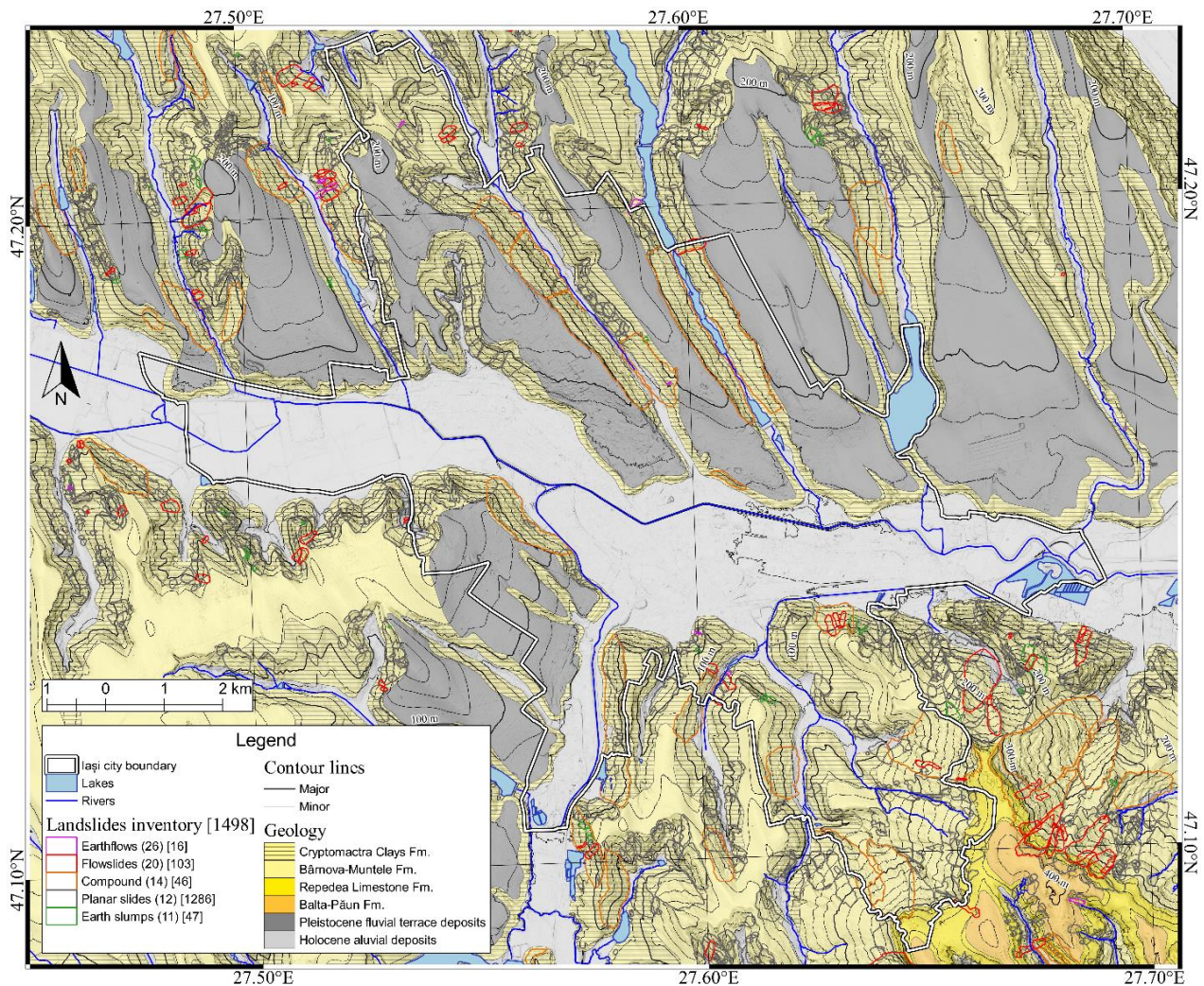


Figure 3 Geologic map of Iași surroundings (compiled after the 1:200 000 Geological Map of Romania, Saulea *et al.*, 1966, completed with maps and information from Martiniuc and Băcăuanu, 1959, Martiniuc and Băcăuanu, 1966, Schram *et al.*, 1977, Brânziliă, 1999, Ionesi *et al.*, 2005) with the landslides inventory styled by landslide type.

- Landslide density (Fig. 6c): computed as a standardized value between 0 and n , where n is the maximum number of landslides that overlap for the same pixel area; for the unaffected pixels values between 0.9 and 0.1 were computed based on their Euclidean distance to the closest landslides;
- Hydrogeology (Fig. 6d): digitized from a map of phreatic level for Iași Municipality (Schram *et al.*, 1977) and expressed as the depth of the phreatic level under the topography level, the type of the surficial deposit (ridge, hillslope, fluvial) and the presence of springs.

Land use was not used as a predictable factor because the entire study area has urban features and the urban pressure on landslides is done in

multiple ways that cannot be synthesized in a geospatial layer: water infiltration from broken urban water and sewage network, remedial measures which are degraded, heavy transport traffic, residential house extension and improvement.

2.2. Methods

The landslide inventory is a geomorphological one, containing all the landslides that were depicted from the remote sensing images and validated by the field observations (Carrara and Merenda, 1976; McCalpin, 1984; Wieczorek, 1984; Carrara *et al.*, 2003; McKean and Roering, 2004; Guzzetti, 2006; Guzzetti *et al.*, 2012).

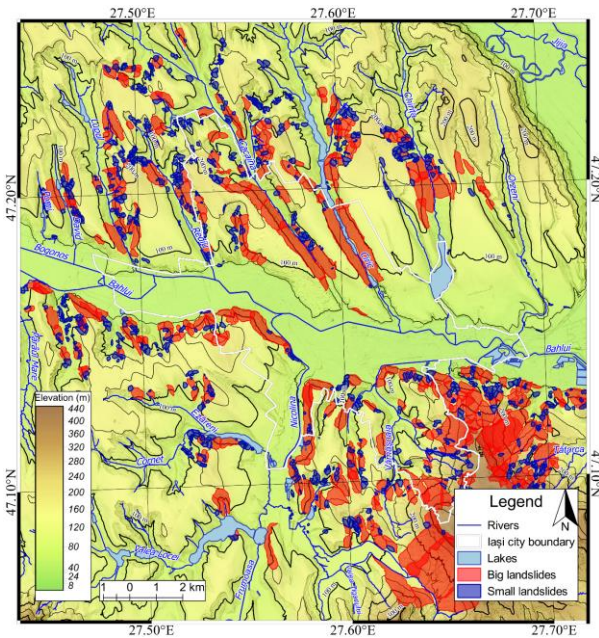


Figure 4 Landslides inventory.

While we recognize the limitations of the inventory, especially regarding the presence of relict or old landslides (Niculiță *et al.*, 2016) we believe that this inventory can be used for susceptibility assessment. We used the inventory for assessing the weights which were given to environmental factors in the analytical hierarchy process. The landslide inventory was performed for an area bigger than the actual boundary of Iași Municipality in order to better assess the regional pattern of landslide activity. The landslide frequency density curve was computed using LANDSTAT R stat (R Development Core Team, 2008) script developed by Rossi *et al.* (2012).

The landslides (1498 in total) were delineated on LiDAR DEM only when at least two of the following landslide elements were identified on LiDAR (Carrara and Merenda, 1976; Varnes, 1978; McCaillin, 1984; Wiczorek, 1984; Varnes *et al.*, 1984; Soeters and Van Westen, 1996; Cruden and Varnes, 1996; McKean and Roering, 2004; Van Den Eeckhaut *et al.*, 2005; Ardizzone *et al.*, 2007; Jaboyedoff *et al.*, 2012; Petschko *et al.*, 2015): (i) main scarp, other minor scarps or the crown, (ii) landslide flanks, (iii) landslide toe, (iv) landslide body with various wavelengths of ruggedness. The use of various shading methods and the 3D anaglyph stereoscopic plotting of the DEM in SAGA GIS greatly improved the mapping.

AHP is a semi-quantitative statistical method which is used for decision making processes using the score given by weights which are obtained using pairwise relative judgements of comparison between the considered factors (Saaty, 1977, 1980, 1987). The factors can be structured in hierarchical networks and the judgements generate a pairwise comparison matrix. The judgments are made based on a scale from 1/9 (considered extremely less important) to 9 (considered extremely more important), a value of 1 meaning equal importance (Fig. 7). For example slope is considered to be 7 times more important (very strong) than hydrogeology (Table 1).

The main advantage of the method is the flexibility of its usage in resolving decision making processes using heuristic judgements and the possibility of checking the consistency of the judgements using the consistency index (Table 1). The main disadvantage is the subjectivity of comparisons and of the used factors (Table 2).

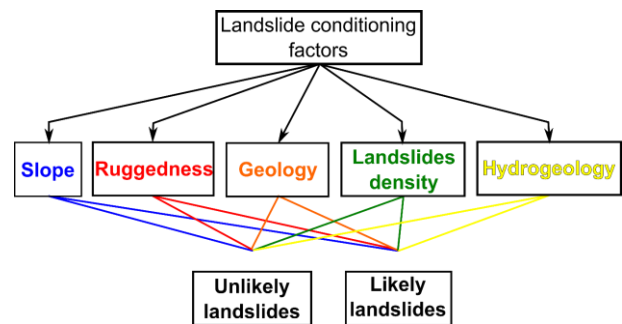


Figure 5 Graphical depiction of the AHP model.

This model was used as a trade-off between the pure heuristic (like geomorphological mapping) and the pure statistical methods (data mining of environmental factors where multicollinearity introduces irrelevant information) given the conditions of an urban area where landslides have different ages and are smoothed and influenced by the human activities.

AHP has been widely used for landslide susceptibility (Barredo *et al.*, 2000; Ayalew *et al.*, 2005; Yoshimatsu and Abe, 2006; Gorsevski *et al.*, 2006; Yalcin, 2008; Wu and Chen, 2009; Akgun and Türk, 2010; Rozos *et al.*, 2011; Akgun, 2012; Hasekioğullari and Ercanoglu, 2012; Mondal and Maiti, 2012;

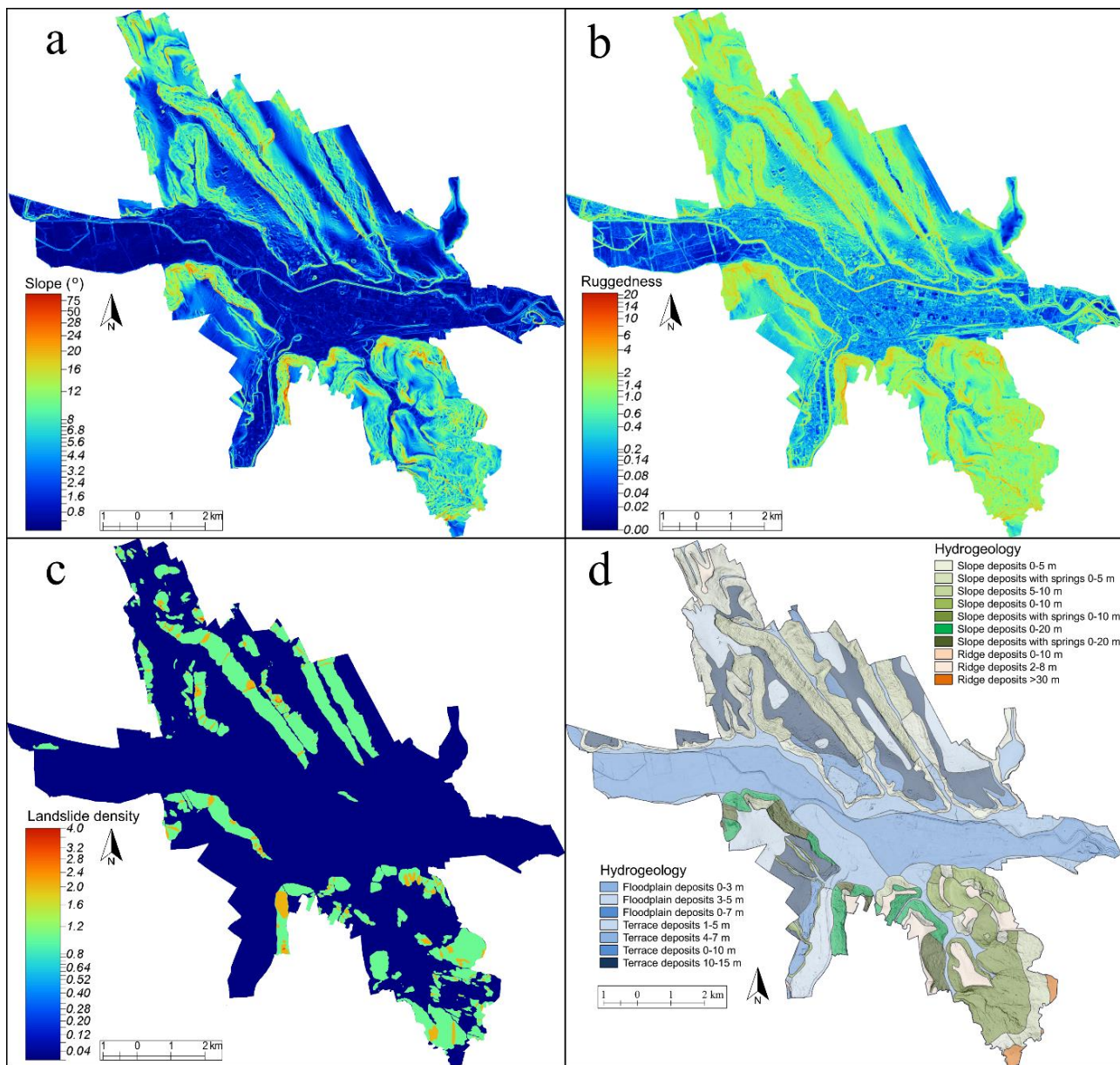


Figure 6 AHP factors: a) slope, b) ruggedness, c) historical landslide density, d) hydrogeology.

Pourghasemi *et al.*, 2012). AHP statistics were computed with the R stat software (R Development Core Team, 2008) ahp package (<https://cran.r-project.org/web/packages/ahp/index.html>). The prediction was assessed using Chung and Fabri (1999, 2003) prediction rate curve. For the success curve we have used the plot of percentage of observed landslides susceptibility versus the percentage of susceptibility values over the entire map (Castellanos Abella, 2008). The class intervals,

used for expressing the susceptibility outcome, were computed using the classInt package (<https://cran.r-project.org/web/packages/classInt/index.html>) for R stat with the k-means clustering method.

More important than									Equal	Less important than								
9	8	7	6	5	4	3	2		1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	
extreme	very strong	strong	moderate							moderate	strong	very strong	extreme					

Figure 7 The scale used for judgement pairwise comparisons.

Table 1 AHP environmental factors pairwise comparison matrix, weights and consistency index

FACTOR	Slope	Ruggedness	Geology	Landslide density	Hydrogeology	Weight
Slope	1	3	4	5	7	0.54
Ruggedness	0.33	1	3	5	6	0.24
Geology	0.25	0.33	1	2	5	0.11
Landslide density	0.20	0.20	0.50	1	4	0.07
Hydrogeology	0.14	0.17	0.20	0.25	1	0.04
					CI*	0.04

*Consistency index

Table 2 Factor weights

Slope		Ruggedness		Geology		Landslide density		Hydrogeology (deposit and phreatic level depth)		
C*	W**	C	W	C	W	C	W	deposit	C	W
0-1	0.02	0-0.15	0.02	Cryptomactra Clays Fm.	0.40	4	0.50	Hillslopes with springs	0-5	0.18
1-3	0.03	0.15-0.5	0.03	Bârnova-Muntele Fm.	0.24	3	0.26		0-10	0.14
3-7	0.05	0.5-0.8	0.05	Repedea Fm.	0.16	2	0.13		0-20	0.11
7-10	0.07	0.8-1	0.07	Balta-Păun Fm.	0.10	1	0.07		0-5	0.10
10-15	0.10	1-1.5	0.10	Pleistocene (terrace deposits)	0.06	0	0.03	Hillslopes without springs	5-10	0.06
15-20	0.15	1.5-10	0.15	Floodplain deposits	0.04				0-10	0.06
20-30	0.23	10-20	0.23						0-20	0.05
>30	0.35	>20	0.35					Terrace	4-7	0.05
									0-10	0.04
									10-15	0.04
									>15	0.04
								Ridge	2-8	0.03
									0-10	0.03
									>30	0.02
								Floodplain	0-3	0.02
									0-7	0.02
									3-5	0.01

*Classes, **Weights

3. Results and discussion

The landslide inventory contains 1498 landslides, with the area ranging from 226 m² to 3.9 mil m². The frequency density distribution of the area can be seen in Fig. 8 (red line), where there are plotted also two other curves for the Moldavian Plateau, one for an inventory which cover the entire Moldavian Plateau (black line) and one for a catchment from the Central Moldavian Plateau (blue line).

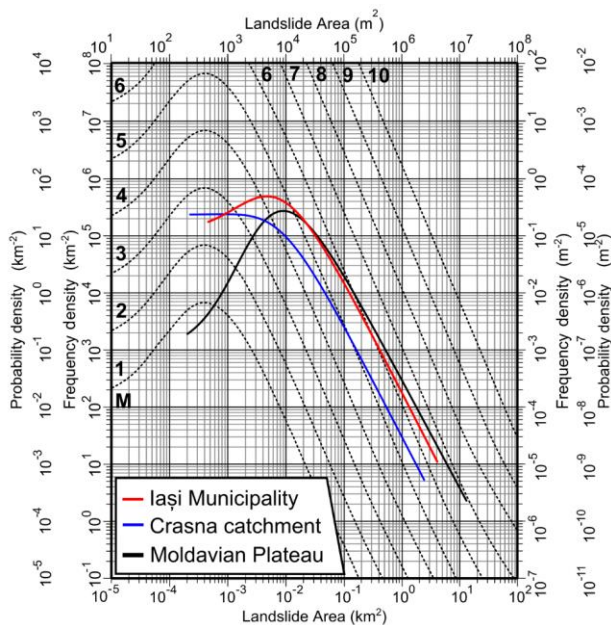


Figure 8 Landslide inventory area frequency distribution for Iași Municipality (red line), Crasna Catchment (blue line - Bejenaru and Niculiță, 2017) and for the Moldavian Plateau (black line - Mărgărint and Niculiță, 2017).

The tail of the curve for Iași Municipality is very similar with the one for the Moldavian Plateau, showing that for big landslides the inventory contains the representative magnitudes. The shape of the distribution curve is also similar with other historic and geomorphologic landslides inventories (Malamud *et al.*, 2004a, 2004b). For smaller landslides, the Iași Municipality inventory is more complete, and this is the reason why we use these landslides for validation. We define small landslides as the landslides that have under 50 000 m² (Fig. 4 – blue polygons). This value was chosen by analyzing the frequency of landslide area and by investigating the morphology of these landslides on LiDAR DEM. The small landslides have a fresh morphology and

have recognizable all the landslide features, thus being considered recent and only 200 to 300 years old (Niculiță *et al.*, 2016).

The histogram of the susceptibility results can be seen in Fig. 9 and the spatial distribution of susceptibility values in Fig. 10. The distribution is lognormal and the k-means derived class intervals are 0, 0.01, 0.2, 0.35, 1.

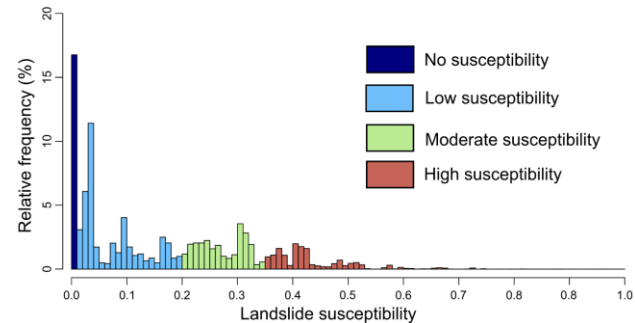


Figure 9 Landslide susceptibility histogram.

The four classes were labeled as no susceptibility (22.6 %), low susceptibility (40.7 %), moderate susceptibility (23.7 %) and high susceptibility (13 %). The recent landslides cover 3.1 % of the Iași Municipality territory, while all the mapped landslides cover 20%. From the area covered by landslides, the susceptibility has the following statistics: 0.1% low susceptibility, 1.2% moderate susceptibility and 1.8% high susceptibility. No landslides appear in the area modelled as no susceptibility. For validation we have used the recent landslide inventory (411 landslides) and we derived the prediction rate curve and the success rate curve (Fig. 11). These curves show us that the model performed well and that the modelled susceptibility can explain reasonably well the recent landslide occurrence in Iași Municipality, 70% of all small landslides being located in 38% of the areas with high susceptibility values. If we compute mean susceptibility values for the recent landslide polygons, all of them have lower to high susceptibility values: 6 low susceptibility (0.3%), 124 moderate susceptibility (30.5%) and 281 high susceptibility (69.2%).

The newest landslide from Iași municipality is represented by the scarp reactivation of the North-East hillslope of Copou Hill in the Ursulea area in May 2017. The scarp was affected on 150 m by a

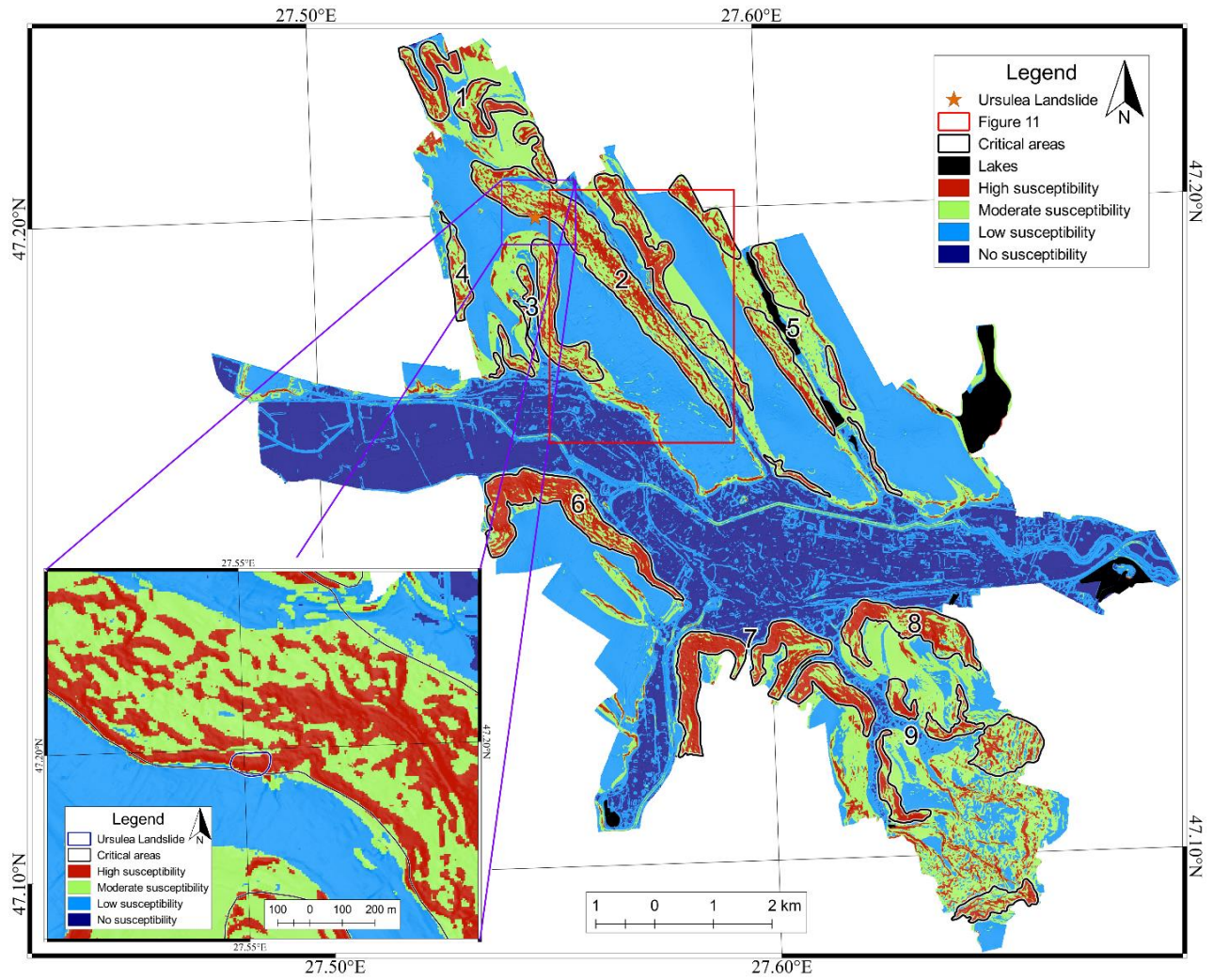


Figure 10 Landslide susceptibility map for Iași Municipality (numbers represent the areas that have the highest frequency of high susceptibility and are discussed in section 3); in inset the susceptibility in the Ursulea landslide area.

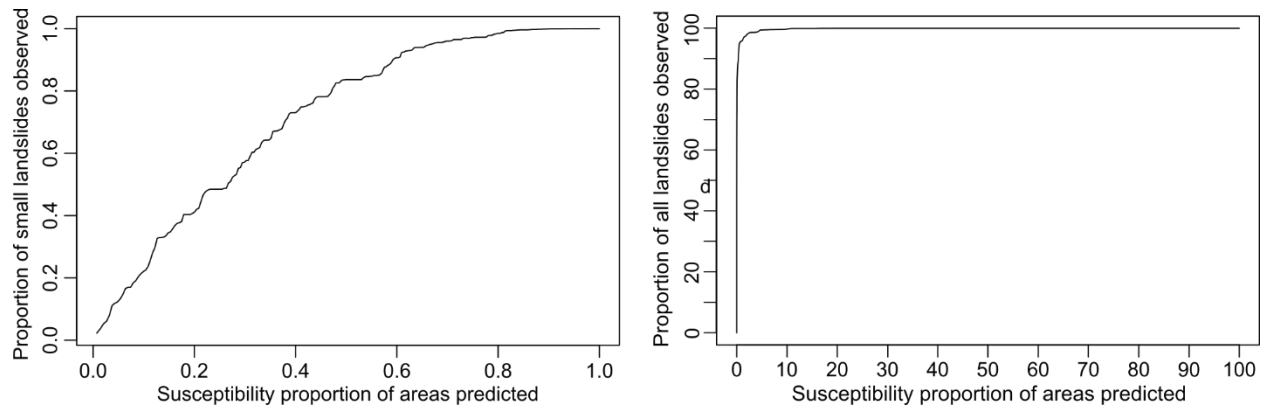


Figure 11 Landslide susceptibility prediction rate curve (left) and success curve (right).

slump which has slid along 60 m. On the modeling the location of the slump is considered to be an area of high susceptibility (the star from Fig. 10). Considering the location of this landslide we can say that scarp areas with high susceptibility are the most susceptible to reactivation, especially

where upslope the scarp, the flat ridge edge has constructions. We considered also the Țicău neighborhood as a validation site (Fig. 12), the area having a high frequency of high susceptibility areas. The area has registered deformations for the 2014-2017 time interval (Necula *et al.*, 2017).

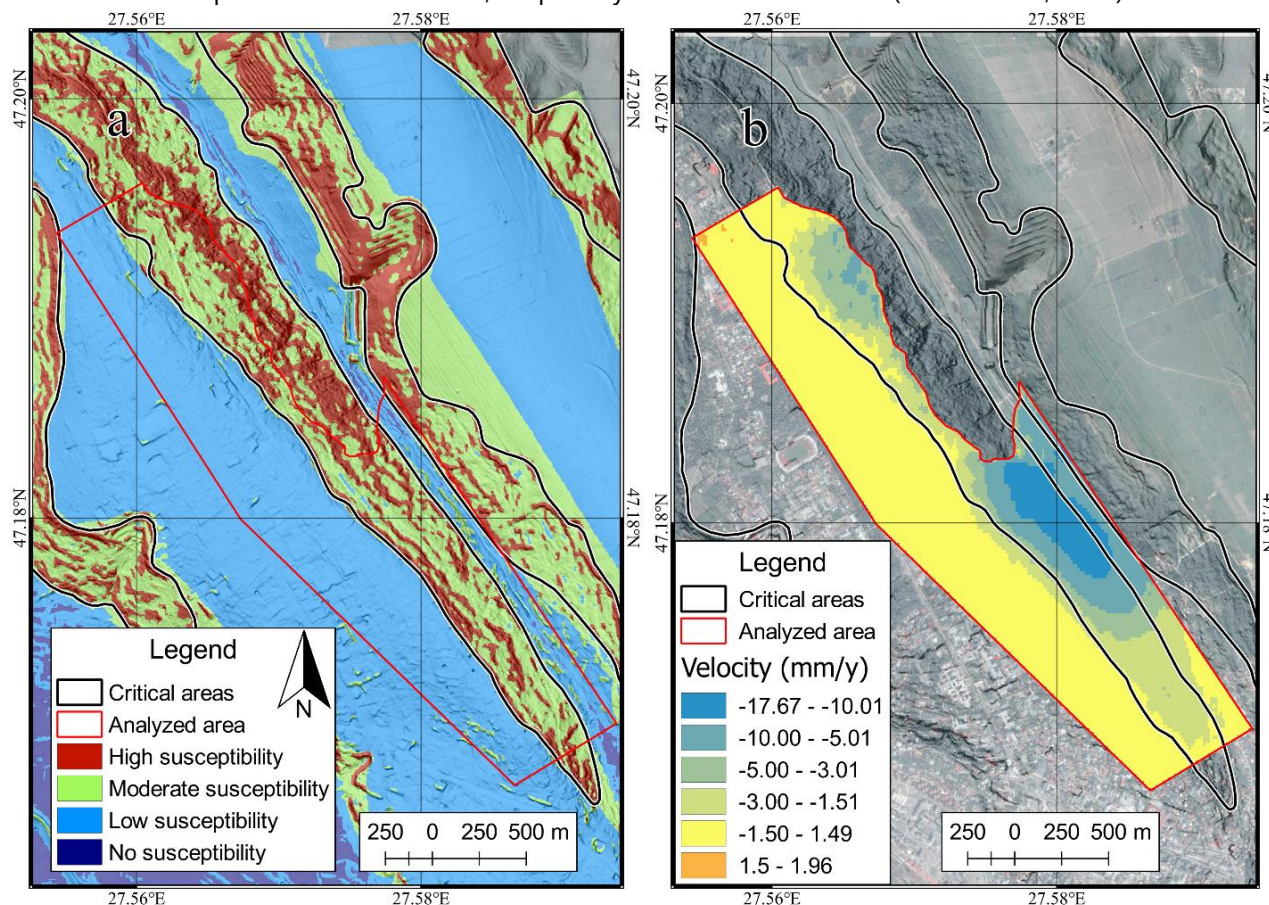


Figure 12 Landslide susceptibility for Țicău area on north-eastern Copou Hillslope (area 2 from Fig. 10) (a) and the velocity found by Necula *et al.*, 2017 using INSAR (b).

Moderate and high susceptibility values are typically characteristic for the steep hillslopes of the cuesta escarpments, especially those who are affected by relict or old landslides. Low susceptibility values are characteristic for the cuesta dipslopes and flat ridges/plateaus, where especially the marginal areas are susceptible to landsliding through retrogressive slumps. The area without susceptibility to landslides covers the flat areas of the Bahlui floodplain and its tributaries. Low and moderate susceptibility appears on the Bahlui River bank levees where a bank failure happened in the beginning of June 2015. The low susceptibility values that appear on the Bahlui floodplain are

related to anthropic features like road, bridge and building embankments.

We have delineated in Fig. 10 the areas (noted from 1 to 9) which have the biggest frequency of high susceptibility and we consider these areas as critical regarding the necessity of taking into consideration the hazard and risk modeling in any future planning activities of these areas. These areas are similar with those identified by the Consiliul Județean Iași (2012) assessment. Copou North-Eastern Hillslope (2), Botanical Garden area (3), Munteni neighborhood (4), Galata Hill (6) and Bucium Hills (9) are areas where the landslide reactivations were frequent during the last 100

years. Beside these, areas like Breazu (1), Cîrc (5) and Cetățuia-Vișani (7) are areas of post-communist urban sprawl which are prone to landslide reactivations.

4. Conclusions

Regarding the problem of landslide susceptibility in Iași Municipality we performed an initial modeling based on a semi-heuristic and semi-statistic method (AHP). The weights were given by expert judgements regarding the influence of preparatory and conditional landslides factors: slope, ruggedness, lithology, historic landslide density and hydrogeology. The weights for the factor values were derived from the historic landslide density over the used factors.

The results show that the most susceptible to landslide reactivations are the steep hillslopes of cuesta hills with relict and old landslides, which have high and moderate susceptibility. High susceptibility areas are especially in the main scarp area. The gentle dip-slopes and the flat ridges have low susceptibility, while the floodplains have no susceptibility.

The recent landslides used for validation are mainly scarp slump or landslide body translational reactivations. The validation showed that almost 70% of recent landslides are located on high susceptibility areas. Future work is needed to improve the susceptibility and extend it to hazard modeling since the Iași Municipality has a long history of landslide reactivations and the slow evolution of old landslides like in Țicău neighborhood could be amplified by future climatic changes or intense human pressure (like in the areas where the urban sprawl is intensive and landslide susceptibility is high).

Acknowledgement

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High mountain relief in marble in Pirin Mountains, Bulgaria: structure, specifics and evolution

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ABSTRACT

The present article is focused on high mountain relief in marble, which combines glacial, periglacial and karstic morphology. High mountain karst is found in Northern Pirin (Vihren and Sinanitsa area) and central Pirin (Orelek area), the latter lacking traces of glaciation due to its low altitude. In the most representative area, Vihren part, several vast and deep cirques-ovals were formed, which comprise a large diversity of landforms. Main factor for the specifics of relief in marble is the structure of the rock, which combines carbonate mineral content and crystalline properties; they favour both the occurrence of karstification and frost weathering. The high elevation of Northern Pirin (up to 2914 m a.s.l.), and the resulting extensive former glaciation enhanced the karst processes by weathering of the morphological surface. At present, surface karst is most developed on elevated sections of cirque bottoms, which were ice free before the beginning of the Holocene and are away from rockfall creep accumulation. A special element of glaciokarstic relief in Pirin are the summer lasting snow/ice features (glacierets and snow patches), two of which are considered centuries old, and still survive despite the temperature warming. In general, karst processes in the high mountain areas of Pirin are less developed than in the western part of the Balkan Peninsula (the Dinarides), due to the greater susceptibility of marble to physical weathering compared to limestone, which leads to a more intensive formation of regolith on the surface, and in result of the generally colder and dryer climate.

KEYWORDS

Glaciokarst; marble; sinkholes; glacierets; frost weathering; Pirin; Bulgaria

1. Introduction

High mountain karst is karst which is formed and functions under high mountain climatic and

environmental conditions (Djurović, 2011; Djurović *et al.*, 2010), typical with low temperatures, long

snow cover duration, and scarce or no vegetation (Meneghel and Sauro, 1990). The term can be applied within the spatial framework of our region, where as high mountain can be categorized mostly the subalpine and alpine areas positioned above the natural treeline, in the case of Pirin mountain, about 2000 m.

In general, glaciokarst is a karst area transformed by glaciers (Maire, 1978; Kunaver, 1983, 2009; Smart, 2004; Veress, 2016). This is a specific type of karst environment, which is observed in high latitudes and high altitudes of the world. Glaciokarst can function only if vertical karst drainage of subglacial waters is active, which results in specific functioning of glaciers as well as in formation of typical geomorphic features. On the other hand, inert vertical karst drainage prevents functioning of glaciokarst and causes only subglacial and postglacial surface modification by dissolution, which is referred to as karsti-glacial action (Žebre and Stepišnik, 2014).

Glaciokarst is spread on numerous high mountain locations throughout South-Eastern Europe. As the present glaciation in this region is restricted to several smallest scale features (glacierets), this type of relief can be categorized as deglaciated karst. Within this context glaciokarstic landscapes encompass karst features and hydrology, as well as inherited erosional features and deposits from former glaciations (Žebre and Stepišnik, 2015). Glaciokarstic forms have been developed on the background of glacial topography, formed during Pleistocene cold phases and the subsequent retreat stages in the Lateglacial and the Holocene.

As at present the main geomorphic process is the chemical denudation exerted by the mainly vertically moving atmospheric waters, glaciokarstic areas are typical with the good preservation of surface landforms, in particular those left by former glaciers (Žebre and Stepišnik, 2015). This is an advantage when trying to reconstruct the evolution of relief.

In the south-eastern part of the Balkan Peninsula (within the Thrace-Macedonian massif) glaciokarst is mostly developed not in limestone or dolostone, as it is in the Dinaric and Pindus

mountain chains, but in marble instead. Marble is carbonate and crystalline rock at the same time, combining features of both. In the climate conditions of the high mountain this leads to the joint action of frost weathering and karstification, and often local topography is what determines which process prevails. Thus a great diversity of landforms is generated.

Glaciokarst and high mountain karst are two different concepts. On one hand, high mountain karst includes also the areas in the subalpine and the alpine belt that were weakly (or possibly not) affected by Pleistocene glaciers – summit surfaces, nunataks, southern slope sections, etc. On the other hand, glaciokarst comprises the formerly glaciated valley sections that descend far below the high mountain belt. However, complete and proper investigation of the maximum extent of Pleistocene glaciers has still not been done for Pirin Mountains, and that is one reason for the present study to be focused not on glaciokarst, but on high mountain karst (at altitudes above 2000 m a. s. l.) instead.

There are various discrepancies throughout different parts of Pirin between glaciokarst and high mountain karst, as, according to author's own observations, glaciers were supposed to have descended to altitudes below 1500 m along the north heading valleys of Northern Pirin, while in Middle Pirin, which is slightly higher than 2000 m, there are lacking any signs of former glaciation (Georgiev, 1991). The present study aims to make the first specialized overview of high mountain karst geomorphological complexes in Pirin Mountain, focusing on glaciokarst, to outline their specifics (climate-related also) that distinguish them from classical limestone and dolomite high mountain relief, and to specify the contemporary trends in the development of these unique landscapes.

2. Study Areas

In the Balkan Peninsula, marble is wide spread, especially in the southern areas, known as Thrace-Macedonian massif. Few places built of marble however exceed the elevation of 2000 m a.s.l.

The most prominent high mountains where marble karst is spread are Pirin (Bulgaria, 2914 m

a.s.l.), Olympus (Greece, 2917 m a.s.l.), Slavianka/Orvilos (Bulgaria/Greece, 2212 m a.s.l.), Falakro (2232 m a.s.l.) and Mt. Athos (Greece, 2033 m a.s.l.). This type of relief is most pronounced in Pirin and Olympus, which in their highest parts reach above 2900 m a.s.l. Pirin Mountains are the second highest in Bulgaria and the third in the Balkans. They are located in the southwest part of the country, and have a generally rhomboidal shape (70 x 35 km) with the longer axis running in NNE-SSW direction. The highest point, Mt. Vihren (2914

m a.s.l.), is situated in the northern part of the mountain range. Two more locations in the central section rise above 2800 m a.s.l., and the higher than 2500 m a.s.l. has a considerable extent. Like most of the mountains in this part of the Balkans, Pirin has a complex geological structure. Three granitic intrusions of Late Cretaceous-Paleogene age (Vatsev, 2005) build up the core of the massif: one in the farthest north, one in the centre, and one in the south.

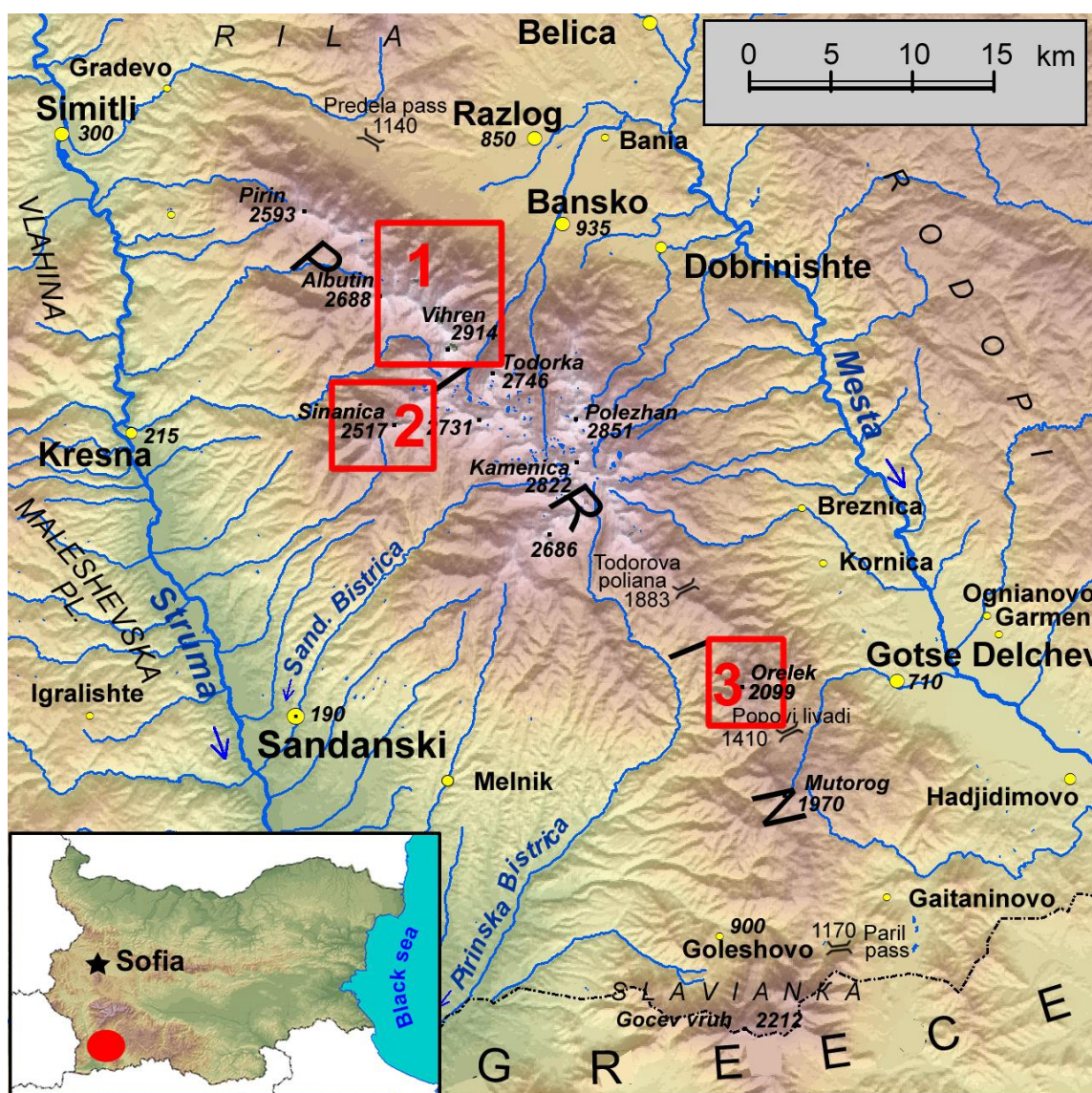


Figure 1 Pirin mountains with study areas: 1) Vihren, 2) Sinanitsa, 3) Orelek (figures next to settlements indicate their altitude)

Around, and between them, the mantle of metamorphic rocks includes gneisses, schists, amphibolites, and marble. Their metamorphism is addressed to the Alpine orogenic cycle (Ivanov *et al.*, 2000). Paleogene and neogene sedimentary rocks are exposed in the periphery, which is surrounded from all sides by faults, producing a classical horst structure. Volcanic rocks occupy the far east of the area. They are a result of eruptive activities along the Mesta graben during the Paleogene (Vatsev and Nedyalkova, 1983).

In Pirin Mountains marble is found in three main areas: the ridges around Vihren peak to the north, which is the highest section in all Pirin, and here marbles have their largest extent, the area of Orelek peak to the south, and the small spot around Sinanitsa peak to the west (Fig. 1).

In Vihren area marbles occupy 2298 ha at altitudes above 2000 m a.s.l. (in projective area), which is 95% of the total area of high mountain karst in Pirin. This is the main ridge and the northeastern mountain slope between the saddles Preslapa (south of Vihren peak) to the south and Suhodolski preval to the north. This is a high mountain section about 5 km long (the lowest point at 2650 m a.s.l.) which includes the highest peaks in Pirin: Vihren (2914 m a.s.l.), Kutelo (2908 m a.s.l.), Banski suhodol (2884 m a.s.l.) and Bayuvi dupki (2856 m a.s.l.). Five vast cirques were carved on the northern slope. From south (SE) to north (NW) these are: Kazanite (Goliam Kazan and Malak Kazan), Kutelo, Banski suhodol, Bayuvi dupki, Kamenitica. Further west on that slope there is the contact with the granites of the northern plutonic body, and marbles occupy parts of the cirques and valleys of Razlozhki suhodol and Albutin. On the southern (SW) mountain slope marbles occupy just the uppermost section and the ridgetop, while the lower areas comprise a contact strip between marble and granite.

In Orelek area the surface lying above 2000 m is very small - 30 ha. Here is the highest mountain in the southern parts of Pirin, Orelek (2099 m a.s.l.) (in Bulgarian geography it is termed "Middle Pirin", but it is situated to the south of the largest and highest part of the mountain). The area represents a typical uplifted karst plateau, with the highest peak rising

slightly at its western end and the main ridge spreading from north to south. Western slopes drop down steeply.

In the western part of Northern Pirin Mountains marbles are spread in the area of Sinanitsa Peak (2517 m a.s.l.) and build up just a single wall in the next cirque of Georgiitsa Peak (2589 m a.s.l.). The total area in marble above 2000 m a.s.l. in this location is 95 ha.

3. Methods of research

This paper presents revised results from more than 10-year research of high mountain karst features in Pirin Mountains. Descriptive methods involved the use of aerial photographs and satellite images, as well as detail work on the field: photographing, description and mapping. The size of the two perennial firn fields (glacierets) has been monitored on a yearly basis. The size (area) of Snezhnika glacieret near Vihren peak has been measured with a rope every autumn since 2008. The area of the glacieret in Banski suhodol cirque was measured with a rope in 2009, and since 2011 ice variation has been recorded according to five fixed positions, marked on the field. Repetitive photography from same positions has been applied to both glacierets to monitor short-term dynamics and long-term changes. A geophysical survey was performed on Banski suhodol glacieret in August 2017 in order to estimate its maximum thickness, with the cooperation of Romanian team lead by Prof. Alexandru Onaca from the West University of Timișoara.

In-situ climatic measurements were organized at several sites in the area: on Vihren Peak air temperature and humidity has been measured since October 2014, ground temperature at Vihren Peak and Golemia Kazan cirque since September 2016, and ground temperature near Banski suhodol glacieret since October 2017.

4. High mountain karst in marble: specifics

High mountain karst in Pirin differs from the classical limestone karst of the high Dinarides, which can be used for comparison to evaluate the specifics

of the former. This is due to two main factors: the peculiar properties of marble as bedrock, and the differences in climate.

Marble is a low-grade metamorphic rock, originating from limestone or dolostone. During metamorphism calcite minerals recrystallize, creating an interlocking mosaic of crystals. At the same time, the primary structure of initial sedimentary rocks is mostly destroyed. Pirin marbles are usually very white in colour, which indicates for the silicate poverty of the protolith (Marinova and Zagorchev, 1993) and results in a very high albedo.

As a product of metamorphism, marble has obtained structural features that bring some similarities to other crystalline rocks, including those with silicate composition (such as gneiss, granite, etc.). These concern the tendency to develop cracks at right angles, and fragment on larger angular blocks under the action of physical weathering rather than on pebble size particles, as it is with limestone. In such particular structural frameworks, marble could be more prone to physical weathering (especially frost action) than limestone. This leads to the consequence that in high-mountain marble areas frost defragmentation is strongly pronounced and is often predominant on slopes and ridges (Fig. 2).



Figure 2 Typical disintegration of marble due to frost weathering

Areas with a low tilt, which were previously in the active zone of frost processes, but later came out of it in the course of post Ice Age warming, have been subject of soil formation, they are smoothened and covered with grass. This additionally slows down the development of surface karst (Fig. 3).

By the specific levels of temperature and precipitation, climate is by no doubt the other major factor for the different appearance of high mountain karst in Pirin compared to its limestone counterparts in the Dinaric, Alpine and other areas.



Figure 3 Smooth grassy surfaces: a result of enhanced loose material and soil formation

According to climatic data average air temperature at Sandanski (190 m a.s.l.) in the SW foot of Pirin, is 13.9°C for the standard period (1961-1990), 14.5°C for the period 1997-2016, and 14.8°C for 2007-2016 (www.stringmeteo.com). Representative temperature data for the high mountain area can be obtained from the station at Musala Peak in Rila (2925 m a.s.l., 55 km away from the highest peak of Pirin), which has been in operation without an interruption since 1933. The averages for this location are: -3.0°C for 1961-1990, -2.2°C for 1997-2016, and -1.8°C for 2007-2016 (www.stringmeteo.com). According to the data, an average increase of 1°C has been registered for the last decade according to the standard period. For the first 22 months of operation, the logger at Vihren Peak (2914 m a.s.l.) has registered temperatures about 0.5°C higher than those at Musala peak (2925 m a.s.l.) (Grunewald *et al.*, 2016), with a good correlation between the daily data (+0.95). This means that for the last decade the averages for the highest peaks of Pirin have been in the range of -1 to -1.5°C. Automatic device installed at Vihren hut at 1970 m a.s.l. by German scientists from Dresden show average temperatures for 2010-2015 of about +4.9°C (Grunewald *et al.*, 2016), which means that in the last years air temperatures at the lower margin of high mountain belt (2000 m a.s.l.) are about +4.5°C.

The described temperatures provide favorable conditions for frost action: the number of days with transition through 0°C ranges between 90 at 2000 m a.s.l. and 80 at 2900 m a.s.l., and the number of frost days (with minimum daily temperature below 0°C) ranges between 170 and 260 respectively (according to data by Grunewald and Scheitchauer, 2008, 2011). In result, exposed ridges at altitudes above 2600-2700 m a.s.l. are strongly weathered, the surface layers of rock disintegrating into cobble-size blocks, and karstification in these areas is oppressed.

On the other hand, the great number of frost and icy days for cirque bottoms at 2200-2400 m a.s.l. (200-220 days with minimum temperature below 0°C and 110-130 days with only negative temperatures, according to data by Grunewald and Scheitchauer, 2008) determines the 6-7 months of snow cover duration at these sites, whereby enhancing karstification there.

Another factor for these differences is also the much smaller precipitation which falls in the mountains of the eastern Balkans, compared to the western parts of the peninsula. Precipitation in Pirin is hard to estimate properly, as no rain gauge stations have been operating within the mountain for the last 35 years. Annual amounts for Vihren hut for the period 1958-1981 were about 1400 mm (Annual bulletins of IHM), while for 1957-1961 an average of 1020 mm/y was registered in Golemia Kazan cirque (Popov, 1964). The rainfall record of Musala peak has demonstrated a considerable decrease from the period 1931-1970 (1177 mm) to present (836 mm for the period 1994-2016). However, this drop is partly due to technical reasons (a shift of the position of the rain gauge in the 1970's) and the decrease is evaluated to be actually about 15% (Nojarov, 2012). As a conclusion, annual sums of about 1000-1100 mm are supposed for the high mountain parts of Pirin (especially the area around Vihren Peak), with 2/3 falling in the period November-April.

The relatively small amount of precipitation acts as a limiting factor for the intensity of karst processes, especially on exokarst. For comparison, in the central ranges of the Dinarides annual sums of about 2500-2600 mm are estimated (500-600 mm solely in December) (Djurović, 2011).

Although barren rock surfaces are wide spread, especially at altitudes above 2400 m a.s.l., typical karren pavements are not observed in Pirin. On some old roche moutonnée within cirques the pattern of surface karstification shows similarities to "mosaic-limestone pavements" (Wilson and Fernández, 2013). Marble faces are also very poor on corrosion microforms. Abundant screes that cover the base of cirque headwall and side walls are made of blocks much coarser than what is typical for the limestone areas. On few sites such debris accumulations form single lobes, or series of lobes, which can be associated with permafrost occurrence and rock glacier activity (relict or even recent). The effect of corrosion on marble rocks is most obvious in the sinkholes on higher cirque floors (at 2300-2500 m a.s.l.) where snow retains for at least 6 months and melting is slowly going all the summer. Dissolution is progressing faster on the perpendicular pattern of cracks in the rocks, producing an "ice cream ball"-looking like morphology (Fig. 4). Shafts are another wide spread surface karst landforms in the area. Usually they are not wider than 1-3 metres. In higher cirque depressions most of them are full of snow all the year.

Despite the weaker expression of surface karst compared to high mountain Dinaric karst, due to the long snow cover duration and the great volume of meltwaters, subsurface karst in Pirin is well developed. 71 caves were found and mapped in the cirque Banski suhodol only, for the period 2000-2016. In 2016 explorers in the cave Banski suhodol 9-11, reached a record depth for all Pirin: -353 m (www.heliktit.info).

Glacierets and summer snow patches are typical features of high mountain karst areas of Pirin. Their existence is favoured by the following factors, which act together: low temperatures (annual +2 to 0°C); high albedo of the lightly coloured bedrock (white marble); drainage of meltwaters that does not favour basal melting of snow; great shading provided by the deeply incised relict glacial cirques; considerable (in some cases great) contribution of avalanche and windblown snow. These conditions have allowed for two glacierets to survive several centuries without complete melt (Grunewald,

Scheitchauer, 2008, 2011; Gachev *et al.*, 2009; 2016) at altitudes 500 to 700 m lower than the suggested

climatic snow line, which is at present estimated to be at 3100 m a.s.l (Grunewald and Scheitchauer, 2010).



Figure 4 "Ice cream ball" stones on the floor of Golemia Kazan cirque

5. Spatial structure and main features of high mountain karst

5.1 Vihren area

This area is the largest in size, and the highest in altitude. In fact, it represents a monocline spreading from SE to NW, heavily eroded by former glaciers on the northeastern side, and much less affected on the southwestern (Fig. 5). The thickness of marble cover reaches 500-700 m, with strata tilted towards NE (Marinova and Zagorchev, 1993). Five large "cirque-uvalas" are entirely comprised in the northerly facing slope in this section. They are deep but short, which is characteristic for glacier exaration in carbonate terrains, as the drainage of melt waters hindered, in part, the basal sliding of Pleistocene glaciers (and hence their downward movement as a whole). When combined with a great snow input, slow sliding resulted in overload of cirques with ice, and, as a consequence, depressions were

overdeepened by glacial erosion. There are local variations in this model throughout the area.

A significant element that unites the spatial structure, is the main ridge, which is sharp along all its length, with almost vertical faces to NE, and surfaces tilted 35-40° to SW. All the peaks along this ridge have pyramidal form, mostly resembling truncated pyramids (Fig. 6). High slope section on the northern and eastern sides are rock faces 250 to 400 m high, with tilts above 50° and straight cross section of the surface. The southwestern slope is an almost straight rocky and grassy surface, without traces of glacial rework (however, this slope seems to have sustained snow patches in nival depressions). Surface karst in these zones is only represented by barren rocky surfaces with scarce grassy vegetation, with no karren. A sinkhole on the very peak of Kutelo and a 5-6 metre deep shaft on the summit of Banski suhodol, have been formed probably by the corrosive action of the patches of windblown snow, or during the long ice free period

when these summits were rising above the Pleistocene ice cover. Ridge top sections and southern slopes are highly weathered and covered with debris of mostly pebble and cobble size. Rocks on summits are disintegrated into loose blocks, which rest unstably on tilted surfaces. A distinctive characteristic of the main ridge is the very little dissection along the longitudinal profile: although very high, the ridge is completely passable on foot.

On the other hand, northern slopes are smoothed and made of solid rock (Fig. 7). The smaller temperature amplitudes here limit the rock disintegration, except the numerous corroded couloirs, which scar rock faces at places. The most prominent of them follow fault lines and represent mylonitic zones which may favour production of great amounts of scree material.

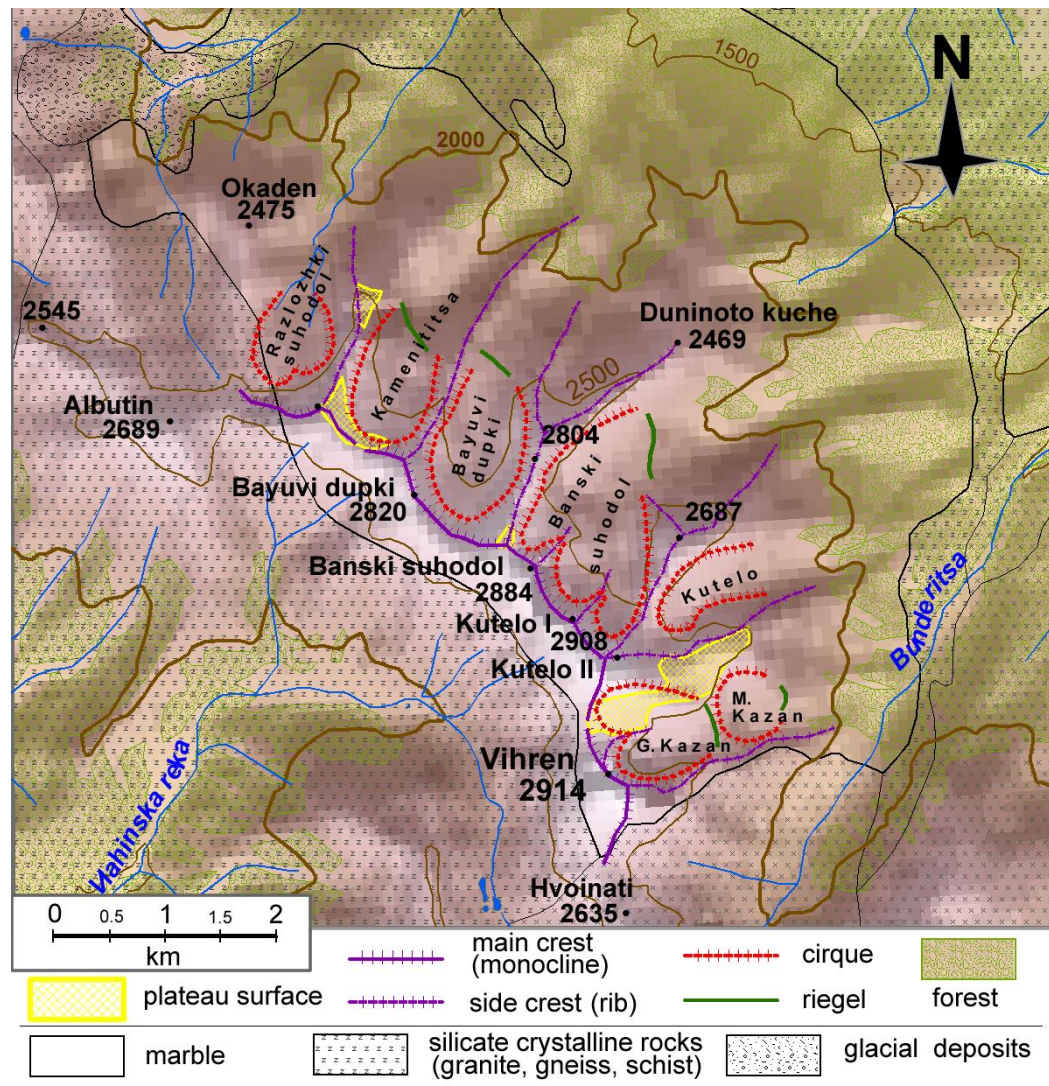


Figure 5 Map of Vihren area (rectangle 1 on Fig. 1)

Cirque bottoms lie on 2200-2400 m a.s.l., their highest sections are covered by screes and dotted by sinkholes. All glacierets and summer lasting snow patches are situated here, the most stable of them at the base of rock walls.

Golemia Kazan (the Great Pothole) is the southernmost of the five large cirques, and the deepest of all (Fig. 8). Its southwestern flank is the 450 m high rock face of Vihren Peak, the tallest in Pirin. The upper section of this wall, called Funiata

(the Funnel) is tilted 60-70°, while the lower section is almost vertical (Popov, 1962). At the base of the wall lies the Snezhnika glacieret. It has a trapezoid shape facing the east, length 70-90 m and width 90-100 m. The drilling, made on this permanent form in 2006 (11 m deep to the base), revealed a glacier ice at depth about 10 m, containing organic particles dated to be about 100 years of age (Grunewald *et al.*, 2008; Grunewald and Scheitchauer, 2008, 2011).



Figure 6 The main ridge of Northern Pirin within the marble area

On the basis of this evidence, and of its present permanency (weak trends of shrinkage in the last 23 years, Gachev, 2016), Snezhnika is now considered the southernmost glacial mass in Europe (Grunewald and Scheitchauer, 2010). Although in a partly sunny position, this small glacier (average area 0.55 ha) manages to retain a long-term stability due to its dependency on avalanche snow contribution, as the catchment area of the glacieret is 22 times larger than its surface.

Snezhnika is surrounded by a moraine crest 5-6 m high from three sides. Radiocarbon dating of fossil soil particles in its base suggests it was modelled in its present shape during the Little Ice Age (Grunewald and Scheitchauer, 2008, 2011). Another, obviously older crescent shaped moraine is situated 150 m to the east, and several much older moraines mark the outlet of the cirque. The cirque bottom contains several sinkholes dotted in a line, which are filled by marble blocks. They represent features of covered karst typical for all cirques,

similar to those described by Veress (2016) in the Dinarides. Blocks are rounded, with evident signs of corrosion. Above the lowest bottom section a grassy terrace is developed on the northern side, partly covered by scree material. Several round shaped sinkholes are formed here also. Two parallel tracks descend from the rockwall to the south. They were described as “avalanche rails” by Popov (1962), and in summer time they act as debris flow tracks.

Malkia Kazan lies to the NE. It represents a continuation of the glacial valley coming NE from Vihren peak. This is one big sinkhole, which grassy floor lies at 2200 m a.s.l. Surrounding slopes are steadier, with weak traces of karstification. A straight rocky ridge 3-5 m high surrounds cirque floor from the east, resembling the cirque riegel. Cirque bottom is entirely covered with grass, and shrubs of *Pinus mugo* grow on slopes.



Figure 7 The smooth rock wall of Koteski chail (Cats' ridge)



Figure 8 Golemia Kazan cirque with Vihren peak and Snezhnika glacieret

Kutelo is the next cirque to the north. It is separated from Golemia Kazan and Malkia Kazan with a steady grassy field, dotted with some small sinkholes. The field must have stayed outside the extent of cirque glaciation, but probably was occupied by relatively thin snow/ice drifts during the Ice Ages, as a small nival depression is carved on the steady slope. Kutelo cirque is deep and relatively narrow, its uppermost floor section being entirely covered by debris. A crescent-shaped crest marks the spread of perennial snow patch (or glacieret?) that used to exist in the previous decades, and probably resembled a small glacier during the Little Ice Age. Below the crest grassy fields appear on the cirque floor. Now in September and October the entire cirque is completely dry.

The next cirque, Banski suhodol (Fig. 9), is the largest of all the five. This giant depression has a general NE aspect and an area of 2.3 km² (Gachev

and Gikov, 2010). Here the abrasive force of the former glacier acted parallel to marble strata, and this led to a weaker incision and a generally shallower cirque. In its upper part the cirque is divided into three sections. There exaration has formed depressions along a dyke of weaker rocks intruded in the marble, that runs in a direction parallel to the main ridge. In the centre of the cirque, to the north of the line of depressions there is a rough slope section, descending to a central and lowermost uvala at 2213 m a.s.l. The rough slope represents a labyrinth of sinkholes and small ridges and is dotted by numerous caves, most of which are vertical. To the east an intra-cirque U-shaped valley was formed by the retreating glacier, with a sequence of moraines left. The valley bottom is dotted by sinkholes, and its east slope covered by screes.

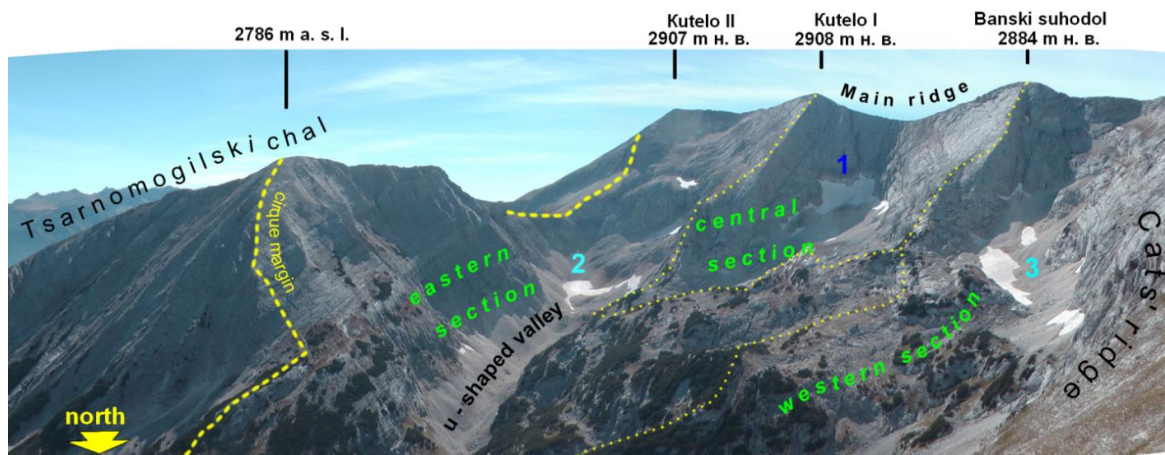


Figure 9 Banski suhodol cirque with permanent features of snow and ice: 1) glacieret, 2) and 3) snow patches. Dashed and dotted lines mark the boundaries of the three cirque sections

Two snow patches and one glacieret are situated in the three upper sections (Fig. 10). The glacieret, which is in the middle one, has a high position, 2620-2700 m a. s. l., and lies in a rocky bed carved in the rock face between the peaks Kutelo I and Banski suhodol. The glacieret, which has an area about one ha, is still surviving due to the northern exposure and strong shading. It does not rely so much on avalanche snow, due to its much smaller avalanche area ratio (5.22 – the ratio between glacieret catchment area and ice surface). The

geophysical survey done in August 2017 recorded a maximum firn/ice thickness of 17 m in the central part of the glacieret. Two parallel moraine ridges are formed at glacieret front, 4-5 m from one another. Considering the state of lichen cover and the overall appearance, the outer ridge is quite similar to the moraine that surrounds Snezhnika, and could possibly be addressed to the Little Ice Age. The internal, smaller ridge is lichen free, with light colour and a very fresh look, probably dating from the 20th century. Another, well preserved moraine ridge,

partly covered with soil and grass, is observed 200-250 m below the modern ice front. Morphologically it can be associated with the crescent moraine in Golemia Kazan.

The two snow patches in Banski suhodol cirque (Fig. 10) occupy scree covered sinkhole bottoms, and have been quite stable in the recent years.

Bayuvi dupki and Kamenititsa are the next two cirques to the west. They have similar morphology, in which the most specific is the lack of distinctive headwall. Instead, a steady slope rises to the main

ridge. Due to this fact the bottom in the upper part is not covered by screes and bare rock is exposed and highly karstified. Vertical shafts down to several meters deep were formed in this area, which are filled with snow all year round (Fig. 10). The most expressive surface karst forms in Pirin are found in these cirques. In recent years it is usual that by the end of autumn cirque bottom becomes dry, but 60 years ago Peev (1960, 1961) reported about the presence of a small glacier up to 500 m long, which is now disappeared.

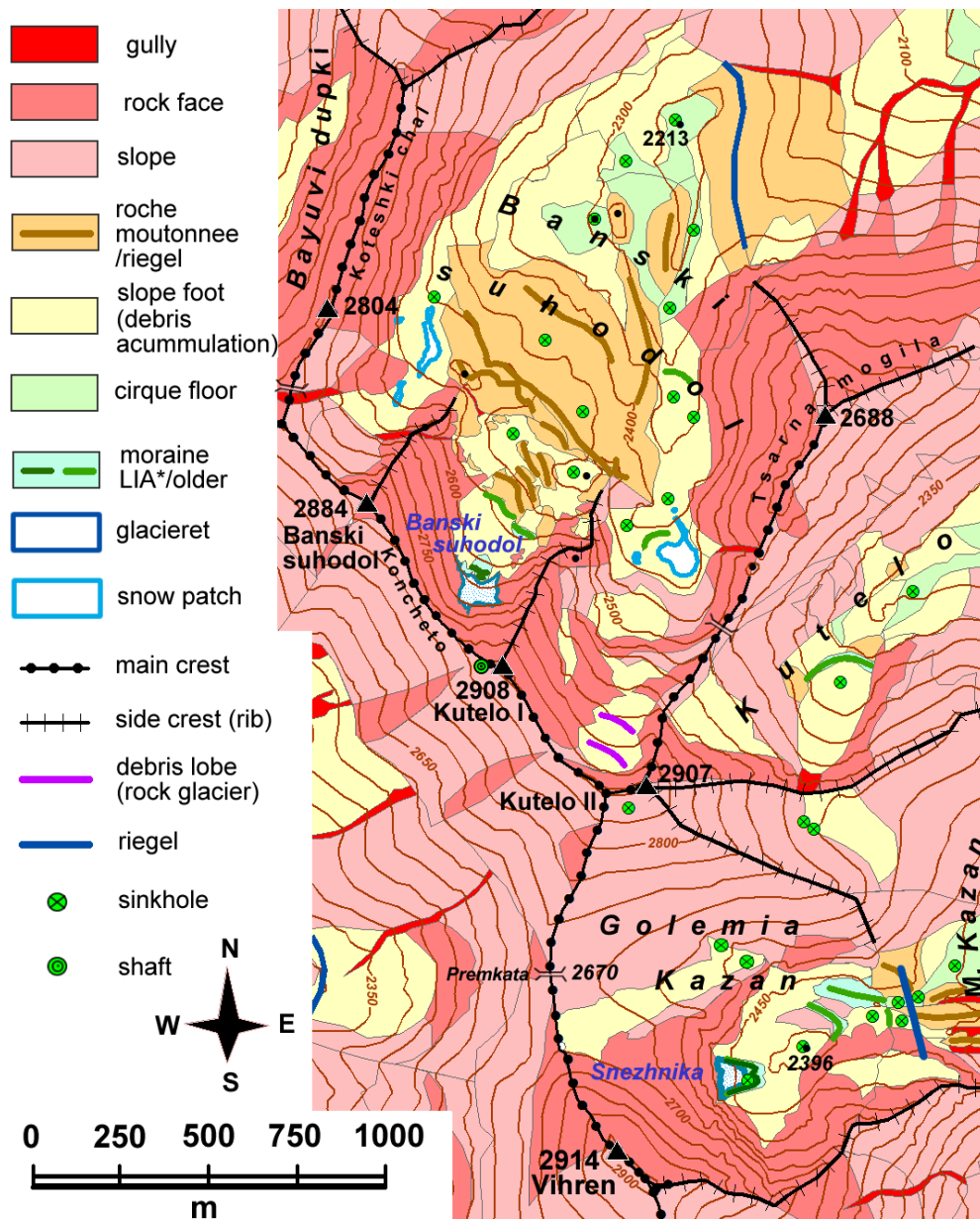


Figure 10 Geomorphological map of the cirques Golemia Kazan, Kutelo and Banski suhodol



Figure 11 The floor of Bajuvu dupki cirque with vertical shafts and abraded rock. The site where was “the small firn glacier” described by Peev (1960, 1961). Picture taken in October 2013

The cirque of Razlozhki suhodol lies in the transition zone between marble and granite. The eastern slope is higher. This is a giant rock face of marble, which to the north descends with several toothed peaks, known as ‘The stairs’. A line of large screes is running along the slope foot. On the contrary, the western slope, carved in granite, is steady, with a much lower altitude.

The granitic part of the bottom is filled with block material, which compose a chaotic pattern of

ridges and furrows (not recognized as a rock glacier), which makes a great contrast to the karstic part. Figure 10 shows the typical morphology for the highest part of Northern Pirin. 50 to 70% of the slopes in the cirques Golemia Kazan and Banski suhodol have gradients above 40-45° and can be categorized as ‘rock faces’. Among all in the marble area, Banski suhodol is the cirque with the most complicated morphology of the floor, and the greatest abundance and variety of karst forms.

5.2 Sinanitsa area

The area around Sinanica peak (2517 m a.s.l.) lies in the western part of Pirin Mountains (Fig. 12, left). The marble is found at the south-eastern margin of the metamorphic mantle along its contact with the granitic body. Marble is exposed just in the area of the peak itself, and this gives it a prominent look from distance. Just one marble rock wall is present in the next cirque to the NE, Georgiitsa (2589 m a.s.l.) (Fig. 13). The mixture of silicate and carbonate bedrock has created a mosaic relief of high diversity in the area.

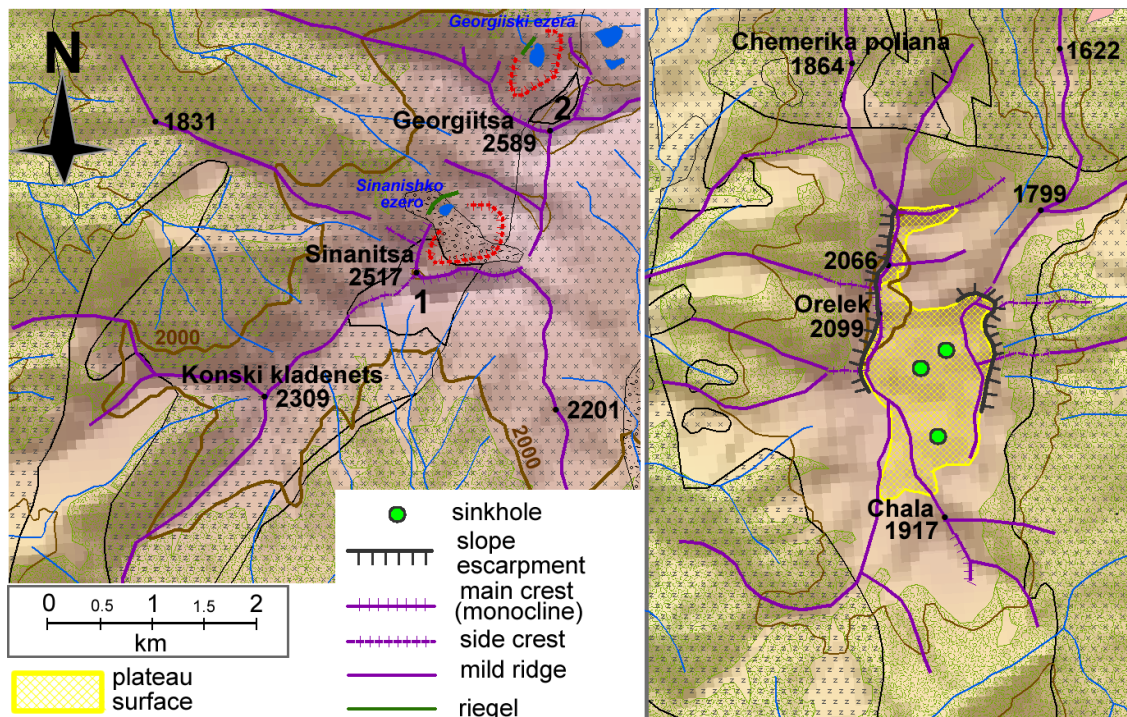


Figure 12 Map of Sinanitsa area (left) and Orelek area (right) (legend the same as in Fig. 5). Numbers indicate: 1. Sinanitsa marble area; 2. Georgiitsa marble area. The lithology symbols are identical to those from the Figure 5

5.3 Orelek area

The area of Orelek (Fig. 12, right) is much lower in altitude, and has a different character. This is a flattened grassy karst plateau with a smooth and rounded surface, dotted with shallow sinkholes. Marble layers sink to ENE, but in general their tilt is low. The western slope is quite steep and rocky, because denudation processes here acted transversely to layers tilt. Several side ribs are also formed on that slope. Similar situation is observed on the eastern slope, but tilts here are steadier. Epikarstic features on the surface of the plateau are presented by a dense pattern of sinkholes with steady slopes and grassy floors. Rock escarpments encompass the plateau from east and west. The western slope is the steepest and the longest. Several rocky ribs and gullies descend down on it.



Figure 13 The peaks Georgiitsa and Sinanitsa seen from the north. The marble wall of Georgiitsa peak is visible



Figure 14 Orelek peak

6. Evolution of high mountain karst relief

Main factors for the development of high mountain karst in the Pirin Mountains have been the tectonic structure, the extensive action of glaciers during the

Pleistocene, and the specific structure of marble, which combines properties of carbonate and crystalline rocks together.

The initial formation of the geomorphological environment of the marble massifs of Northern and Central Pirin has a similar mechanism. Marble, which is less erodible than some of the surrounding rocks (Kanev, 1988; Georgiev, 1990, p. 340), remained higher than the neighbouring landscape, protecting the rocks below from denudation.

Contemporary high mountain karst relief has been formed in the course of many millennia. In high mountain conditions, the specific structural features of marble make so that weathering produces some amount of loose material due to crystalline defragmentation. So, if no other agent is present, the landscape tends to be smooth and grassy, with sporadic stone blocks and no traces of surface karst, except for some dolines with steady slopes. This is well demonstrated in the high mountain area of Orelek, which was under the snow line even in the strongest glacial phases of the Pleistocene. The long period upon which karst processes acted without interruption, and the flat surface that tend to retain snow for longer throughout the year, led however to the considerable development of subsurface karst, and a dense network of dolines on the surface. The mild landscape formed during this long evolution now shows a trend towards the rise of treeline.

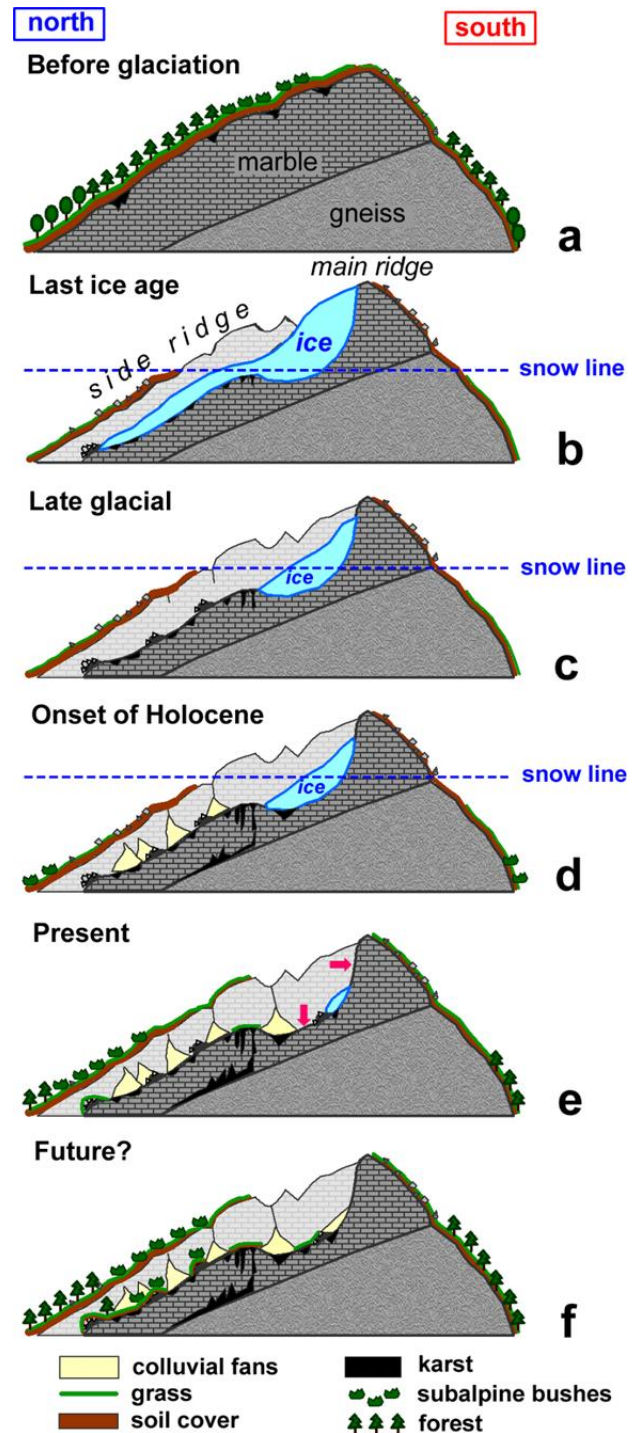
The specific development of relief in the higher parts of Pirin can be traced back to the last Ice Age, at least the Wuermian period of the Pleistocene (Fig. 15). Dating of terminal moraines in the neighbouring Rila Mountains indicate that the largest extent of glaciers in the mountains of SW Bulgaria occurred in the beginning and the end of the LGM, 24 and 18 ka respectively (Kuhlemann *et al.*, 2013). Although absolute dating is missing for Pirin, the same conclusion can be drawn for this mountain on the basis of the close proximity of both massifs.

So, during their maximum extent, Wuermian glaciers reworked large areas in the marble parts of Northern Pirin, mainly on the northern slope, where the snow line is estimated to have dropped to 2200 m a.s.l. (Kanev, 1990), thus producing glaciokarstic

relief. In the valley of Bunderitsa, adjacent to, but mostly outside the marble area, the glacier in this period went down to 1100 m a.s.l., closely above the present day town of Bansko (Lilienberg and Popov, 1966). However, glaciation in the marble area was not so extensive in horizontal plan, due to the hard conditions which karstic rough terrain and the drainage of melt waters produced for the advance of glacier tongues. The smaller length was somehow compensated by overloading with ice mass and enhanced exaration in the accumulation zone, which produced some of the deepest cirques in Bulgarian mountains (e. g. Golemia Kazan). On the other hand, southern slopes were much less (or not at all) affected by glaciation, and contemporary landform features there are mostly of a structural origin. Besides the southern slope, some areas on and around the ridge tops were left outside the strong impact of glaciers. These represent remaining fragments of the old summit surface, rounded grassy fields on which sporadic epikarst forms (dolines and shafts) are scattered.

Figure 15 Scheme of the evolution of high mountain karst relief in the formerly glacierised areas of Northern Pirin: a) initial stage (prior to glaciation), in which soil and grass cover are well developed, and karst process is present, but suppressed (especially surface karst); b) glacial stage, in which the northern slope is subject to exaration, incision and exfoliation. Cirques are formed. Karst process runs only below the snow line, in open spaces and under 'warm' glacier ice; c) Late Glacial stage, in which lower parts of cirques are ice free. There karst develops intensively on barren rock. d) Younger Dryas/Onset of Holocene stage, in which glaciers go on retreating, and depressions below them that are close to rock walls are filled with debris (covered karst develops there). Karst remains intensive on uplifted parts of cirque bottom; e) present stage, in which ice (glacierets) exist only on the most optimal locations. On surfaces which have been recently freed from ice (red arrows) karst processes are still in the beginning. f) possible future stage, in which ongoing warming leads to a rise of treeline, eventual melt out of glaciers, and karstification of upper cirque parts. Light grey indicates the contour of the side ridge, and the red arrows on e) – areas with strong domination of physical weathering.

Within cirques, which are the major products of glaciation, the surface was exfoliated from weathering materials and soil cover, and, after the retreat of glaciers, was exposed to the corrosive action of snow and rain waters.



At the same time the enhanced contrast of topography, generated by former glaciers, produced favourable conditions for the occurrence of paraglacial processes, expressed mainly in rockfall and colluvial activity. In result the negative forms under the side and back walls of cirques were gradually filled with block material, and this once again limited the corrosive action of waters at the surface, turning the environment from open to covered karst. However, said fact did not trouble underground karst, and the generation of abyss caves and wells, which developed in sinkholes below the scree cover, and produced suffosion depressions on the surface.

The areas which are most prone to the development of surface karst are the elevated sections of cirque floors, such as roches moutonnées and riegels, distant from side walls, because they have remained outside the range of colluvial processes. During their existence, glaciers filled with sediment mostly the karstic depressions in their ablation zone, and much less those in the accumulation zone. This seems to be in force also for the cirques in the Pirin Mountains. The lowermost cirque floors, located at altitudes 2200-2300 m a.s.l. were at the end of the Wuermian glacial epoch, during the cirque phase of glaciers, sites where glacier tongues reached and terminated. Glaciers carried and deposited considerable amounts of coarse and fine sediment material which accumulated in these low altitude depressions, producing flat cover, now grown with dense grass. A considerable amount of peat is deposited on the floor of Malkia Kazan cirque. High cirque floors, situated at 2300-2500 m a.s.l., are now covered with coarse debris and are soil free. This provides better conditions for penetration of rain and melt waters and their corrosive action.

Already in Late Glacial times glaciers were preserved in the high cirque sections, and the low areas were subjected to paraglacial action and karstification. Depressions in the lower cirque parts were filled with finer sedimentary material, and this continued to cause a restrictive effect on the development of epikarst. With the progress of colluvial action, sinkholes in the upper unglaciated parts were filled with debris, and covered karst

developed. As it is known from the studies of Ford and Williams (2007), Veress (2010, 2016) and others, the corrosive action of waters is dependent on the thickness of debris cover. In the case of glaciokarst the thickness of epikarst is down to several meters below the surface, so if the debris cover is thicker than 3-5 m the water will become already saturated when it enters the actual sinkhole.

Contrary to glacially reworked cirque depressions, conditions for karstification became optimal for the areas of the riegels and roches moutonnées that were freed from the ice. At present, these areas demonstrate stronger development of epikarstic landforms, and their appearance is similar to that of classical Dinaric karst (areas coloured in orange on Fig. 10 that have altitude below 2500 m a.s.l.).

In the higher cirque zones glaciers retreated later, probably after the Younger Dryas cold episode. Surface karst in these areas is much more weakly expressed. Shafts are the most spread in these locations. These karstic forms started to develop still under the ice, when, with rising temperatures, melting at glacier base gradually intensified. Roches moutonnées surfaces in these highest cirque sections look almost untouched by corrosion, and only signs of physical weathering are observed. The low temperatures, the relatively thin and not so long-lasting snow cover, and the short time which passed after their final deglaciation are the combination of factors that makes these areas one of the least affected by karstification.

On the ridge tops and in the highest cirque sections frost processes dominate. Small remains of former glaciers are still preserved in two locations, even in the conditions of present warming. Enhanced frost action in the highest parts produces large amounts of debris, which pile in rockwall bases and on the glacier ice.

In conditions of rising temperatures, the development of glaciokarstic relief will show trends towards further activation of rockfall and scree development in the highest areas, and stabilization of grass and bushy vegetation in the lower zones. The reduction of snow cover thickness and duration, and the overall decrease of precipitation will lead to decrease in karst activity, and the rise of the share of

physical weathering in the geomorphic processes that shape high mountain relief.

In the course of the last two decades glacierets in Pirin demonstrate stagnation and relative stability (Fig. 16). One reason for this was the droughts in the 1990s, which made ice and snow cover shrinkage. The 2004-2010 period was characterized by increased winter snow accumulation, and this led to a positive balance and spatial increase of glacierets, despite the warming trends. The second decade of

this century has been characterized by rising temperatures, decreased snow accumulation, and often abundant summer rains, which again caused glacier shrink. However, changes in Pirin glacierets have been much less expressed than those of glaciers in the Dinarides, which in the summer of 2017 were on the verge of disappearance. This is indicative for the more stable and balanced long-term climatic conditions in Pirin.

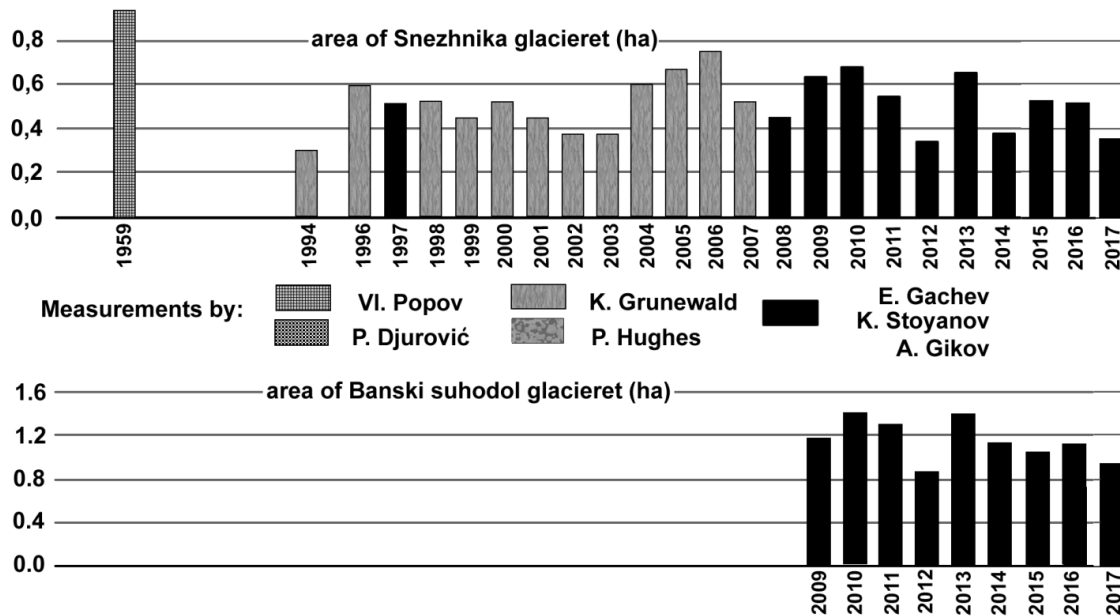


Figure 16 Areas of the glacierets Snezhnika (1994-2017) and Banski suhodol (2009-2017) measured in autumn (September-November), in the end of the balance year

7. Conclusions

High mountain karst is spread on three locations throughout the Pirin Mountains – around the peaks Vihren (to the north), Sinanitsa (to the west) and Orelek (to the south). If, as an altitude of the natural treeline, 2000 m a.s.l. is accepted for the lower limit of high mountain karst in the area, more than 9/10 of the high mountain karst areas are in the northern (Vihren) area. Karst in the high mountain zone of Northern Pirin can be categorized also as glaciokarst, as most of the territory was subject to glaciation during the Pleistocene. The most typical surface forms are the sinkholes with steady slopes (at lower altitudes) and the shafts (at higher

altitudes). Being probably the most representative forms of classical epikarst, karren are not typical for the high mountain environment of Pirin, nor the corrosion microforms, which are wide spread in the Dinarides. Instead, corrosion of marble has produced “ice cream balls” in depressed areas where snow duration is longest.

In general, the high mountain karst in marble is typical with weaker surface expression of karst processes compared to the classical Dinaric karst, due to the coarser rock fragmentation of marble by physical weathering and the production of higher amounts of regolith. Another reason is the considerably smaller amount of atmospheric precipitation in Pirin (about 1000-1100 mm/y, 40%

of that in the high Dinarides). Subsurface karst is however well developed. It is presented by numerous caves, most of which vertical. Most of them contain seasonal or perennial ice.

The action of Pleistocene glaciers increased the potential for the development of surface karst by exfoliating the surface on northern slopes. The vast cirques formed there during Pleistocene glaciations are at the same time complex dolines (or uvalas). Surface karstification is strongest in the elevated areas of cirque bottoms, which are not covered by screes. Specific element of the high mountain karst complex in Pirin are the two glacierets (in fact small glaciers), which still survive despite the temperature rise, and even have demonstrated some stability in the last decades. At present, these are recognized as the southernmost glacial masses in Europe.

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Application of the SHALSTAB model for the identification of areas susceptible to landslides: Brazilian case studies.

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ABSTRACT

Since the 1960s, catastrophic and generalized events of hazardous mass movements caused millions of dollars in economic losses and resulted in thousands of fatalities and homelessness in Brazil. To understand these processes and attempt to predict them, mathematical models have been utilized world-wide describing the physics of the process through mathematical equations. The objective of this study was to present two areas widely affected by shallow landslides where the SHALSTAB model was applied to understand the process and to predict potentially unstable areas in several hydrographic basins. Simulations utilized the types of distinct data that were available in each area. From both areas, geotechnical data collected in the field, topographical data from digital topographical maps and Digital Terrain Models (DTM) from Light Detection and Ranging (LiDAR) were utilized. Susceptibility maps were validated using two indexes, scar concentration (SC) and landslide potential (LP), based on landslides that occurred in 1985 and 2011. Both indexes showed satisfactory results given that the unconditionally unstable category described more than 45% of the landslide events, and the LP index displayed the highest values for the most unstable categories.

KEYWORDS

Serra do Mar; LiDAR; Landslide Potential; Natural Disasters

1. Introduction

Landslides in Brazil occur predominantly in steep slopes associated with high rainfall indexes, particularly in summer. Between 1988 and 2015, 4,000 fatalities were recorded as a consequence of 773 events in 243 municipalities (Macedo and Martins, 2015). These authors also showed that the states of Rio de Janeiro, São Paulo, Minas Gerais and Santa Catarina had the highest number of fatalities. Starting in the 1960s, important events considered catastrophic were recorded, resulting in millions of dollars in economic losses, thousands of fatalities and homelessness. A few events marked the history of Brazil, particularly in the years 1966, 1967, 1985, 1988, 1995, 2008, 2009, 2010, 2011 and 2014 (Fig. 1).

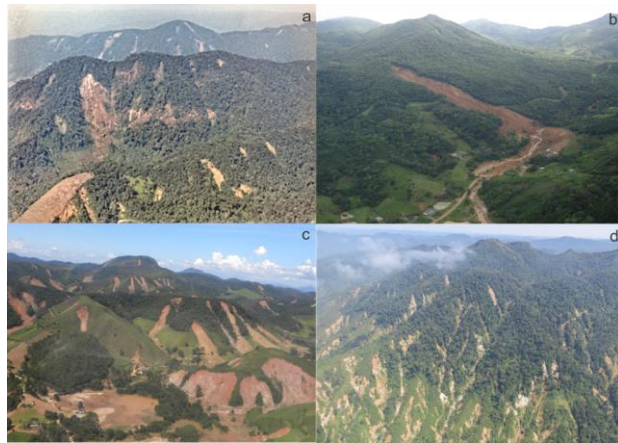


Figure 1 (a) Mass movements at Serra do Mar near the municipality of Caraguatatuba in 1966/1967, at Santa Catarina in 2008, at Rio de Janeiro in 2011 and at São Paulo in 2014. Sources (a) Caraguatatuba municipality archives, (b) and (d) photo credits: Marcelo Gramani, and (c) personal archives

2. Serra do Mar and Study Areas: Copebrás Basin and Bom Brinquedo Basin

The Serra do Mar mountain range in southern Brazil is a geological-geomorphological compartment that extends for 1,500 km. It is characterized by frequent mass movements associated with the rainy season between December and March when 60% of the annual mean precipitation of 3,300 mm occurs

(Meis and Silva, 1968; Fúlfaro *et al.*, 1976; de Ploey and Cruz, 1979).

One of the largest events occurred in the municipality of Caraguatatuba, São Paulo State, where precipitation reached 947 mm in March 1967, with 115 mm on the 17th and 420 mm on the 18th of that month. This triggered numerous landslides and debris flows across a radius of 15 km resulting in 440 fatalities (de Ploey and Cruz, 1979).

On January 23rd and 24th, 1985, 380 mm of rain over a 48 h period, corresponding to 40 to 60% of the typical January monthly rainfall in the area, caused severe shallow landslides that reached the main drainage network at Serra do Mar in the municipality of Cubatão (state of São Paulo), and caused a highly destructive debris flow (Massad *et al.*, 2000; Kanji *et al.*, 2003).

On January 11th and 12th, 2011, rainfall reached approximately 300 mm/48 h and more than eight municipalities in the Serra do Mar region located in Rio de Janeiro were affected by 3,562 landslides that caused more than 1,500 deaths and serious damage to urban and rural infrastructures due to heavy preceding rainfall (Coelho Netto *et al.*, 2011).

In view of this, efforts have been made to comprehend mechanisms that trigger these processes and to integrate factors related to the soil, topography, morphometry of relief and drainage, rainfall volume, and hydrological monitoring (Fernandes *et al.*, 2004). Furthermore, particularly after the 2011 mass movement events, the Brazilian government passed a law related to the production of susceptibility maps, particularly regarding landslides and flooding, to ensure the production of maps that indicate areas with higher or lower degree of susceptibility focused on hydrographic basins.

To exemplify the application of the SHALSTAB model, two areas in Serra do Mar that were widely affected by shallow landslides in different periods were selected, one located in the state of São Paulo and one in the state of Paraná (Figures 2 and 3).

Serra do Mar is one of the most relevant orographic features in the Atlantic coast of the South American continent, and it is known for

having the most “Tormented” relief in Brazil due to its slopes, tectonic processes and faults. It is an outstanding feature in the Brazilian terrain for its grand geomorphological features and its role on human occupation from the colonial period to present (Almeida, 1953).

Geomorphological features in the São Paulo State portion of Serra do Mar display several natural features, primarily those associated with lithological, structural and climatic conditions. Geologically, the main escarpments of this unity are associated with the most resistant rocks such as granite, granite gneiss, alkaline and basic intrusions and quartzite. Thus, natural processes of mass movement are common in this area, which is subjected to high annual mean rainfall and long-lasting rainfall events. Some stretches display the highest volumes of rain in Brazil, together with the Amazon region, where approximately 5,000 mm/year has been recorded.

where the main petrochemical companies in the country are hosted. Migmatite and schists are the predominant rock types, 60% of the escarpments are convex and concave at 30 to 40 degree angles, and a large portion faces the southeast, south and southwest (Vieira *et al.*, 2010).

The *Bom Brinquedo Basin* extends for 0.16 km² and is located north of the urban perimeter of the Antonina municipality (state of Paraná). In March 2011, the municipality was affected by generalized mass movements triggered by 98.6 mm of rainfall on the day of the occurrence and an accumulation of 263 mm between March 1st and March 11th, 2011. In this basin area, porphyritic granite is the predominant rock type, interspaced by diabase dikes, with the slopes most affected by landslides having an inclination of 20° to 30° and predominantly concave (Martins *et al.*, 2017b).

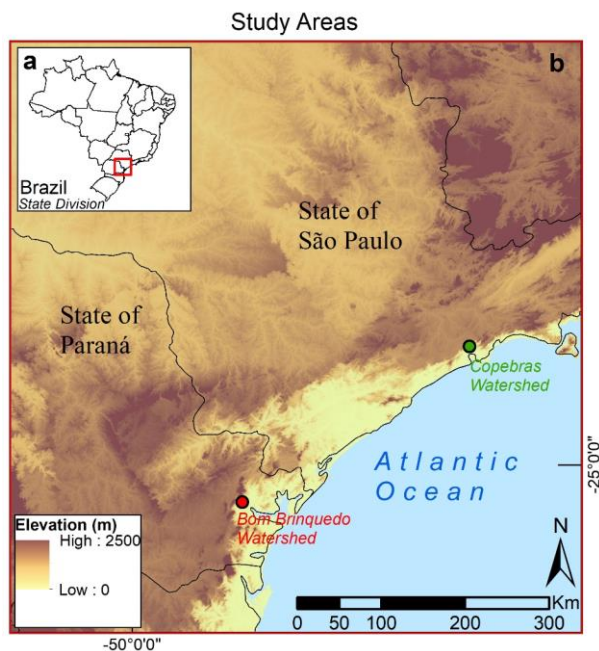


Figure 2 Location of the two basins in the states of São Paulo and Paraná related to Serra do Mar.

The *Copebrás Basin* in São Paulo state extends for 3.6 km² and was affected by approximately 400 shallow landslides on January 23rd and 24th, 1985. The basin is located in a heavy-traffic highway network through which a large portion of Brazilian exports are transported to the port of Santos. The Cubatão Industrial Park is also located in this region,

3. Methods and Materials

3.1 Model

One of the methods used to predict shallow landslides in susceptible areas employs physics-based mathematical models, which physically describe the processes through mathematical equations and disregard the subjective or direct opinion of the researcher. Beginning in the 1990s, two important physics-based mathematical models were developed: the *Distributed, Physically Based Slope Stability Model* (dSLAM), created by Wu and Sidle (1995), and the *Shallow Landsliding Stability Model* (SHALSTAB) of Montgomery and Dietrich (1994). In the late 1990s and early 2000s, three additional models were developed: *Stability INDEX MAPping* (SINMAP) by Pack *et al.* (1998); Pack *et al.* (2001); *Transient Rainfall Infiltration And Grid-Based Regional Slope Stability* (TRIGRS) and *Shallow Landslides Instability Prediction* (SLIP) by Montrasio and Valentino (2008).

SHALSTAB was developed from propositions by Montgomery and Dietrich (1994), Montgomery *et al.* (1998) and Dietrich *et al.* (1998) that spatially represent the potential susceptibility of shallow translational landslide occurrences for a given hydrographic basin with the compilation of a slope

stability model and a steady-state hydrological model, which is analyzed based on the topography. The combined models provide a ratio between the precipitation and soil transmissivity that can lead to slope failure (Equation 1). The first model is based on the slope stability model that uses the infinite slope equation, which defines a ratio between the support tension and material destabilization. The second model is based on the propositions by O'Loughlin (1986), who considers the ratio between the concentration and transmissivity of water in the soil, providing the spatial standard of soil saturation equilibrium, defined by an upstream source area. The combined model may be expressed in terms of the critical ratio of rainfall to soil transmissivity necessary to cause a landslide:

$$\text{Log} \left(\frac{q}{T} \right) = \frac{\text{sen} \theta}{\left(\frac{a}{b} \right)} \left[\frac{C'}{\rho_w g z \cos^2 \theta \tan \phi} + \frac{\rho_s}{\rho_w} \left(1 - \frac{\tan \theta}{\tan \phi} \right) \right]$$

where,

q = critical rainfall to cause rupture [mm/day]

T = soil transmissivity [m^2/day]

a = contribution area [m^2]

b = length of cell contour [m]

θ = slope angle [$^\circ$]

ρ_w = water density [g/cm^3]

g = gravity acceleration [m/s^2]

z = soil thickness [m]

ρ_s = global density of saturated soil [g/cm^3]

ϕ = angle of internal friction [$^\circ$]

c' = effective soil cohesion [kPa]

In Brazil, most studies utilize mainly the SHALSTAB (Guimarães *et al.*, 2003; Fernandes *et al.*, 2004; Zaidan and Fernandes, 2009; Vieira and Ramos, 2015; Martins *et al.*, 2016) and SINMAP models (Lopes, 2006; Michel *et al.*, 2014; Nery and Vieira, 2014) and, to a lesser extent, the TRIGRS model (Rabaco, 2005; Vieira *et al.*, 2010). Thus, the objective of this study was to present two areas widely affected by shallow landslides in Serra do Mar where the SHALSTAB model was applied to understand the process and to predict unstable areas in hydrographic basins of distinct dimensions.



Figure 3 (a) Generalized landslides in Serra do Mar near the Copebrás Basin. Source: Institute for Technological Research of São Paulo and (b) landslide in the Bom Brinquedo Basin. Source: personal archives.

3.2 Topographic Data

To evaluate the landslide susceptibility, simulated scenarios were created using data available from each area. For the Copebrás Basin, a 5 m resolution Digital Terrain Model (DTM) was used from a topographic contour map at a 1:10,000 scale.

For the Bom Brinquedo Basin, the 1 m resolution DTM was obtained from an airborne LiDAR system using an OPTECH 2050 device. Raw data from LiDAR were processed in ArcGIS Desktop version 10.3 (<http://desktop.arcgis.com/en/arcmap/10.3/get-started/quick-start-guides/arcgis-desktop-quick-start-guide.htm>). First the LiDAR data was filtered to include only data corresponding to the terrain using the *LAS Dataset* toolbox, subsequently it was applied the Natural Neighbor interpolator to

generate a raster surface. While these settings were appropriate to generate the DTM, limitations were identified caused by the data point density corresponding to terrain and, consequently, the interpolation of these points in a continuous surface. These limitations tend to directly affect the grid quality and, thus, the spatial resolution of the cells. These limitations are discussed in the literature for quite some time, e.g., Cowen *et al.* (2000), who evaluated the effects of forest canopy density on the number of points corresponding to terrain, estimating that between 10% and 40% of the laser pulses will reach the terrain surface in an area of 80% and 90% of forest coverage.

3.3 Geotechnical Data

To generate susceptibility scenarios for both basins, field data collected in other studies were used. For the Copebrás Basin, geotechnical data by WOLLE and CARVALHO (1989) were used, who collected and analyzed field data near one of the scars (Table 1). This was one of the main *in situ* geotechnical and hydrological surveys that aimed to understand infiltration of pluvial waters in non-saturated soils and its effect on triggering shallow translational landslides by the elimination of suction pressure. In this study, two pilot areas in Serra do Mar located on steep ($>30^\circ$), linear slopes were selected, one of which is near the Copebrás Basin.

Table 1 Topographic and geotechnical data used in both basins.

Parameters [unit]; Basin	Copebrás	Bom Brinquedo
DTM	topographic map (1:10,000 scale)	LiDAR
Soil cohesion (c) [Pa]	1000	0
Internal angle of friction (Φ) [$^\circ$]	34	31
Total unit weight of soil (ρ_s) [g/cm^3]	1.7	2.6
Soil maximum thickness (z) [m]	3.0	1.0

For the Bom Brinquedo Basin, detailed *in situ* geotechnical data were obtained by Lopes (2013) for soil physical properties (angle of friction, cohesion, natural relative specific weight and saturated relative specific weight) to correlate soil

thickness and the water table level within unstable areas of the slopes.

3.4 Validation of the Susceptibility Maps

To validate the susceptibility maps, two indexes were used based on scar maps of landslides that occurred in 1985 in the Copebrás Basin and in 2011 in the Bom Brinquedo Basin: scar concentration (SC), defined as the ratio between the number of cells from each category affected by scars and the total cells affected in the basin; and landslide potential (LP), defined as the ratio between the number of cells from each category affected by scars and the total number of cells from the corresponding category.

The Copebrás Basin scar map was generated from an aero-photogrammetric survey (color diapositive infrared films) performed by the National Institute of Spatial Research in August 1985 at a 1:25,000 scale. Mapping was based on a visual analysis using the absence of vegetation and the slope position as the primary criteria. Slope position was defined from other studies performed in the Serra do Mar in São Paulo State, showing that ruptures of shallow translational landslides occur in the upper third portion of the scar.

The scar map for the Bom Brinquedo Basin was obtained by Martins *et al.* (2017a) by evaluating previous studies and producing a new map based on the terrain morphology characteristics, such as slope inclination and curvature associated with the contribution of the basin area.

4. Results and Discussion

4.1 Copebrás Basin

Class frequency (F) showed that 30% to 40% of the basin area was classified as unconditionally unstable (**Figures 4 and 5**). The area corresponding to the other categories decreased dramatically, remaining fairly constant until the class $\log(Q/T) > -2.2$. The unconditionally stable category occupied less than 7%.

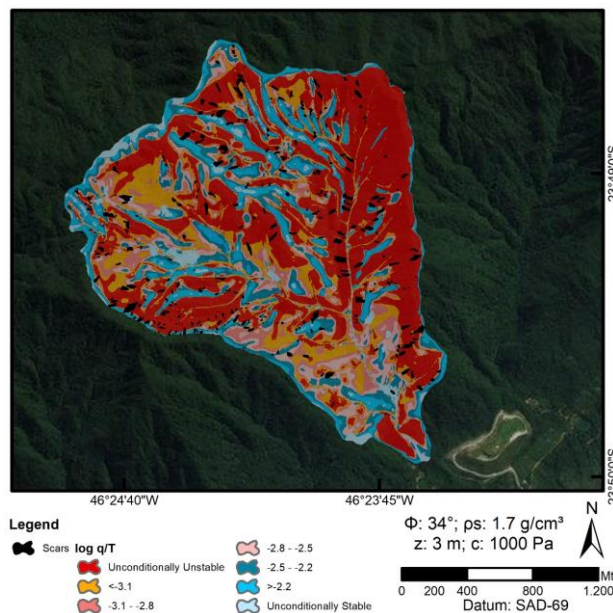


Figure 4 Copebrás Basin susceptibility map.

The evaluation of SC showed that the unconditionally unstable category characterized approximately 66% of the scars. However, considering the cumulative percentages of this index in each class, 76% of the landslides were in the $\log(Q/T) < -3.1$ category, 82% in the $\log(Q/T) < -2.8$ category, and 89% in the $\log(Q/T) < -2.5$ category. These results are similar to those reported by Montgomery and Dietrich (1994) and Dietrich *et al.* (1998) in studies in the Western United States, for which 83% to 100% of the scars were characterized by $\log(Q/T) < -2.5$. Slightly lower cumulative percentages were obtained by Dietrich *et al.* (1998), who identified that only 54% of the landslides correspond to $\log(Q/T) < -3.1$, 68% correspond to $\log(Q/T) < -2.8$ and 90% correspond to $\log(Q/T) < -2.5$.

Such variability in scar concentrations, considering the cumulative percentages and the limits of $\log(Q/T)$, is a function of the quality and resolution of the DTM grids. According to these authors, to obtain more than 60% of the scars in a 30 m² grid, a $\log(Q/T) < -2.5$ limit is needed. For a 10 m² resolution grid, a $\log(Q/T) < -2.8$ limit may be more appropriate and for high resolution DTM, the limit can be $\log(Q/T) < -3.1$.

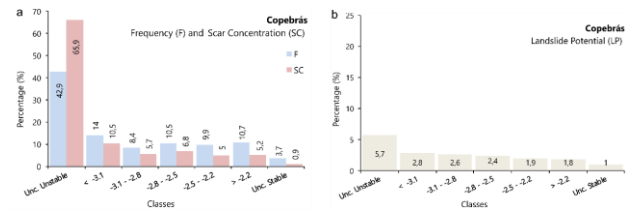


Figure 5 Susceptibility class distribution (F), scar concentration (SC) and landslide potential (LP).

The LP analysis reveals a better agreement between the SHALSTAB predictions and the scar map. The highest LP indexes were recorded in the unconditionally unstable category, decreasing dramatically in the $\log(Q/T) < -3.1$ category and then gradually until the $\log(Q/T) > -2.2$ category. The lowest LP values were identified in the unconditionally stable category.

4.2 Bom Brinquedo Basin

In contrast to the previous basin, the highest frequency values were obtained for the two most stable categories (unconditionally stable and $\log(Q/T) < -2.2$), which together represented almost 80%, followed by the unconditionally unstable category, which corresponded to approximately 20% (Figures 6 and 7).

The four intermediate classes had very low values that altogether accounted for less than 1%, and two categories had null values ($\log(Q/T) -2.8$ to -2.5 and -2.5 to -2.2). However, in the SC index, the unconditionally unstable category had the highest value, nearly 45% of the scars, and the two most stable categories together accounted for 55% of the scars.

Notably, scars occurred in all areas defined as unconditionally unstable, which is considered a positive model output. Although there are areas belonging to this category that were not involved in the 2011 event, they can still be considered susceptible to slope failure given that the model does not provide a timeframe for the occurrence of landslides. Thus, it is not feasible to interpret an overestimation of the model in that regard.

Intermediate categories also displayed null values or values lower than 0.12% for this index, which was reflected in the LP and, in turn, had the

highest values for the unconditionally unstable (24.80%) and the $\log q/T < -3.1$ (20%) categories. The two most stable classes displayed values similar to the previous scenarios, together accounting for nearly 16% of the basin area. The classes $\log q/T < -3.1$ and -3.1 to -2.8 had high values for this index despite being less relevant when the frequency and scar concentration results were analyzed.

The distribution of values and particularly the null values in some of the categories are similar to results previously reported by (Martins *et al.*, 2017a), including null values for the same categories. These authors analyzed the effects of data in the generation of the Digital Terrain Model, comparing models generated from contours and from LiDAR, using the SHALSTAB in a basin adjacent to the Bom Brinquedo Basin.

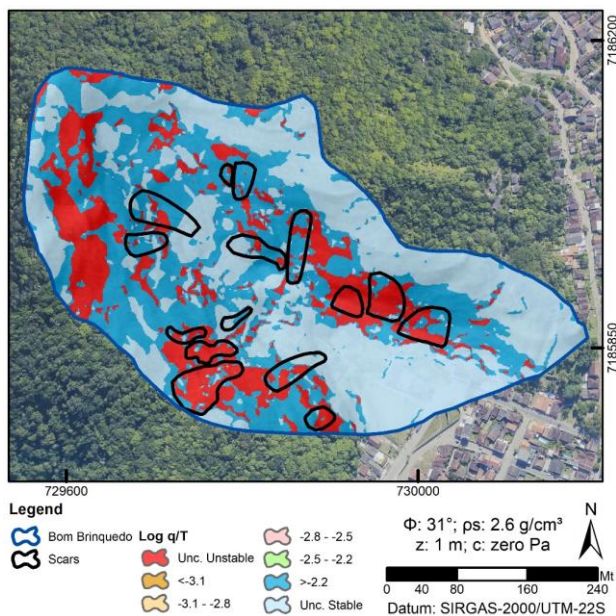


Figure 6 Bom Brinquedo Basin susceptibility map.

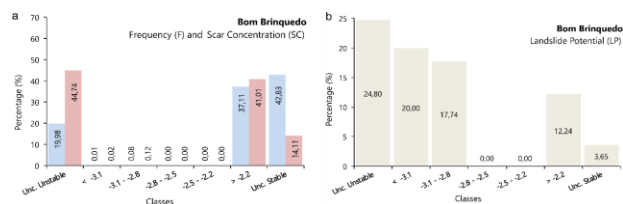


Figure 7 Susceptibility category distribution (F), scar concentration (SC) and landslide potential (LP).

In the context of Serra do Mar, it is important to highlight that some authors argue that landslides can occur when permeable materials are in direct contact with less permeable materials in the altered mantle, which favors the rapid development of positive pore pressure. Another rupture mechanism is associated with the loss of suction and decreased apparent cohesion due to the continuous increase of deep hydraulic conductivity. Such an increase may be due to the presence of fracture systems in the altered mantle, which allow the drainage of sub-superficial water and prevent total soil saturation (WOLLE and CARVALHO, 1989; Kanji *et al.*, 2003; Gerscovich *et al.*, 2006; Lacerda, 2007). Our results showing that these areas are unconditionally unstable mean that they should fail when dry – this means that root strength (which is not considered in the model as formulated here) is critically important for stabilizing slopes.

5. Conclusions

The effect of these processes in developing countries is associated in most cases with human loss in highly occupied urban areas, which can be attributed to the absence of preventive measures and the intense landscape alterations. Therefore, the SHALSTAB model can be combined with land use maps can contribute on assessment of vulnerability and risk. However, even with the great potential for public management, SHALSTAB, as well as other mathematical predictive models, are rarely used for this purpose in Brazil. The LP analysis revealed the agreement between the SHALSTAB predictions and the scar map, especially because the highest LP indexes were recorded in the unconditionally unstable category, decreasing until the $\log (Q/T) > 2.8$ category. The model performance tested in Brazil comparably to performance in Western North America, indicate it as viable tool for identifying potentially hazardous zones in the tropical region.

Acknowledgements

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Comparative analysis of large scale scenario-based landslides hazard zonation maps. A case study in Iasi City, Romania

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ABSTRACT

Large-scale landslides hazard analysis is based, among other methods, on the numerical evaluation of the safety factor using physical and mechanical parameters measured in the field. The safety factor is determined as the ratio between the forces acting in the favor of sliding phenomenon and the resistance of the earthen massive. The main purpose of the paper is to create two bi-dimensional models of landslides hazard assessment based on the estimation of the stability factor, under different degrees of soil saturation and considering different scenarios of seismic acceleration. Slope stability analysis allows the simultaneity of two exceptional loads such as saturation and earthquake. The first model follows the methodology provided by the national law. In this case, the safety factor is determined by applying limit equilibrium methods using specific geotechnical engineering software. The second model aims to create a deterministic model for safety factor assessment implemented in a GIS system. This one is based on the infinite slope model. The secondary objectives of the paper are: providing theoretical principles, attaining the comparative analysis between the methodologies mentioned above, identifying the critical points of the created models and the reciprocal validation of the results. The study area is a hilly area located in the North-Western part of the Iasi City, Romania. The geotechnical parameters were obtained from the laboratory tests carried out on samples taken from 22 boreholes. The geomorphological parameters resulted from the high quality digital elevation model with 1m resolution. The final maps representing the spatial distribution of the safety factor values are reclassified using a common scale. Similarity analysis of the results indicates a good mutual validation.

KEYWORDS

Landslides; hazard maps; safety factor; limit equilibriaum method; infinite slope model; GIS

1. Introduction

The natural phenomenon of "landsliding" represents the movement of earth mass, rock or shallow debris, along a slope, under the direct influence of gravity (Cruden, 1991; Cruden and Varnes, 1996). The most common factors that act as triggers for landslides are prolonged intense rainfalls, rapid snow melting, earthquake, freeze-and-thaw weathering, floods and anthropogenic activities (a frequent and current cause, but acting mainly as a preparing factor) (Wieczorek, 1996; Crosta and Frattini 2008).

Landslides represent a natural hazard, which in many areas of the world causes economic damage, loss of life and in certain situations proving to be more destructive than other natural hazards (McConnell and Brock, 1904; Heim, 1932; Crozier, 2005; Mandal and Maiti, 2014).

Long term demographic analysis, over a range of about 160 years, shows that Europe's population has grown from about 200 million people, registered in the 1850s to 739 million registered in 2017 (Cameron, 1993; European Statistical System-EES). In the same period, according to the Romanian National Institute of Statistics, the population of Romania has increased from 4 million (in 1850) to 19 million (in 2017), with the peak of 23 million reached in 1990. The human number growing is inevitably associated with intensive, sometimes excessive, local land exploitation, new housing development and construction of roads, railways and other specific works. The population growth, the expansion of settlements and the mandatory ways of communication have invariably led to landslides triggering and have significantly increased the impact of landslide hazards. Consequently, managing this type of hazard has become a continuing concern of Europe's environmental policies and also of Romania.

Unlike other natural hazards (e.g. floods), systematic investments in structural measures to reduce the landslides risk in very large areas cannot be practically done. For example, to limit floods in hydrographical basin can be implemented structural measures such as flood control dams or long lengths levees. These are hydrotechnical structures which can prove costly, but they have an effect that

controls the entire basin. Constructive measures used to combat and stabilize landslides have a local effect, often reducing the risk only on restricted areas, frequently a single slope or a part of the slope. It is therefore extremely difficult, economically speaking, to eliminate the landslides risk in very large areas (such as basins). As a consequence, the solution seems to be the implementation of prediction and prevention systems, as well as land-use planning regulations aimed to avoid costly combating projects. This solution is based on extensive studies for landslides hazard assessments and it is a challenge for scientists and decision-makers and even for concerned citizens.

The hazard cartography should not be perceived as a simple editing process, or as a set of computer tools designed to display information about landslides occurrence, but represents a whole set of theories and methods, patterns and techniques for obtaining, analyzing and generating relevant information intended to the final users.

Large-scale landslides hazard analysis (also called local scale analysis) is achieved in most cases using quantitative methods based on the creation of physical models. These types of hazard assessment involve mathematical modeling of the slope failure mechanism.

The scientific literature shows that the main quantitative methods used at large and very large scale for landslides hazard assessment are the finite element methods (3D), the limit equilibrium (2D) methods and the deterministic methods implemented in geographic information system (2D) (Corominas *et al.*, 2014). The paper follows the application into particular cases of the last two types of methods.

These models have a higher predictive capacity than heuristic and statistical models because they use measurable parameters. The parameters used in the stability models building (geotechnical parameters, morphological parameters, seismic parameters and hydrogeological parameters) are being considered state variables that have a unique value at a given moment in time and space.

The main indicator that evaluates the steady state of the slope is the safety factor whose physical significance is expressed by comparing the stress states along the potential failure surface as a relation (ratio) between actions and soil resistances. The safety factor can vary between the critical value represented by the minimum value that marks the stable equilibrium limit and large and very large values, theoretically infinite values, when the slope is stable (Manea, 2009).

2. Natural and anthropic conditions influencing landslide hazard in the study area

Regional-scale landslides hazard analysis reveals that Iasi City, located in the North-Eastern part of Romania, is an area with medium-high and high potential for landslides occurrence (Coman and Manea, 2017).

The natural landscape of Iasi City is represented by wide interfluvies and hilly areas partly affected by erosions and landslides (Adomnitei, 2010). Iasi City is an active morpho-dynamic area and, sometimes, is affected by landslides with high magnitude and which generates significant damage. Here are presented only few examples (Fig. 1.a.): the Eastern side of the Copou Hill, the segment between Sararie and Ticau, the right bank of the Cacaia River, the Bucium Hill, the Galata and Niculina districts (Adomnitei, 2010).

In the last decades, extensive work has been done to reduce the landslides risk; nevertheless the potential for instability is still high in the Iasi area (Adomnitei, 2010).

3. Site characterization

The study area is represented by a hilly area with altitudes between 50m and 100m (Fig. 1.b.) a.s.l., located in the North-Western part of Iasi City, on the left bank of the Bahlui River. The natural terrain slopes vary between 0° and 43° (Fig. 1.c.).

The regional geological map (scale 1:20 000) indicates the presence of the Bessarabian (bs) deposits represented by clays, silty clays, sands and sandy clays. The Bessarabian is known as the oldest deposits in this region and with the widest spread.

The geotechnical characterization of the site resulted from the processing of geotechnical parameters determined in laboratory tests, on samples taken from the 22 boreholes (Figure 2) with 10m maximum depths. The groundwater level was intercepted in depths ranging from 5m to 7m.

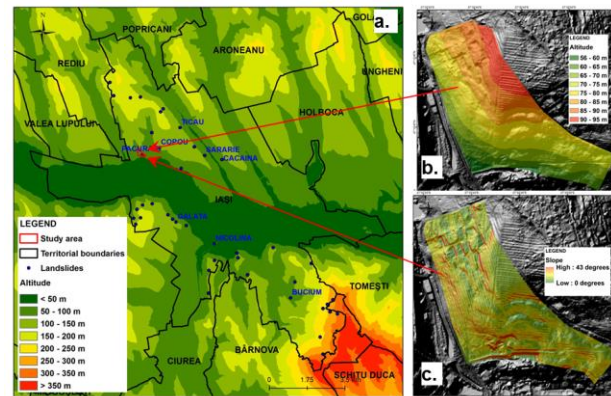


Figure 1 a. Altitude map and historical landslides – Iasi City; b. Altitude map – Study area; c. Slope map – Study area

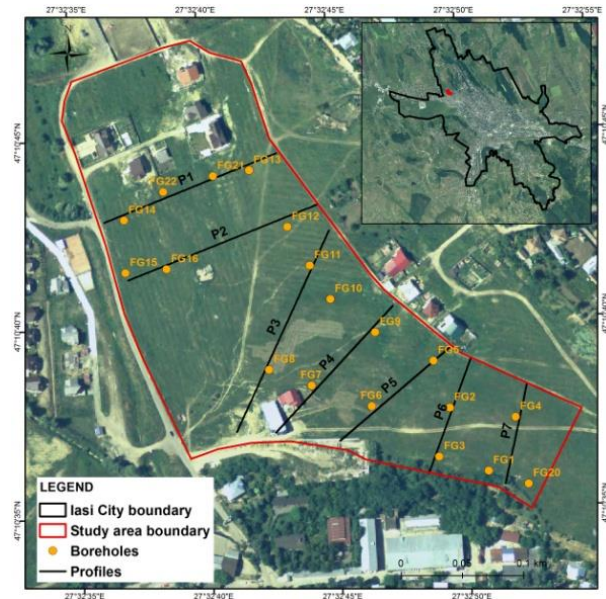


Figure 2 Study area – boreholes location

The general stratification of the earthen massive indicates the overlay of the following layers: under the topsoil layer distinguish a succession of yellow clays, gray clays and brown coal clays, with a lot of sand fractions, which represents a very favorable setting for landslides occurrence. The

average values of geotechnical parameters that characterize the site are 20 kN/m³ for soil unit weight, 65 kPa for cohesion and 15° for internal frictional angle.

4. Data and methodology

4.1. Input data

The database needed to build the two models proposed by this paper consists of morphological data, geotechnical data and seismic data.

The morphological data resulted from the digital elevation model (DEM) made available for this study by the Prut - Barlad Water Basin Administration. The DEM has a pixel resolution of 1 m obtained from LIDAR (Light Detection and Ranging) scanning. The ground physical and mechanical characteristics resulted in laboratory tests on samples extracted from 22 geotechnical boreholes. The ground tests were conducted in the laboratory of Department of Geotechnical and Foundation Engineering from Technical University of Civil Engineering, Bucharest. The seismic activity of the study area is characterized by a peak ground acceleration value of 0.25g for earthquakes with the mean recurrence interval 225 years and the control period 0.7 sec (according to the Romanian Seismic Design Code for Buildings - Part I - indicative P 100-1/2013).

The model created approaching the national methodology does not require the development of thematic maps in advance, because it is based on the direct calculation of stability on the lithological profiles.

The infinite slope model requires the construction of a series of thematic maps for all the parameters involved in the evaluation of the safety factor. The geomorphological parameters maps (slope map and the trigonometric functions of the slope) derived from digital elevation model using GIS tools. The geotechnical parameters maps (unit weight map, cohesion map, internal frictional angle map) were built interpolating the 22 points of prospects (measured data).

4.2. The methodology provided by national legislation

According to the Romanian "Methodological norms regarding the elaboration and content of natural landslides hazards maps" approved by Government Decision no. 447/2003, the construction of detailed maps (large-scale maps) is based on the results obtained from the slope stability numerical modeling using physical and mechanical soil parameters determined in the laboratory tests.

The methodology consists in determining the safety factor on characteristic profiles for an arbitrary number of slip surfaces (usually non-circular slip surfaces) and drawing the safety factor variation diagram along the slope. This model applies Janbu method which is one of the various limit equilibrium method commonly used for slope stability analysis (Janbu 1968, Abramson 2002). This model uses GEOSTRU software for safety factor calculation. The safety factor assessment must be done on an adequate number of characteristic profiles, traced over the entire length and along the slope concerned. In this paper, 7 profiles are analyzed (Fig. 2).

For a high accuracy results, the methodology recommends for boreholes spatial distribution a field layout in maximum distances of 300 ÷ 500 m. For the stability assessment were used the calculation values of the geotechnical parameters, established according to the Romanian "Normative regarding the determination of the characteristic and calculation values of the geotechnical parameters - indicative NP 122/2010".

The final hazard maps are drawn as an envelope of the minimum safety factor values ($F_{s,min}$) from the safety factor diagram and reclassified according to the intervals established as the inverse of the average hazard coefficient. The table below shows the classification ranges (Table 1).

The landslides hazard map building main steps are presented below, in the following logic scheme.

4.3. The infinite slope model

The infinite slope stability model is a high degree simplified model, which oversees the destabilizing components of gravity in relation with the resistance

components given by cohesion and friction along a failure plane, considered parallel to the natural ground surface (Fig. 4). The model accounts for different trigger factors such as the transient groundwater response of the slopes and/or the effect of earthquake excitation.

Table 1 Classification ranges of safety factor

Zero	Low	Medium	Medium - High	High	Very High
Average hazard coefficient (K _m)					
< 0,30	0,31 ÷ 0,40	0,41 ÷ 0,50	0,51 ÷ 0,60	0,61 ÷ 0,80	0,81 ÷ 1
Safety factor (F _s)					
> 3,33	3,33 ÷ 2,5	2,5 ÷ 2	2 ÷ 1,66	1,66 ÷ 1,25	1,25 ÷ 1

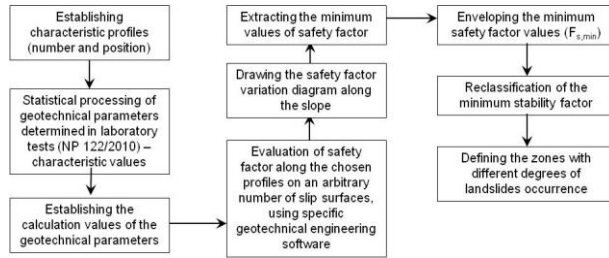


Figure 3 Landslides hazard map main steps – National methodology

The infinite slope model calculates the safety factor according to Equation 1 (Brunsden and Prior, 1984).

$$F_s = \frac{c' + \left(\gamma - \frac{z}{z_w} \gamma_w \right) z \cos^2 \beta \tan \phi'}{\gamma z \sin \beta \cos \beta} \quad (1)$$

Where:

- c' effective cohesion (Pa);
- ϕ' effective internal friction angle (°);
- γ unit weight of soil (N/m³);
- γ_w unit weight of water (N/m³);
- z depth of slip surface (m);
- z_w groundwater table height above slip surface (m);
- β terrain slope (°).

Under seismic loads the mathematical formula proposed for safety factor evaluation is given by Equation 2 (Brunsden and Prior, 1984).

$$F_s = \frac{c' + (z\gamma \cos^2 \beta - z\rho\alpha \sin \beta \cos \beta - z_w\gamma_w \cos^2 \beta) \tan \phi'}{\gamma z \sin \beta \cos \beta + z\rho\alpha \cos^2 \beta} \quad (2)$$

Where:

- ρ bulk density (kg/m³);
- α peak ground acceleration (m/s²).

This model builds safety factor maps considering the following assumptions:

- the geotechnical (physical-mechanical soil parameters) and morphological parameters are the ones that determine the construction of the model and they are most often measurable;
- it can be applied on relatively limited areas when the geological and geotechnical conditions can be considered relatively homogeneous;
- it is intended to be used for shallow landslides (less than a few meters in depth), generally for translational sliding (not for deep-seated landslides types, rock falls, debris flows etc.)
- the two-dimensional model divides the analysis range into discrete elements of the pixels size;
- the effect of the neighboring pixels (the edge effects) is ignored.

5. Results

The large - scale landslides hazard models were designed considering four scenarios: completely dry conditions, saturated conditions, completely dry conditions and seismic loads, saturated conditions and seismic loads. The following maps will present each of the four scenarios for both models.

5.1. Scenario 1 – Spatial distribution map of the safety factor considering dry conditions

The assessment of the safety factor using the national methodology is done for 7 lithological profiles. The results of the characteristic profile P1 are presented as examples. The safety factor assessment for the other 6 profiles is made following the similar procedure of P1, according to the steps presented in Fig. 3.

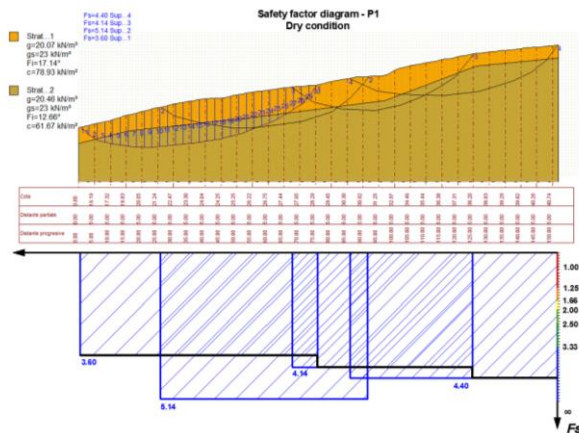


Figure 4 Safety factor diagram, P1 – Dry conditions

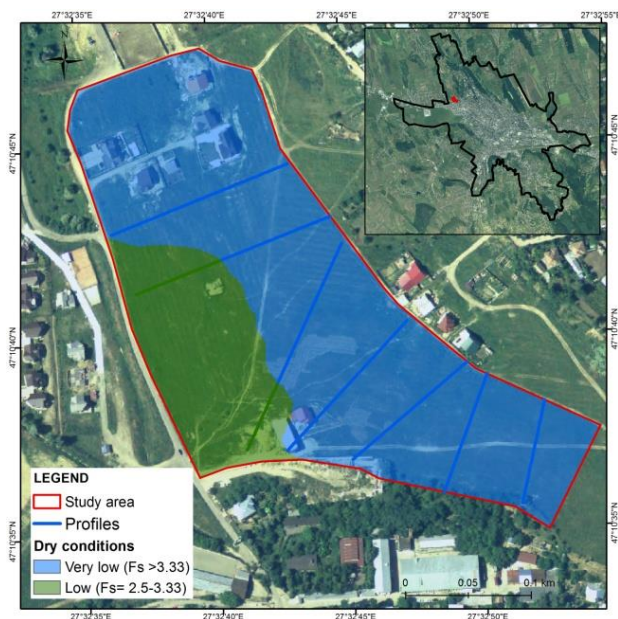


Figure 5 Landslides hazard map, dry conditions - National methodology

Stability factor values (which were greater than 3 for all the 7 profiles) indicate low and very low potential for landslides occurrence.

In the infinite slope model, the safety factor is assessed on the assumption that the soil is completely dry, so the groundwater action is equivalent to 0. The term z_w from Equation 1 is equal to 0. For each term of Equation 1 parametric maps are constructed and overlapped in GIS systems according to the mathematical formulas provided. The final hazard maps are obtained using

the same reclassification system adopted by the previous method.

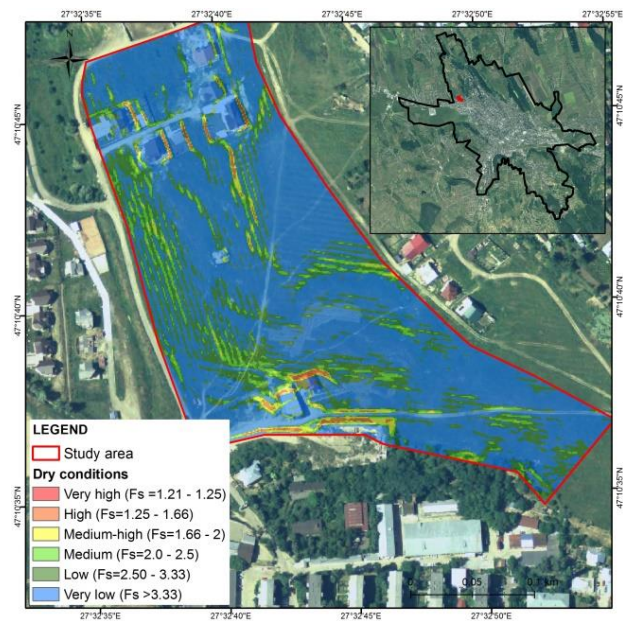


Figure 6 Landslides hazard map, dry conditions – Infinite slope model

This scenario is the most optimistic situation. The study area proves to be generally stable for both models with relatively minor unstable areas for the infinite slope model.

5.2. Scenario 2 – Spatial distribution map of the safety factor considering saturated conditions

The ground saturation conditions led to a decrease of the stability factor to 2,8 (the minimum value). This translates into a slight increase in the potential of instability, but it still remains low.

The second scenario assumes that the terrain is completely saturated. In this case, the infinite slope model considers the term z_w equal to the term z from Equation 1. It is noticed that the presence of groundwater produces a slight increase of instability potential zones compared to the previous scenario. Comparatively with the previous model results, for the same scenario, the infinite slope model indicates increasing areas with high and very high instability potential. This may be a consequence of the high degree of simplification of failure mechanism. The

infinite slope model overestimates the safety factor. The minimum safety factor decreases to 0.97.

Also, the very good resolution of the digital elevation model is important. If the work would not have been done with a high precision model, it is possible that these high-potential areas do not appear or be very small.

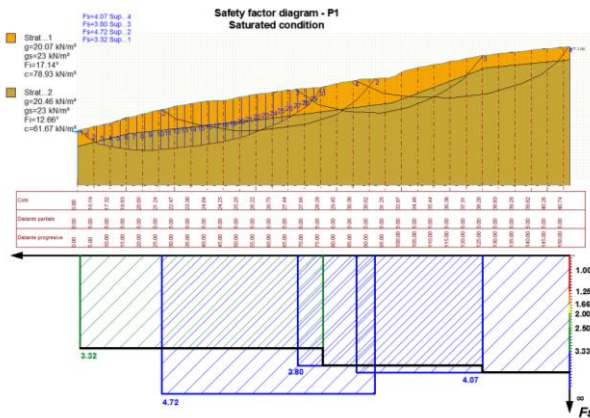


Figure 7 Safety factor diagram, P1 – Saturated conditions

5.3. Scenario 3 – Spatial distribution map of the stability factor considering dry conditions and seismic action

The third scenario studies the influence of the seismic activity on the stability of slopes. The occurrence of geodynamic loads shows a significant decrease of the safety factor. The safety factor diagrams for all the 7 calculation profiles indicate minimum values of 1.29.

For the third scenario, dry ground conditions and seismic loads are considered. For each term of Equation 2 parametric maps are created and overlapped in GIS systems according to the mathematical formulas provided in the previous chapter. The seismic actions correspond to the peak value of the seismic acceleration that characterizes the site. This scenario proves more detrimental than the saturated scenario under static conditions, for national methodology based model and also for infinite slope model. The instability areas have increased considerably.

Applying the infinite slope model, in this scenario, it is noted that the minimum value decreases to 0.91, but there is also noticed a

considerable extension of the areas with high potential for sliding.

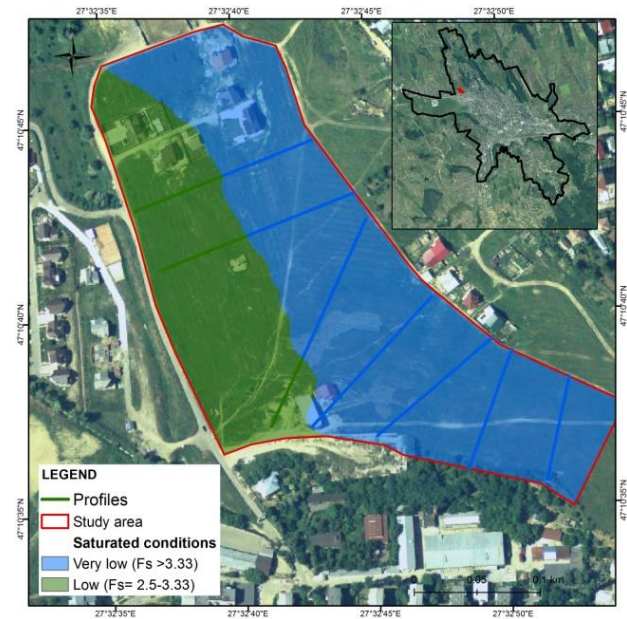


Figure 8 Landslides hazard map, saturated conditions - National methodology

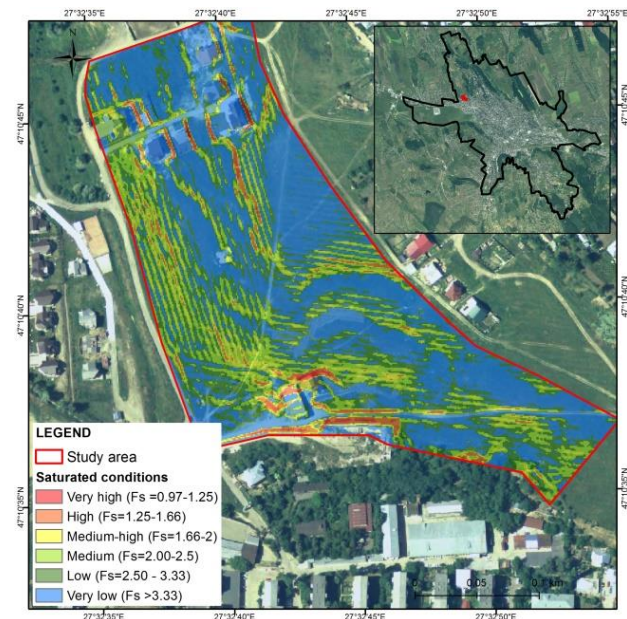


Figure 9 Landslides hazard map, saturated conditions – Infinite slope model

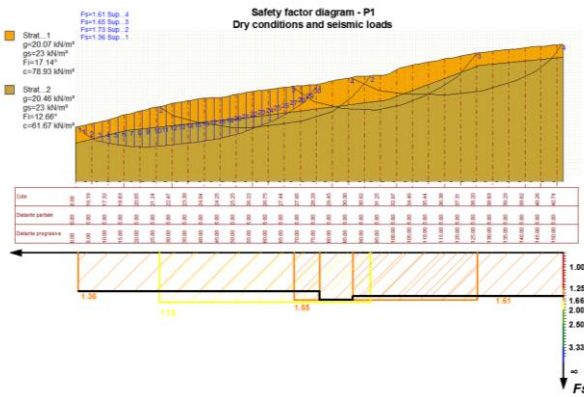


Figure 10 Safety factor diagram, P1 – Dry conditions and seismic loads

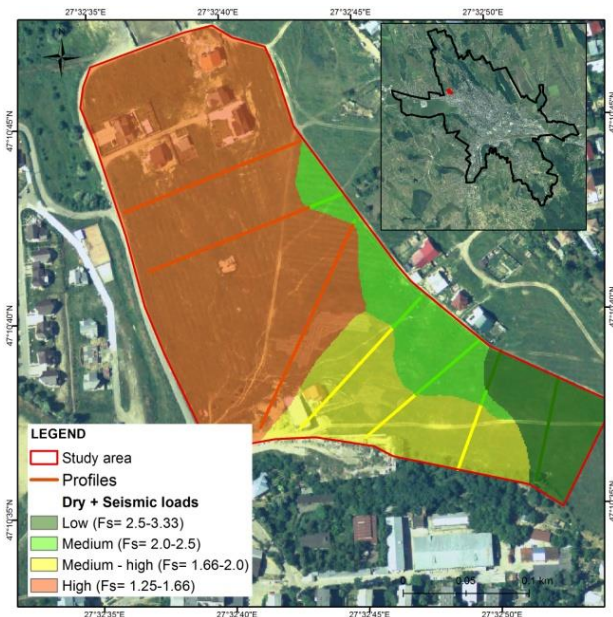


Figure 11 Landslides hazard map, dry conditions and seismic loads - National methodology

5.4. Scenario 4 – Spatial distribution map of the safety factor considering saturated conditions and seismic action

Unlike the design of structures, in the slope stability calculations, the simultaneity of two exceptional actions such as those considered in this scenario is accepted.

Applying the national methodology the results indicate a decrease in the stability factor values below the limit of 1,25 and this indicates the occurrence of areas with very high potential for

landslide occurrence. The most unfavorable slip surfaces have been identified along the P2 profile, for all the four scenarios.

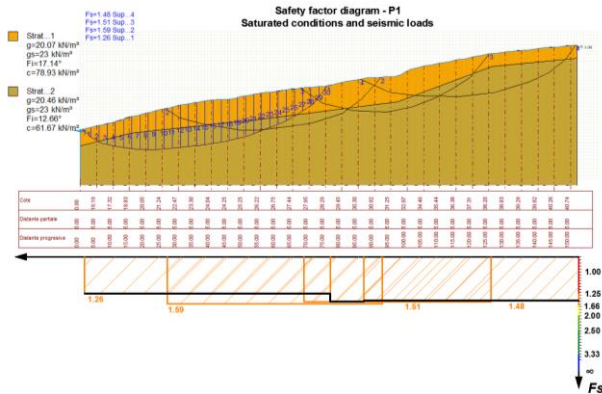


Figure 13 Safety factor diagram, P1 – Saturated conditions and seismic loads

For this scenario, the instability potential is generally large and very high.

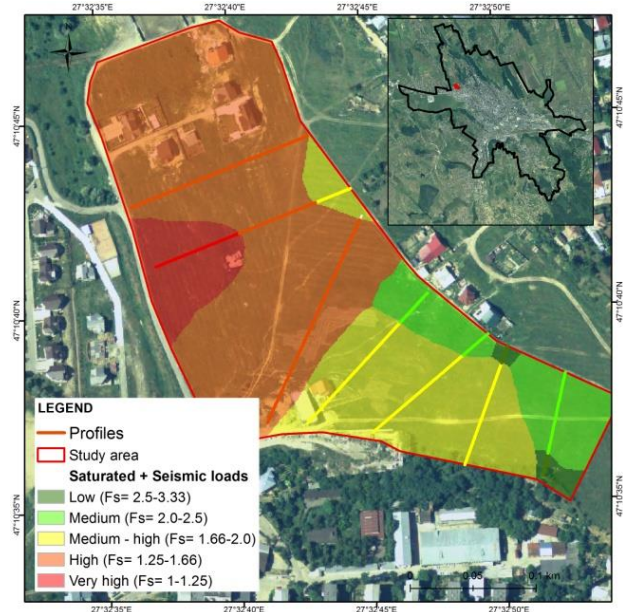


Figure 14 Landslides hazard map, saturated conditions and seismic loads -National methodology

The last of the four scenarios, approached also in the infinite slope model, considers that the soil is under saturated conditions and under seismic loads associated with the peak value of the seismic ground acceleration. In this case, the safety factor reaches the minimum value of 0.75 and the areas

with very high instability potential signal an important extension in the study area.

6. Discussions

The similarity analysis indicates a good mutual validation of the two deterministic models created for the large scales landslide hazard assessment. The four scenarios considered are extreme situation and may not occur in region such as Iasi City but give the most optimistic and the most pessimistic situations.

The hazard assessment methods used to conceive these mathematical models, one with respect to each other, provide a number of critical points.

The model created using national methodology calculates the safety factor using specific geotechnical methods and engineering software, while the infinite slope stability model provides a high degree simplified model of slope failure mechanism applied in geographic systems. Multi-layered and non-homogeneous layer evaluations are allowed by the national methodology while the infinite slope stability model is suitable for stratifications in which geological and geotechnical conditions can be considered relatively homogeneous.

The analysis range is meshed into slices (vertical discretization) by the national methodology while the analysis range is meshed into pixels size elements (1m horizontal discretization) by the infinite slope model. It can be noticed that the infinite slope model achieves a finer safety factor spatial distribution. The accuracy of the results obtained using the national methodology is closely related to the density of the geotechnical boreholes while the infinite slope model is directly dependent on the digital terrain model resolution.

The execution of a large number of geotechnical boreholes but also obtaining a digital terrain model with very good resolution can sometimes prove economically inaccessible. This is one more reason which justifies why these analyzes are suitable for local scales.

Observing these cumulative critical points, it can be concluded that from a scientific point of view, the national methodology has important

advantages to the detriment of the infinite slope model.

The landslides hazard maps generates relevant information on landslides and provides certain net benefits, knowing that the risk will be properly controlled, kept under review, and further reduced as and when possible. The ultimate goal of large scale hazard maps is to be introduced and taken into account in development plans, so the assessing of landslides hazard and risk levels is a scientific and technical process as much as a political and economical decision-making process.

The input data underlying such analyzes may prove costly in both cases, requiring high precision. Although it achieves an overstatement of the safety factor, the infinite slope model proves more accessible. Consequently, the end users may feel attracted by the approach of the infinite slope model that can be implemented easily in geographic information systems. Obtaining geotechnical data, required by the national methodology, is a long process through field sampling, laboratory testing and then data processing, costly as the number of boreholes increases.

7. Conclusions

The landslides hazard assessment models, similar to those created in this paper, have higher prediction capability than other qualitative or quantitative methods, for example statistical methods, because it evaluates the potential slip following a calculation based on the parameters measured in the field, while the other quantitative methods are based on historical data (landslides inventories).

The landslides hazard assessment based on the stability factor is preferably to be used for local analyzes. It can hardly be applied at national scales due to the variability of geotechnical data and the difficulty of building a national geotechnical database with high precision.

The safety factor maps keep the purpose and the quality of the hazard maps and will not serve the constructions design activities but can serve for prediction and prevention plans.

All the conclusions set out in the paper are the results on the landslides hazard assessments within

the Iasi City, located in the north-west of Romania. However, the selected examples and the lessons learned are general and applicable in other areas in Romania or even in other countries facing the same situations.

Acknowledgments

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Morphometric analysis of river subwatersheds using geographic information system and principal component analysis, northeast of Algeria

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ABSTRACT

In the present paper an attempt is made to study the morphometric characteristics of five watersheds which are part of Seybouse and Coastal basin of Constantine located in northeast of Algeria. The study focuses on evaluating the effect of morphometric parameters on land degradation. The Geographical Information Systems which represent efficient tools in determination of drainage basin morphometric properties and principal component analysis are applied to ten geomorphic parameters on twenty subwatersheds, to group the parameters under different components based on significant correlations. Some morphometric parameters are computed and analyzed such as basin area, drainage density, stream frequency, form factor, orographic coefficient, hypsometric integral, and lithology index, basin slope, average overland flow distance, basin relief ratio. Outcomes of the matrix of correlation and principal component analysis of ten geomorphic parameters clearly depict that fifty percent of the variables are strongly correlated with the components like basin area, drainage density, stream frequency, orographic coefficient and relief ratio. It has been found that Guis sub-basin, three sub-basins of the Saf Saf watershed and all the sub-basins of the Mellah watershed are subjected to high land degradation, thus, creating an urgent need for applying soil and water conservation measures.

KEYWORDS

Subwatershed; GIS; morphometric analysis; correlation matrix; principal component analysis; Algeria

1. Introduction

Morphometry is the measurement and mathematical analysis of various characteristics of a drainage basin that can be quantitatively described (Pidwirny, 2006). Morphometric descriptors, which include classes of linear, areal, and relief aspects, represent relatively simple approaches to describe basin processes and to compare basin characteristics (Mesa, 2006) and enable an enhanced understanding of the geological and geomorphic history of a drainage basin (Strahler, 1964).

The quantitative analysis of morphometric parameters is of great importance in river basin evaluation, watershed prioritization for soil and water conservation, and natural resources management. Geology, relief, and climate are the key determinants of running water ecosystems functioning at the basin scale (Frissel et al., 1986). In addition, the hydrological response of a river basin can be interrelated with the physiographic characteristics of the drainage basin, such as size, shape, slope, drainage density and size, and length of the streams, etc. (Chorley, 1969; Gregory and Walling, 1973).

A number of studies have utilized the technique of Geographical Information System and digital elevation models for assessing various terrain and morphometric parameters of the drainage basins as they provide a flexible environment and a powerful tool for statistical, comparative and analytical analyses for better understanding (Vijith et al., 2006; Fahren et al., 2017). In the present paper many morphometric data have been extracted using GIS environment (ArcGIS) from SRTM data.

The statistical method for reducing a large number of interrelated variables into a smaller number of dominant variables is called principal components analysis (Wuttichaikitcharoen et al., 2014). Synder (1962), Wong (1979) and Sharma et al. (2013a) have clearly shown the use of multiple regression analysis for establishment of hydrological prediction equations using morphometric parameters. Mishra and Satyanarayana (1988) have applied principal component analysis on ten geomorphic parameters at Damodar Valley

catchment and grouped the nine parameters into three significant components, like drainage, slope and shape. Singh et al. (2009) also applied principal component analysis to thirteen geomorphic parameters collected for sixteen subwatersheds of Chambel catchment of Rajasthan. Sharma et al., 2013b; Sharma et al., 2014a; Bilewu et al., 2015; Hajji et al. 2015; Fahren et al., 2017; Meshram and Sharma, 2017; Sunil and Mukhopadhyay, 2015 have used PCA for their works on geomorphic parameters for hydrological modeling, for redundancy of morphometric parameters and identifying the dominant descriptors which contribute to explain the watershed erosion.

The main objective of the study is to determine and analyse some morphometric characteristics and relate them to land degradation variability in various subhumid areas located in the eastern part of Algeria. The present study depicts the process to evaluate the various morphometric parameters by using prioritization of subwatersheds and multivariate statistical approach to the Seybouse basin (Bouhamdane, Ressoul, Mellah watersheds) and Coastal basins of Constantine (Kebir West and Saf Saf watersheds).

2. Study area

Watersheds of northern Algeria constitute a Mediterranean domain where different forms of erosion are highly distributed. Most Algerian wadis are developed in areas of young and rugged terrain with usually a very complex geological structure. In the Tell, the hillslopes formed in marly formations of Cretaceous or Tertiary clay layers favor the spatial extension of gullies and mass wastings (Kouriet al., 1997). The establishment of the hydrographic network of the basins of the Algerian Oriental Tell is made from a topography that existed in the Pliocene. At the end of the Pliocene, tectonic movements gave the Tell its mountainous volume (Marre, 1992). These movements are at the origin of the resumption of downcutting of the rivers which could incise deep valleys and gorges.

The northeastern part of Algeria's climate is a humid temperate climate. The Algerian basins are dominated by two climate regimes: coastal temperate climate and Tellian Atlas climate. This study is based on data from five watersheds representing different physico-climatic regions of northern Algeria (Figure 1). Selected basins have areas that extend from 103 to 1130 km² and receive average rainfall ranging between 550 mm and 900 mm. Considering the hydrologic conditions, it

appears that the Mellah, Saf Saf and Ressoul watersheds behave as a highly efficient runoff-generating unit, with annual runoff coefficients ranging between 22% and 27%. The stream flow response to rainfall becomes less pronounced when the runoff efficiency of Kebir West and Bouhamdane wadis is examined, where annual runoff coefficients are 12% and 20% respectively. The mean annual water discharges range between 0.93 m³/s in Ressoul Wadi to 3.25 m³/s in Mellah Wadi.

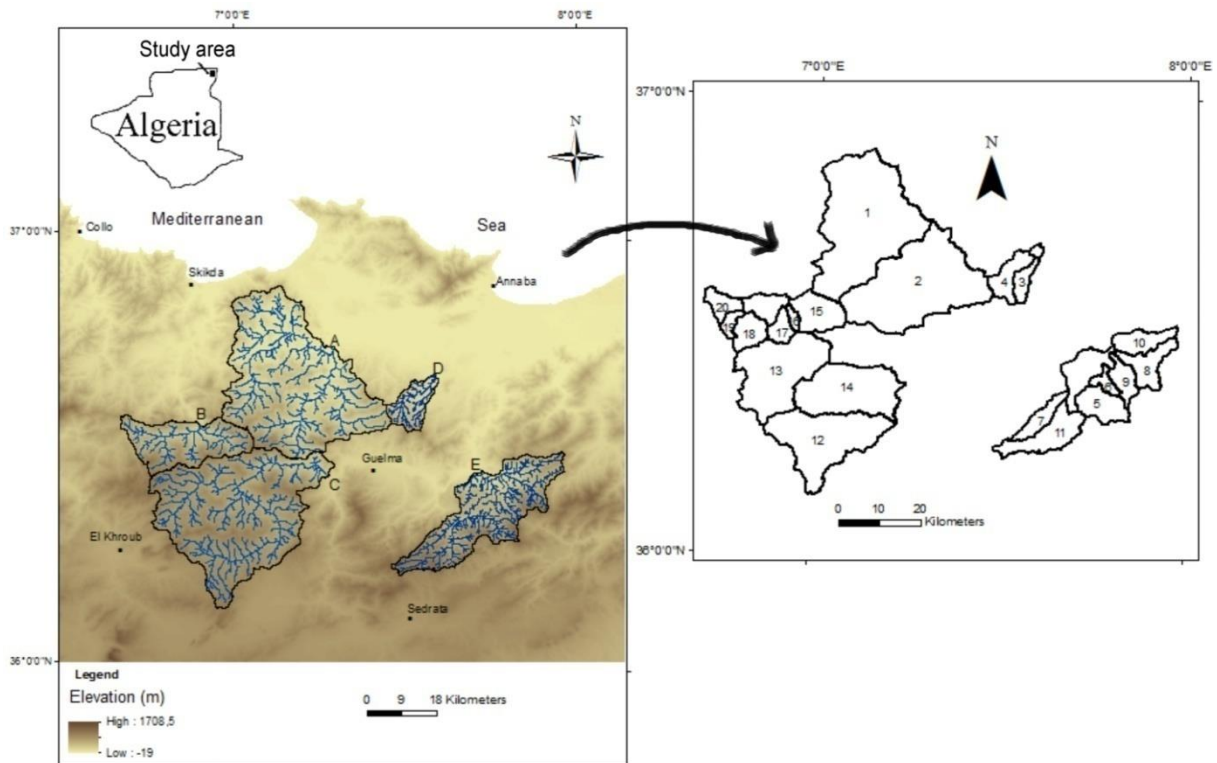


Figure 1 Location map of the study subwatersheds. Watersheds: A: KebirWest ;B: SafSaf;C: Bouhamdane; D: Ressoul; E: Mellah. Subwatersheds : 1: Emchekel; 2: el Hammam; 3: Guis; 4: Bouala; 5: Rirane; 6: Cheham; 7: Hammam; 8: Meza; 9: Aouassia; 10: Bouredine; 11: R'biba; 12: Zenati; 13: Sabath; 14: Bouhamdane; 15: Khemakhem; 16: M'taRhumel; 17: Khorfane; 18: Rararef; 19: Beni Brahim; 20: Bou Adjeb

The basins of the Constantine Coastal region and Seybouse are characterized by a considerable distribution of resistant rocks such as Oligocene sandstone and moderately to weak rocks such as Cretaceousmarly limestone, triassic formations, marl and clay of different ages. Aggressive flows were able to scar on erodible rocks by carrying huge amounts of suspended sediment in the wadis of Mellah, Saf Saf and Kebir West.

The evolution of the Algerian Oriental Tell is marked first of all by a rapid transgression. At the end of the Miocene, there is a gradual emergence of Tell. Due to the neotectonics (characterized by faults and thrust sheets at the end of the Miocene and during the Pliocene and Quaternary) the Algerian Oriental Tell acquired its mountainous volume (Marre, 1992). Also, the mountain character of the Tell is due to its humid and cool climate on the

summits and steep hillslopes. The proximity of the sea is at the origin of very active downcutting of the valleys. There is an evolution equivalent to that described in northern Sicily (Hugonie, 1979) and in Calabria (Gueremy, 1977). It is from the existing topography in the Pliocene that the drainage network is realized (Dresch, 1950). The tectonic movements are the origin of the resumption of downcutting of streams that have developed deep valleys and gorges.

After the establishment of the thrust sheets, the Saf Saf River settled on an old topography constructed by detrital materials of the Upper Oligocene. It was from there the river would be superimposed (inadapted to the geologic structure). It is at the end of the Miocene that there is a resumption of erosion on Saf Saf River which has downcutted its current valley through the Numidian chain (sandstone, clay, flysch) and conglomerates.

The morphostructural study of the Neritic limestones in the North Guelmian Tell (eg. Bouhamdane, Mellah and Ressoul watersheds) has permitted to highlight the important role of tectonic accidents such as faults in the formation of reliefs in the region; it is post-mio-pliocene tectonics (late Tertiary and Quaternary). These disturbances accentuated the reliefs such as Djebels Debagh, Taya, considered young reliefs and accelerated the establishment of the hydrographic network which crossed softer rocks. Finally, the mountains that surround the large Azzaba Basin, a principal part of the Kebir West watershed, to the north, west, and south consist of Numidian sandstones and the bottom is covered by quaternary sediments. This is a hollow area in which came to settle the Numidian clays due to thrust sheet dynamics. The tectonic accidents gave birth to the different reliefs and erosion has been able to release deep valleys by a river network thought to have been surimposed during the end of the Tertiary.

Using the French classification of soils (Duchaufour, 1983), most of the watersheds have extended areas of poorly developed soils (lithosols and regosols). Soils developed on sandstone and limestone, with slopes exceeding 12%, are constantly rejuvenated and have a less differentiated soil profile (Bneder 1980 and 1995).

Besides the poorly developed soils in the Saf Saf, Mellah and Kebir West watersheds, calcareous soils (calcisols), and deep brown soils are developed on slopes less than 15% steep. The vertisols are frequent in the Kebir West and Bouhamdane watersheds. They are deep and rich in clay, usually montmorillonite which causes the soil to shrink and crack upon drying and to swell and produce surface runoff when wet (Khanchoul et al., 2007 and 2008).

The natural vegetation that protects the soil is disturbed by man. The cultivated areas are the most vegetation cover of the study areas. In the Saf Saf and Bouhamdane watersheds 65% and 57% of their basin areas are cultivated with wheat and barley. The lands of Kebir West and Ressoul watersheds, and especially Mellah basin, are less used for farming, occupying 40% and 17%. Dense forests (mainly *Oak cork*) and shrubland (*Oleo-lentiscus* and *Erica europa*) are less developed in the Saf Saf and Bouhamdane watersheds, with 26% and 12% of their basin areas respectively. The rest of the basins are better covered with forest and grassland, exceeding 30%.

3. Materials and methods

For delineation of the Bouhamdane, Resoul, Mellah, Kebir West and SafSafwatersheds and preparation of drainage map the information regarding the topography is needed. In this study, the Digital Elevation Model (DEM) is used, which is tagged information file format (TIFF) format with 30 m ground resolution. Further, the developed DEM is processed to generate or delineate the watershed and drainage network (Fig. 1), using the hydrology tool of Spatial Analyst module of ArcGIS 10 (Meshram and Sharma, 2017). Further, twenty subwatershed boundaries are also determined from the five principal watersheds: Kebir West (two subwatersheds), Saf Saf (six subwatersheds), Ressoul (two subwatersheds), Mellah (seven subwatersheds) and Bouhamdane (three subwatersheds).

The order is given to each stream by following a stream ordering technique of Strahler (1964). The term "stream order" is a measure of the position of a stream in the hierarchy of tributaries where the 1st order streams are those, which have no

tributaries. The 2nd order streams are those where two 1st order channels join, when two 2nd order channels join, a segment of 3rd order is formed. When two 3rd order segments join, a 4th order channel is formed and so on.

Morphometric analysis is carried out for the watersheds and their subwatersheds. The parameters computed in the present study using geological maps (1:50,000 scale) and GIS technique, within the attribute tables to compute necessary morphometric quantities, include stream order, stream length, basin area, drainage density, stream

frequency, orographic coefficient, maximum and minimum elevation, mean elevation and hypsometric integral (Table 1). The input parameter for the present study such as lithology index is obtained from digitized coverage of geological maps in GIS environment. Supplementary geomorphic parameters such as form factor, average basin slope, average overland flow distance and basin relief ratio are added to find out the qualified significance of each variable. The different morphometric parameters for the watersheds and subwatersheds are determined as shown in Table 2.

Table 1 Methods of calculating morphometric parameters

Geomorphic parameters	Formula	Source
Basin area (A)	Calculate geometry in attribute table	DEM and Arcgis
Meanelevation (Hmean)	Raster calculator expression: Con("DEM">1500, "DEM")	DEM and Arcgis
Drainage density (Dd)	Dd= Lu/A Lu: total stream lengths of all orders using Arcgis	Horton (1945)
Stream frequency (F1)	F1 = N1/A N1: number of all 1st order streams using Arcgis	Horton (1945)
Form factor (C)	C = A/Lb ² Lb: basin length	Schumm (1956)
Orographic coefficient (OC)	OC = Hmean x tang α tang α = $\frac{Hmean - Hmin}{A}$ Hmean: mean elevation; Hmin: minimum elevation	Fournier (1960)
Hypsometricintegral (HI)	HI = $\frac{Hmean - Hmin}{Hmax - Hmin} \times 100$ Hmean: mean elevation; Hmin: minimum elevation; Hmax: maximum elevation	Pike et Wilson (1971)
Lithologic index (IL)	Rock erodible area/basin area Erodible area (marl, clay, marly limestone)	Demmak (1982)
Average basin slope (BS)	Average slope of the triangles or cells comprising this basin. A triangle or cell's slope is computed as the change in elevation divided by the change in XY or plan distance.	DEM and Watershed Modeling System program (WMS)
Average overland flow distance (OFD)	- Averaging the overland distance traveled from the centroid of each triangle to the nearest stream. - L = A/2W A: basin area; W: channel length	DEM and WMS
Basin relief ratio (Rh)	Rh = R/L R: total relief (max elevation – min elevation); L: maximum basin length	Horton (1945) Schumm (1956)

Table 2 Morphometric characteristics of the watersheds and subwatersheds of the study area

A: basin area; Dd: drainage density; F1: stream frequency; HI: hypsometric integral; OC: orographic coefficient; IL: lithologic index; C: form factor; BS: average basin slope; OFD: average overland flow distance; Rh: basin relief ratio

	Code	A (km ²)	Dd (km ⁻¹)	F1 (km ⁻²)	HI (%)	OC	IL (%)	C	BS (%)	OFD (km)	Rh
Watersheds											
Kebir West	-	1130	2.60	5.28	21.17	62.24	32.51	1.14	15.33	0.70	0.035
SafSaf	-	322	3.60	5.90	41.62	823.00	16.10	1.27	19.08	0.75	0.045
Bouhamdane	-	1105	2.61	4.30	49.50	350.41	23.89	1.76	11.99	0.74	0.022
Ressoul	-	103	3.41	6.84	29.06	780.43	34.21	1.25	12.35	0.68	0.050
Mellah	-	550	4.53	6.07	42.93	590.69	20.27	1.45	18.55	0.77	0.037
Subwatersheds											
Emchekel	Eck	641.60	2.96	5.71	24.91	0.92	26.71	1.40	13.73	0.70	0.017
el Hammam	Ehm	485.00	2.75	5.89	29.37	2.72	40.07	1.20	11.24	0.70	0.029
Guis	Gui	64.65	3.58	8.00	30.51	13.02	31.23	1.49	13.10	0.66	0.048
Bouala	Bal	33.45	3.00	5.06	25.79	20.02	43.31	1.45	12.17	0.68	0.073
Rirane	Rrn	79.03	3.98	7.81	53.19	50.61	26.92	1.22	18.81	0.83	0.060
Cheham	Chm	29.81	4.90	6.07	44.44	103.05	60.88	1.67	14.27	0.69	0.078
Hammam	Hmm	54.46	4.30	7.38	44.00	59.93	18.32	1.54	21.78	0.68	0.051
Meza	Mez	77.03	4.72	4.87	55.38	34.78	21.45	1.64	16.55	0.84	0.057
Aouassia	Aos	48.11	4.48	3.62	56.38	74.91	13.01	1.31	15.99	0.88	0.075
Bouredine	Brn	64.40	3.78	3.79	49.01	26.91	28.54	1.43	15.98	0.87	0.038
R'biba	Rbb	128.66	2.74	6.19	54.62	36.76	11.32	1.55	21.97	0.68	0.037
Zenati	Zen	575.17	2.42	3.68	46.34	4.04	36.18	1.47	10.51	0.70	0.013
Sabath	Sab	314.18	2.09	3.50	44.8	9.42	5.15	1.61	11.36	0.71	0.025
Bouhamdane	Bhm	215.65	3.84	7.08	39.00	10.79	55.98	1.29	16.85	0.88	0.030
Khemakhem	Kmk	99.47	3.26	5.36	41.47	26.49	26.03	1.37	20.86	0.71	0.054
M'ta Rhumel	Rml	13.78	3.81	8.85	43.50	157.07	23.44	1.43	21.07	0.79	0.134
Khorfane	Kfn	35.24	3.29	5.05	50.72	86.50	12.57	1.19	19.39	0.82	0.094
Rararef	Rra	58.80	3.06	3.93	53.31	59.68	1.54	1.34	19.01	0.76	0.069
Beni Brahim	Bbr	68.19	4.84	7.86	31.93	22.30	15.69	1.48	19.70	0.65	0.086
Bou Adjeb	Baj	46.52	3.36	6.47	37.97	32.82	15.65	1.25	14.42	0.70	0.041

The statistical methods are applied to validate data and to obtain further precise results. The various morphometric parameters are studied for their inter-relationship which helps to depict the nature of the subwatersheds. Thus, a statistical analysis of multivariate types is used to manage the information provided by the used parameters. Multivariate analysis is a useful technique for identifying common patterns in data distribution, leading to a reduction of the initial dimension of

data sets and facilitating their interpretation (Castellano et al., 2007).

Statistical analyses are carried out by the statistical software (STATISTICA version 8). The interpretation of the correlation between the variables will be done using the correlation matrix. Then, for the grouping of geomorphic parameters principal component analysis will be used on the geomorphic parameters for twenty subwatersheds.

Principal component analysis (PCA) is applied for all geomorphic parameters to summarize the information contained in a large array of numbers, to identify patterns, to better understand the tangible relationship between the variables, and thus to reduce data in order to highlight the essential elements related to the erosion process. Factor analysis is a classic form of multivariate analysis, widely used in the social sciences since the 1960s. In this analysis we have used the STATISTICA software, which is designed to be used as simply as possible.

4. Results and discussion

4.1 Geomorphic parameters analysis

4.1.1 Drainage density

Drainage density is of great interest because it is directly controlled by the interaction of geology and climate (Ritter, 1984). The drainage density has been related to a number of climatic indices (Gardiner and Park, 1978). Gregory and Gardiner (1975) have examined variation of drainage density in relation to both world climatic zones and precipitation within one zone. In general, surfaces with a resistant substrate or those characterized by high infiltration capacities have spaced streams and therefore low drainage densities. As surface resistance or permeability decreases, runoff becomes more important, resulting in tighter rivers and drainage density tends to become higher. Added to that the abundance of precipitation, which is responsible for the perennality or the intermittence of the rivers.

The drainage density values obtained from sub-basins are between 2.09 and 4.90 km⁻¹. The sub-watersheds of Mellah and Saf Saf show the highest values, with averages equal to 4.13 km⁻¹ and 3.60 km⁻¹, respectively. This is also evident in those basins which reach the highest values (Table 2). Much of the other sub-basins belonging to the Kebir West and Bouhamdane show better drainage, especially in fractured sandstones and plains, with an average of 2.86 km⁻¹ and 2.78 km⁻¹.

4.1.2 Stream frequency

This is obviously a parameter that accounts for a density-in-number effect, certainly comparable to the density-in-length effect that Dd represents. The frequency values of the talwegs (F1) vary between 3.00 and 8.85. The calculated averages show that the sub-basins of Ressoul and that of SafSaf have values greater than 6.00, while the sub-basins of Mellah and Kébir West have mean values of 5.68 and 5.80. The permutation of the Ressoul and Mellah wadis on the basis of the values of the drainage density and the frequency of the talwegs reveal the existence of a larger number of talwegs, often shorter (lower orders), which evolve on erodible surfaces composed of clay-sandstone and marl-limestone in the Ressoul watershed. The streams of Mellah Wadi, on the other hand, tend to develop more by lateral erosion, hence its increase in sinuosity and length. The lowest values of the frequency of the talwegs are observed in the Zenati and Sabath sub-basins which form part of the Bouhamdane watershed.

Without taking into account the used averages, we find that the wadis of Mellah, Saf Saf and Ressoul generally have the highest drainage density values and the frequency of the talwegs (Table 2).

4.1.3 Relief relations

This group indicates the vertical dimensions of the basin; it includes gradient and elevation factors. The mean elevation of the sub-basins has not been systematically analyzed in the various discussions of the relief since it is more a characteristic of state whose influence is mainly felt at the level of the climate (rainfall, temperature). It is better represented by the orographic coefficient and hypsometry.

The orographic coefficient reflects the energy of a morphometry favorable or unfavorable to erosion. It is therefore an indicator of the intensity of the processes of erosion operating on the slopes of which it measures the general steepness of the basin. This coefficient is probably similar to the relief ratio proposed by Melton (1957). Most of the values of the orographic coefficient of the

subwatersheds range from 157 to 2.72. Taking into account the calculated averages of this coefficient, we note that Saf Saf Wadi ($\overline{CO} = 64$) and Mellah Wadi ($\overline{CO} = 55$) have the highest values, which implies a high energy of landform favorable to erosion. But if the coefficient is recalculated by the formula in Table 1 for the five basins, we note that the wadis of Saf Saf and Ressoul come first, followed by Mellah Wadi (Table 2). It is usually the sections of the subwatershed not considered in the calculations that change the classification of the basins.

Subjected to geomorphological processes, the shape of a basin changes over time. According to Davis's classical analysis (1899, 1905), hillslopes, gradient of streams and drainage density increase rapidly during the youth stage to reach their maximum at the beginning of maturity, before they decrease slowly (Schumm, 1956). Davis suggests that the basins are developed after an abrupt tectonic uplift followed by soil erosion. Hack (1960) has provided an enthusiastically embraced alternative to Davisian thought that has established the concept of dynamic equilibrium landforms as a fundamental time-independent geomorphic model. In addition, Scheidegger (1987) has contradicted the Davisian hypothesis by asserting that the uprising is a continuous process and that, through the history of the basin, there is a tendency towards equilibrium between the two opposing forces, tectonics and erosion. Thus, the youth stage would correspond to a strong activity of these two antagonistic processes. The stage of maturity corresponds to an average activity and therefore to dynamic equilibrium.

The analysis of the different stages of the evolution of the relief is determined from the hypsometric curve, data collected from the altimetric maps and the hypsometric integral (HI). Hypsometric analysis (area-altitude analysis) has been used to differentiate between erosional landforms at different stages during their evolution (Strahler, 1952; Schumm, 1956; Pike and Wilson, 1971). Thus, it has been possible to calculate the current mass of the relief which is not yet consumed by erosion. A hypsometric curve, having a concave-convex shape with a hypsometric integral between

35 and 60%, shows a stage of maturity where the equilibrium state of the basin development is reached. A strongly concave curve and a hypsometric integral of less than 35% give an end-maturity stage predominantly dominated by hills and ridges. This is the monadnock phase (Strahler, 1952). The values of the integral hypsometric range between 24.91% and 56.38% of which 25% of the values are less than 35%.

The sub-basins of the Kebir West, Ressoul Wadi, the sub-basin of the Beni Brahim Wadi (belonging to Saf Saf watershed) correspond to an advanced stage of maturity, which leads to a hypsometrically concave curve, more elongated downwards. These sub-basins have reached the monadnock phase where they are characterized by a predominance of scattered hills, generally medium to low, with often rounded summits. This is clearly visible in these sub-basins where the proportion of low-lying areas resting on less resistant rocks increases progressively at the expense of a higher topography formed of resistant rocks. According to Strahler, this situation is transitory and when it is completed, it will result in the restructuring of a curve giving a normal steady-state form (Rafael, 1990). This is possible only when the hard rocks are exposed, leaving a certain contrast between the topography of the erodible parts and the more resistant ones of the basin. This result is also apparent in the basins of Kebir West and Ressoul (Table 2).

Among the sub-basins which are in a state of dynamic equilibrium (mid-maturity stage), we note that Aouassia Wadi and Bouhamdane Wadi present the most extreme hypsometric integral values, with respectively 56.38 % and 37.35% (Table 2). As a result, Aouassia Wadi presents a less concave curve whose "sub-maturity" condition can be explained by insufficient time to reach full mid-maturity. The relief, developed in conglomerates and fractured sandstones, seems to be accentuated and the drainage density is quite high.

Overall, the Bouhamdane, Saf Saf and Mellah watersheds show a mid-maturity stage where more than 50% of the initial relief is consumed by erosion. These are basins in equilibrium; therefore, there is an attainment of a regular state related to the processes of erosion and transportation within

the fluvial system and its contributing slopes. In this stage, a system of channel slopes and valley-wall slopes has been developed which is most efficiently adapted to the reduction of the landmass with available erosional forces, balanced against the resistive forces of cohesion, maintained by the bedrock, soil, and plant cover (Strahler, 1952).

The relief ratio measures the overall steepness of a drainage basin and it is an indicator of intensity of erosion processes operating on the slope of the basin. Relief ratio normally increases with decreasing drainage area and size of a given drainage basin (Gottschalk, 1964). The values of relief ratio in the study watersheds range between 0.022 and 0.050. This is a dimensionless height-length ratio and allows comparison of the relative relief of any basin regardless of difference in scale or topography. The values of the relief ratio in the study subwatersheds range between 0.023 and 0.122 (Table 2). It has been observed that areas with low to moderate relief and slope are characterized by moderate value of relief ratios. Low value of relief ratios are mainly due to the resistant basement rocks of the basin and low degree of slope.

4.2 Multivariate analysis of the physical parameters

Some physical parameters have been used in the PCA analysis for the sub-basins of the Seybouse and the coastal basins of Constantine in order to determine the affinities between the sub-basins and to deduce accordingly the most characteristic parameters with regard to erosion.

The PCA method has been applied to 20 cases (sub-basins) and 10 geomorphic variables that could contribute to erosion. The major selected variables are sub-basin area (A), drainage density (Dd), frequency of talwegs (F1), hypsometric integral (HI), orographic coefficient (OC), lithological index (IL). Four additional variables, sub-basin shape parameter (C), basin slope (BS), average overland flow (OFD) and basin relief ratio (Rh) are considered as extended variables.

4.2.1 Principal component analysis of major dataset

PCA is used iteratively to provide a number of outputs, all of which require interpretation leading to an inherent tradeoff between simplicity and precision. The first output provided by a PCA is a correlation matrix (Table 3). A Spearman correlation matrix is used because it is sensitive to outliers than the more commonly used Pearson correlation matrix. Table 3 demonstrates moderate negative correlations between sub-basin area and drainage density, orographic coefficient. The negative correlation between basin area and drainage density and stream frequency suggests that there should be a positive correlation between basin area and total stream length, total number of streams. The computed coefficient of correlation between basin area and total stream length is equal to 0.98. The four basin characteristics that change in response to the changes taking place in basin area, as a result of drainage re-organization following the removal of the remnants of the pre-existing planation surface, are total stream length, drainage density, stream frequency and the relief ratio that will be treated in the following section (Mather and Doornkamp, 1980). By considering the mean values of these parameters for the subwatersheds, the slight decrease in drainage density (from 3.60 to 3.43 km⁻¹), during maturity (35% ≤ HI < 60%) to late maturity-old (HI < 35%) stage, shows that in the ratio total stream length/basin area, the area increases more than total stream length, leading to a decrease of the drainage density value. Meanwhile, the simple linear relationship between basin size and mean elevation fails to explain this association, which is not significant ($r = -0.33$).

Much weaker positive correlations are apparent between drainage density and orographic coefficient and between hypsometric integral and orographic coefficient. In addition, a weaker negative correlation is observed between hypsometric integral and lithologic index. It is the combination of these variable correlations that PCA is introduced to capture mathematically.

The correlations shown in Table 3 are translated into PCs by computing eigenvalues where the greater the eigenvalues, the greater the proportion of variability is explained by the component (Table 4).

Table 3 Matrix of correlations between geomorphic variables

Parameters	A	Dd	F1	HI	OC	IL
A	1.00					
Dd	-0.57	1.00				
F1	-0.26	0.38	1.00			
HI	-0.36	0.19	-0.34	1.00		
OC	-0.57	0.43	0.27	0.43	1.00	
IL	0.17	0.19	0.22	-0.41	-0.10	1.00

Table 4 Eigenvalues of correlation matrix and related statistics

	Eigenvalue	% Total variance	Cumulative Eigenvalue	Cumulative %
PC1	2.40	40.08	2.40	40.08
PC2	1.71	28.49	4.11	68.57
PC3	0.76	12.61	4.87	81.18
PC4	0.52	8.66	5.39	89.85
PC5	0.36	5.93	5.75	95.78
PC6	0.25	4.22	6.00	100.00

Table 5 Factor coordinates of the variables, based on correlations

Parameter	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
A	0.86	0.02	0.08	-0.26	0.42	0.13
Dd	-0.75	0.36	0.28	0.35	0.25	0.21
F1	-0.37	0.73	-0.48	-0.09	0.21	-0.22
HI	-0.53	-0.71	0.28	-0.08	0.24	-0.28
OC	-0.82	-0.04	-0.03	-0.53	-0.06	0.21
IL	0.15	0.74	0.60	-0.19	-0.12	-0.15

The correlation between the six variables (Table 3) and between the variables and principal components (Table 5) are represented graphically in the correlation circle provided in Figure 2. The correlation circle is a graphical tool for determining the variables that contribute the most to the formation of the principal component analysis. The angle of the vectors relative to the two PC axes reflects the degree of association between the variables and the PCs. Similarly, the angle of each

vector relative to other vectors reflects the degree of correlation between the variables (US Department of Energy, 2012).

The circle of correlations of the variables shows that the factors 1-2 represent almost 69% of inertia. Drainage density (Dd) and orographic coefficient (OC) are negatively well represented on PC1 based on the small angle between the vectors. The sub-basin area (A) is opposed to the later two variables. Stream frequency (F1) and lithologic index (IL) are positively correlated with the second component, PC2 (the vertical axis). On this axis, the hypsometric integral (HI) is negatively correlated with PC2. The position of the vectors for F1, IL at about less than 45° angles to PC2 axis, indicates that these constituents are more or less well represented in the PCA as are the other variables such as Dd and OC.

The tendency to link the parameters of drainage density and relief to sub-basin area on factor 1 seems to be able to express the active morphology of the field under various lithological formations (Fig. 2). A high value of the orographic coefficient and drainage density characterizes the sub-basins with small areas. The sub-basin area increases to high values when the proportion of the sub-basin to the low relief increases and the intensity of erosion decreases.

In order to interpret this relationship on the basis of our data, it is imperative to specify that the analyzed sub-basins are in a stage of maturity, which implies that they are distinguished by more aerated reliefs with well developed alluvial plains or micro-plains. Thus, sub-basins with fairly high to high reliefs are characterized by high drainage densities because the steepness of the slopes contributes enormously to the intense gullying. However, erosion continues by the development of the hydrographic network and contributes to the widening of the valley and the reduction of the relief. The expansion of the upstream parts of the drainage system results in the consumption of most undissected surfaces and consequently leads to the elongation of the basin (Miller et al., 1990). With the reduction of the relief, the intensity of the gullying decreases progressively because the slope of the basin becomes less favorable to the high flows. In

addition, the existence of the plains promotes the infiltration of runoff into the soil and the development of the meandering system.

The circle of correlations, connected to factors 1-3 with almost 53% of inertia, shows that axis 3 is mainly controlled by the lithologic index with a positive correlation. The position of its vector at small angle to PC3 indicates that it is as fairly well represented in the PCA and the frequency stream variable is less correlated because the position of the vectors are at about 45° angles to PC1 and PC3.

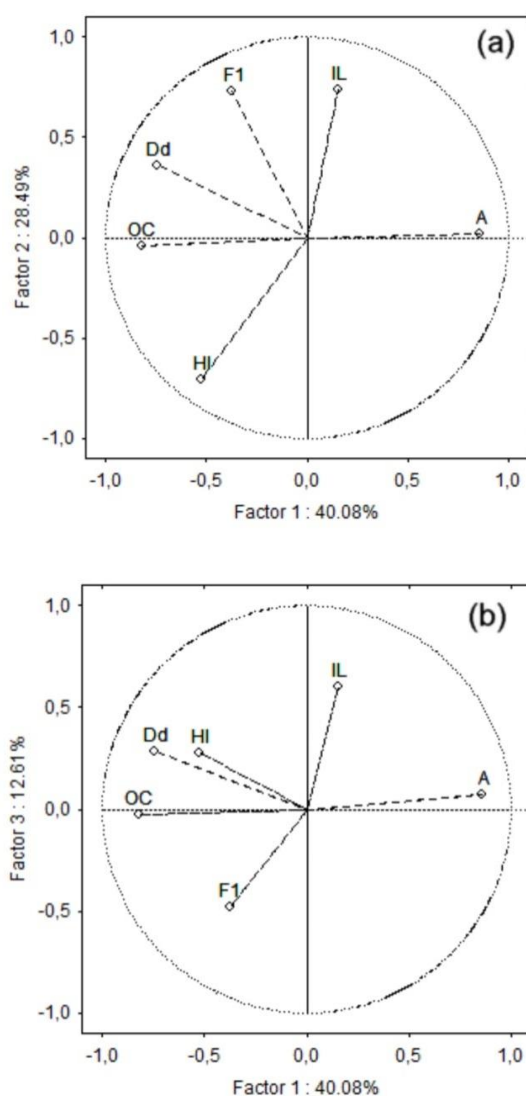


Figure 2 Projection of the variables on the factor-planes; a: (1x2), b: (1x3)

On PC1 and PC3 axes, the incision by the talwegs of the lower stream orders becomes more aggressive on the less resistant rocks. This case is particularly observed in the wadis of Cheham, El Hammam and Bouhamdane (Table 2). Conversely, a decrease in the distribution of erodible rocks will lead to a reduction of gullying, especially when the overall topography of the basin is reduced. On axis 1, we note that the hypsometric integral is associated with the two variables of drainage density and orographic coefficient. This HI parameter shows, in fact, that it becomes more representative on the axis 1, by still describing a high relief of the group of sub-basins that it represents.

In general, the association of the variables IL, Dd, F1 and HI is at least greatly solicited by several authors who worked on the principle of these relations in order to give explanations of the geomorphic processes and factors, hierarchy of the network and the evolution of relief (Zavoianu, 1985; Miller et al., 1990). According to Strahler, the parameters of erosion, rock resistance often show a negative relationship with the hypsometric integral during the youth stage and from the maturity stage.

On the basis of the quality of representation and contribution of each individual on the axes and in relation to circles of correlations of the variables, it is shown that the factorial projection of sub-basins (PC1 and PC2) has allowed us to see the distribution of individuals (sub-basins) with the six variables. The sub-basins are subdivided into four groups (factor 1-2). On axis 1, the first group, defined by the Hammam, Rirane, M'ta Rhumel wadis, shows a high erosion and an important orography but smaller areas, lower than their mean. On the other hand, the second group, represented by Zenati, Emchekel and El Hammam wadis, has a larger area of their sub-basins and low erosion and relief (Fig. 3). These sub-basins show a dominance of erodible rocks which are mostly characterized by the mid-maturity stage to end of maturity. Sabbath wadi is also distinguished by its high area but its fairly distant position on axis 1 seems to be the existence of another constraint, maybe it is the dominance of the resistant rocks which has made this sub-basin located away from the group.

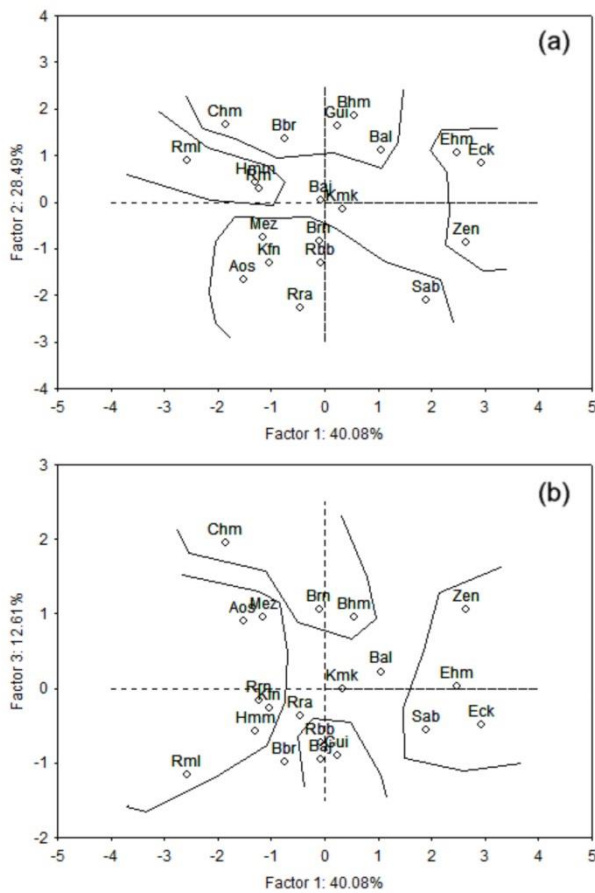


Figure 3 Projection of the subwatersheds on the factor-planes; a: (1x2), b: (1x3)

The third group, which includes the sub-basins of Guis, Bouala, Bouhamdane, Cheham and Beni Brahim wadis, is distinguished by high values of the frequency of the talwegs and the lithologic index. The quality of contribution of the Beni Brahim wadi to this relationship is rather low (33%) because it has a smaller distribution of erodible rocks. In contrast, the fourth group composed of Meza, R'biba, Aouassia, Rararef, Sabath, Khorfane and Bouredine wadis shows rather high values of the hypsometric integral (greater than 44%). The opposite position of the two variables (IL, F1) is mostly well represented because if the hypsometric integral is low in the sub-basins of the third group, the values of the frequency and the lithological index are generally low in the fourth group (Figure 3). Moreover, the subwatersheds of the fourth group are distinguished by a substrate of more resistant outcrops and a mid-maturity stage with streams having thoroughly dissected the

former highlands, and the whole area is covered with a well developed drainage network. This situation leads to the appearance of a more sparse drainage pattern than that of the third group, which is distinguished by a well-hierarchized river network developed on erodible rocks and a modest topography.

On the 1-2 axes, the same sub-basins of the first group (axis 1) plus Meza and Aouassia wadis are opposed by their erosion and topography to the second group which includes the Emchekel, El Hammam, Sabath and Zenati wadis (Fig. 3). The second group is well represented by the large areas of the sub-basins, the low values of the drainage density and generally by the modest to low topography. On axis 3, sub-basins located in the positive part of the axis are distinguished by high linear erosion due mainly to the vulnerable nature of the rocks (eg. Guis sub-basin) and, on the other hand the regional drainage pattern, geology (eg. R'biba sub-basin) will also influence the location of individual streams within a drainage basin via the action of differential erosion -i.e. as the landscape is worn down by erosion, streams will naturally tend to occupy lines of weakness caused by different rock types, faults or joints, or slight variations in rock strength. For the opposite group (group one), the intensity of the gullying depends more on the vulnerability of the clayey, marly and marly limestone lithologies.

4.2.2 Principal component analysis of extended dataset

In this section, the same statistical approaches are used to evaluate the major variables, principal component analysis is applied to an expanded dataset to try to explain the erosional phenomena of the sub-basins. Table 6 shows the correlation matrix derived for the expanded data set. This table is partially redundant with the initial correlation matrix of Table 3, so this discussion will focus on correlations not previously identified.

Table 6 shows that BS is negatively correlated with A and positively correlated with OC, and to a lesser extent with F1 and HI. OFD is positively correlated with HI and weakly correlated with the other variables. Rh is negatively correlated with A and positively correlated with Dd, BS, and strongly

positively correlated with OC. Table 7 presents the component loadings for the expanded dataset eigenvalues, the explained variability, and the based on these correlations.

Table 6 Spearman Correlation Matrix using extended dataset

Parameters	A	Dd	F1	HI	OC	IL	C	BS	OFD	Rh
A	1.00									
Dd	-0.57	1.00								
F1	-0.26	0.38	1.00							
HI	-0.36	0.19	-0.34	1.00						
OC	-0.57	0.43	0.27	0.43	1.00					
IL	0.17	0.19	0.22	-0.41	-0.10	1.00				
C	-0.07	0.19	-0.06	0.07	0.03	0.06	1.00			
BS	-0.56	0.38	0.41	0.43	0.51	-0.38	-0.06	1.00		
OFD	-0.22	0.29	-0.22	0.57	0.27	-0.01	-0.36	0.18	1.00	
Rh	-0.69	0.50	0.36	0.18	0.84	-0.13	-0.04	0.51	0.17	1.00

Table 7 Eigenvalues, Explained Variability, and principal component loadings with extended dataset

	Eigenvalue	% Total variance	Cumulative Eigenvalue	Cumulative %
PC1	3.76	37.57	3.76	37.57
PC2	1.91	19.13	5.67	56.69
PC3	1.25	12.46	6.91	69.15
PC4	1.16	11.6	8.07	80.75
PC5	0.70	7.00	8.77	87.75
PC6	0.48	4.77	9.25	92.52
PC7	0.31	3.09	9.56	95.61
PC8	0.2	2.00	9.76	97.61
PC9	0.18	1.79	9.94	99.4
PC10	0.06	0.60	10	100

Correlations between variables and factors (factor loadings)

	Factor 1	Factor 2	Factor 3	Fact. 4	Fact. 5	Fact. 6	Fact. 7	Fact. 8	Fact. 9	Fact.10
A	0.83	-0.07	0.09	-0.07	0.00	-0.42	-0.33	-0.09	-0.01	-0.05
Dd	-0.67	0.32	0.20	0.40	0.30	0.20	-0.29	-0.07	-0.15	0.02
F1	-0.36	0.75	0.07	-0.34	0.27	-0.20	-0.01	0.27	0.02	-0.03
HI	-0.53	-0.72	-0.09	0.24	0.13	-0.21	0.12	0.11	-0.19	-0.10
OC	-0.84	0.05	0.01	0.03	-0.42	-0.29	-0.04	0.03	-0.08	0.14
IL	0.23	0.55	0.57	0.43	-0.05	-0.18	0.27	-0.12	-0.03	-0.03
C	0.00	0.22	-0.64	0.70	0.04	-0.12	-0.02	0.05	0.18	0.00
BS	-0.76	-0.04	-0.22	-0.32	0.38	-0.19	0.10	-0.27	0.09	0.02
OFD	-0.40	-0.56	0.64	0.16	0.11	-0.03	-0.08	0.09	0.25	0.02
Rh	-0.84	0.22	0.00	-0.10	-0.43	0.07	-0.10	-0.07	0.09	-0.16

As shown in Table 7, the first two components (PC1 and PC2) explain 37.57% and 19.13%, respectively, of the total variability contained in the used variables. The third component explains 12.46% of the variation, and the remaining components explain gradually decreasing contributions (with eigenvalues < 1). The first two components together account for 56.70% of the variation in the original dataset. This value is lower than the 68.57% accounted for in the PCA of the major geomorphic dataset. Addition of a third component increases the percentage of total explained variability to 69.12%. The PC loadings in the lower portion of Table 7 can be interpreted as follows:

a- reflecting the contribution of the new geomorphic variables, PC1 is strongly correlated with A, and negatively correlated with OC and Rh.

b- listed in decreasing order of correlation, PC2 is most associated with F1 and HI and to lesser extent with OFD. The correlations with F1 and HI are consistent with those revealed in the initial PCA (Tables 4 and 5).

- PC3, accounting for only 12% of the variability in the data, is mainly correlated with C and OFD (less strong correlations).

These associations are shown graphically in the correlation circle provided in Figure 4. Similar to the correlation circles in Figure 2, this figure graphically represents the correlations between variables and factors shown in Tables 6 and 7.

Figure 4 is interpreted as follows:

- Dd, and OC are negatively correlated with PC1 and with each other, as Rh and BS which are well represented, having BS variable slightly shorter vector length. Basin area's positive correlation on PC1 is represented as a prominent variable.
- F1 is well represented on PC2 based on the length of the vector but IL is less apparent shown by its slightly shorter vector length. The variable C has a weak correlation on PC2 because of its location on the axis.
- HI is negatively well represented on PC2 with a lesser extent for OFD variable. They are both positioned at about a 45° angle but with a shorter vector length for OFD (less strongly correlation).
- OFD and C are slightly well associated with PC3; they are opposing each other. These two extended

variables did not account for much variation in the association.

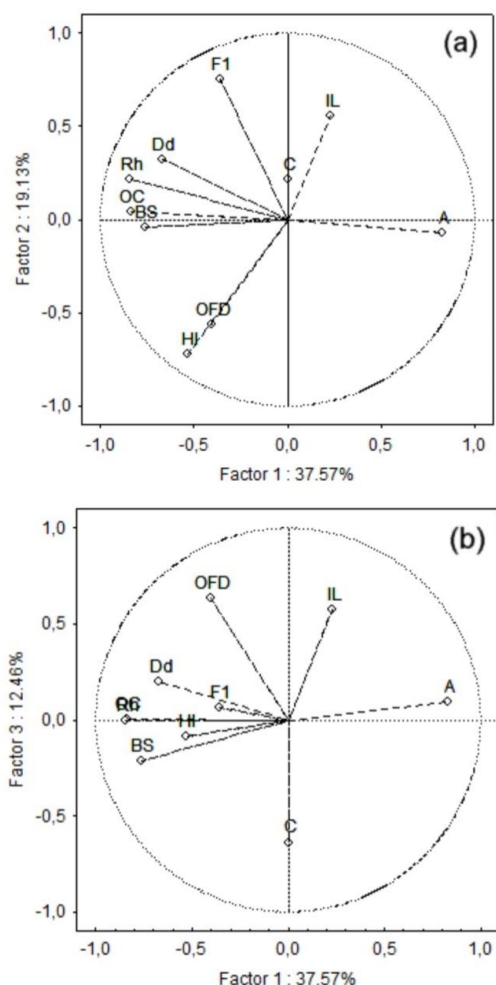


Figure 4 Projection of the variables on the factor-planes; a: (1x2), b: (1x3)

This study can be achieved by a simple comparison regarding the erosion implications using mainly drainage density (Dd), stream frequency (F), relief ratio (Rh) and average basin slope (AVS) at other watersheds located in the Mediterranean region. Few studies have discussed morphometric analysis of watersheds and the available ones are from Egyptian and Lybian regions. Abdel Ghani (2015) has investigated twenty five watersheds located between Qusseir and Abu Dabbab area at the Red Sea Coast for prioritization rating for flash flood risk estimation using morphometric parameters. Moreover, Ashmawy et al.

(2014) have used remote sensing data, Shuttle Radar Topography Mission, coupled with geological, geomorphological data for the estimation of the flash flood risk in al-Kouf watershed, Northeast of Libya. For that, they have used morphometric analysis trying to understand the runoff potentiality in these ephemeral watersheds. Both Egyptian and Libyan regions belong to the arid-semiarid climates with intensive storm events as flood hazards. The purpose of the comparison is focusing on the drainage morphometry and its influence on erosion. The comparison between the four used morphometric parameters is being undertaken by averaging the values of each variable (Table 8).

Table 8 The calculated mean values of the morphometric parameters

Watersheds	Dd	F	Rh	AVS
Algerian	3.56	5.81	0.06	24.90
Qusseir-Abu Dabbab	1.86	1.95	0.03	43.10
al-Kouf *	1.57	1.71	0.015	64.84

* no mean value is calculated for the watershed.

The values of the previously mentioned parameters companied with the geologic units and geomorphological features are used to discuss erosion. They are provided that the northeast Algerian subwatersheds can be classified as moderate to high runoff potentiality and the evidences of this runoff can be observed from the drainage density and stream frequency values leading to severe floor incision and fluvial deposits at basin outlets. The geological (extended erodible and fractured rocks and more impermeable subsurface soils), topographic and climatic (subhumid) conditions have favored the incision of the surface and the development of the river network. Meanwhile, the Qusseir-Abu Dabbad and al-Kouf watersheds are missing most of the later hydro-geomorphic conditions. Thus, the difference in the range of drainage density and stream frequency shown by the Qusseir-Abu Dabbad and al-Kouf watersheds may be explained by contrasts in differences of rock type and structure, evolution of landform and climate.

The Qusseir-Abu Dabbad subwatersheds are mainly composed of sedimentary rocks (sandstones, conglomerates and carbonate rocks) and granite. The area is subjected to tectonic and depositional stages which favor the existence of faults and fractures in rocks and consequently drainage channels are rapidly formed providing least resistance to erosion. The network pattern of parallel and trellis drainage confirms the steepness and strike valleys of the area. Nevertheless, these watersheds stay less eroded in comparison to the study Algerian subwatersheds because of the hydrologic basins dissecting the mountainous area of the limited Qusseir-Abu Dabbad areal extent due to durability of basement rocks to weathering processes (Abdel Ghani, 2015).

The al-Kouf watershed exhibits contrasting landform evolution and erosional features. The effect of surface runoff in the basin is reduced because of karstification in the carbonate rocks leading to high infiltration capacity (Ashmawy, 2014). According to the author, the area is distinguished by a moderately soil erosion susceptibility and a less eroded basin because of its belonging to the youth stage where only 23% of the relief is consumed. The relative convexity shape of the hypsometric curve indicates higher relief energy (Table 8), dominated by subsurface processes.

5. Conclusion

The morphometric assessment has helped in the elaboration of primary hydrological diagnosis in order to predict approximate behaviour of the watershed if correctly coupled with geomorphological and geological data. Drainage density and stream frequency are both important factors that affect erosion process. Therefore, their management can cause erosion control in the regions seriously threatened. They depend on geomorphic conditions and amount of flow through the channel.

Hence, prioritization of the twenty subwatersheds is crucial, and emphasizes the need to use appropriate soil conservation measures, in order to maintain future farming sustainability. In the present study, GIS, morphometric analysis, and principal component analysis techniques have been

employed to prioritize the subwatersheds opportunities to improve policies for their land management practices by the decision-makers.

The principal component loading matrix, using correlation matrix of six major parameters and four extended dataset, reveals that the three components together have explained 81% and 69%, respectively, of the total explained variance. From the principal component analysis, factors 1-2 contribute to 69% of the total variance of six variables. The most discriminating ten variables are basin area, orographic coefficient, drainage density, stream frequency and relief ratio.

Thus, taking into account the geomorphological and geological data such as drainage density, stream frequency, topography and lithology, there are mainly Guis sub-basin, 50% of the sub-basins of

the SafSaf watershed and 100% of the sub-basins of the Mellah watershed that are affected by gullying and lateral erosion. It emerges from that, the watersheds of Mellah and Saf Saf are most affected by the erosion processes. The watershed's morphometric features determined suggest a general fragile topography which may continue to be modified by the different geomorphic processes.

The study demonstrates that the attained results have determined subwatersheds of noticeable land and water degradation, and thus of high "potential" for application of immediate conservation measures. Further studies on the subject may contribute to a better understanding of the interaction of morphometric parameters and geology in sub-basins.

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Speech of
Prof. Constantin GRASU
During the opening of the National Symposium on Geomorphology,
Piatra Neamț, Romania, May 19-22, 2016

The Rise and Twilight of an Institution / Stălucirea și crepusculul unei instituții¹

Dragi colegi și stimați invitați

Metaforic, Paul Valery spunea că evenimentele se nasc din tată necunoscut, în timp ce mama lor este, dintotdeauna, NEVOIA.

Evenimentul de azi stă și el sub zodia Nevoii. Nevoia de a nu ne uita trecutul, care, într-un fel, este un prezent îmbătrânit, în timp ce noi înșine am ajuns deja bătrânii prezentului.

Întâlnirea de azi ne amintește că în urmă cu șase decenii, la Pângărați, ființa o instituție de cultură, cea care a fost și va rămâne în memoria posterității, Stațiunea Stejarul.

Dear colleagues and honored guests,

Paul Valery metaphorically said once that events are born from unknown fathers, but always the same mother, the NEED.

The event today stays under the need star. The need not to forget our past, that, in a way, is an aged present, while we ourselves have already become the elders of the present.

Today's meeting reminds us that six decades ago, in Pângărați, there was a cultural institution, the one that was and will remain in the memory of posterity, Stejarul Station.

¹ A note from the translator,

The translation of the speech given by prof. Constantin Grasu in the opening of the 32nd National Symposium of Geomorphology is only approximate. Mostly, the peculiar language was lost. Prof. Grasu is a big admirer of some great nineteenth century writers, such as Ion Creangă, Calistrat Hogaș, Ion Luca Caragiale, and he is influenced by them in his writings. One used only with professional English, like myself, cannot reveal the soul of his message. For this reason, I warmly invite the Romanians and the Romanian language speakers to read the Romanian version of the speech. I apologize to the other readers, but I assure them that the facts presented are accurate. I have introduced the footnotes to help foreign readers get along with so many names and references.

Crina Miclăuș

Menită cercetării, într-un cuvânt neliniștii, să observăm, nu fără semnificație, că un anume destin a făcut ca ea să ființeze în ctitoria lui Alexandru Lăpușneanu, cel mai zburcitat voievod moldovean, rămas în istorie prin pana bătrânului Negruzzi, dar demn chiar și de cea a marelui Will.

Așadar, în urmă cu șaiszeci de ani, pe sub zidurile lăcașului mușatin, halatele albe luaseră locul sutanelor negre, iar ceea ce se plămădise aici avea să aibă o existență efemeră, un sfert de veac numai, prețul unei generații și-n același timp o istorie care, până la urmă, avea să împrumute câte ceva din drama nefericitului voievod.

După cum constatați, evocarea momentului ne-a revenit. Am făcut greșeala de a ceda insistențelor colegilor, atâția câți am mai rămas, alături de care, zi de zi, vreme de 16 ani, am urcat Dealul Păru, pe același drum călcat în vremuri de mult trecute de părintele Stratonice, egumenul zgârcit și ursuz creionat admirabil de blândul Hogaș, Moș Calistru în epocă.

Trebuie să recunoaștem că ne-ar fi fost mult mai confortabil într-un fotoliu de unde să ascultăm opintelile altcuiva în salvarea subiectului, asta cu atât mai mult cu cât, fiți siguri, că nici nouă nu ne lipsește voluptatea cârcotelii.

Sinceri să fim, maniera de abordare a subiectului ne-a dat mari coșmaruri și încă nu avem nici o garanție că ne-am apropiat cu suficientă trăire de încărcătura emoțională a momentului. Ceea ce ne-a fost clar de la început, a fost doar faptul că dintotdeauna am urât evocările saturate de statistici aride, împănate de fapte minore scăpate în melodarmă, evocări care îmbracă adesea haina sobrietății, uneori inumane, cum ar fi spus mentorul Junimii, a sobrietății țanțoșe la umbra căreia pot fi strecurate cu ușurință orgoliile megalomane și suficiența păguboasă.

Până la urmă am ales întrucâtva calea simbolurilor și, din acest punct de vedere, credem că istoria acestei instituții merită un generic. De aceea am spus cândva că pe firmamentul a tot ce s-a clădit aici, ar putea sta scris: Pîngărași sau *Setea Muntelui de Sare*.

Aimed to research, in other word to unquietness, we have to observe, not without significance, that a certain destiny made it to exist in the founding of Alexandru Lapușneanu², the most tumultuous voivode of Moldavia, known in history by old Negruzzi's³ quill, but noticeably enough even for the one of the Grea Will⁴.

So, sixty years ago, beneath the walls of Mușat dynasty's place of worship⁵, the white gowns took place of the black stitches, but what began here would have an ephemeral existence, a quarter of century alone, the price of a generation and, at the same time, a history that eventually borrowed something from the drama of the unfortunate voivode.

As you can see, the evocation of this moment has come to me. I made the mistake to give way to my colleagues' insistence, as many as they are still going, along with whom, for sixteen years, I have climbed the Părului Hill over the same road the Father Stratonice climbed, the avaricious and the bitter prior so admirable portrayed by the gentle Hogaș⁶, the Old Calistru as he was known in its time.

I have to admit that I would have been more comfortable in an armchair from where to listen to someone else's torture in saving the subject, and this the more so as, be sure, that I do not lack the niggle enjoyment.

To be sincere, the approach of the subject has given to me great nightmares and I still have no certitude that I have come close with enough soul by the emotional load of the moment. What was

² Alexandru Lăpușneanu, the voivode of Moldavia in 1552-1561 and 1564-1568, was illegitimate son of the voivode Bogdan III (1479-1517), son of voivode Stefan the Great (1438-1504) of Moldavia. They belong to Mușat Dynasty (1363-1668).

³ Costache Negruzzi (1808-1868), the author of the novel *Alexandru Lapușneanu*, published in 1840 in *Dacia Literară*.

⁴ William Shakespeare

⁵ The *Stejarul* Station functioned in the Monastery built by Alexandru Lăpușneanu in 1560 to replace an older wooden sketen built in 1460 during Stefan the Great and fired by ottomans in 1476.

⁶ Calistrat Hogaș (1847-1917) was a Romania writer who loved to travel and describe his travels. His book *On the mountain roads* is a travel journal.

Așa cum sarea adună hulpav și parcimonios fiecare picătură de apă, așa a fost setea de cunoaștere și de împlinire profesională a cercetătorilor, în majoritate, alegere făcută de dascălii noștri, mulți dintre ei academicieni, ultimii din generația de elită interbelică, epoca de vârf a culturii românești.

Făcând o scurtă paranteză, mărturisim că titlul emblematic la care ne-am oprit este luat din opera lui Marin Sorescu, autor cu care am fost în vremea studenției coleg de dormitor; nu de cameră, pentru că dormitorul cu 40 de paturi se lăbărta copios aidoma unui stadion și pe care poetul din Bulzești Olteniei, veșnic în căutare de metafore, propusese să-l înnobilăm cu titlul de Hanul lui Mânjoală, aluzie la povestirea lui Conu Iancu, vajnicul mușchetar întru apărarea ortografiei, motiv pentru care căpătase în epocă porecla de Moș Virgulă.

Domnilor!

Revenind la subiect, e cazul să reconstituim, în primul rând, câte ceva din istoria acestui *Pion din munți al Almei Mater*, cum i-am zis cândva. Rămânem cu tot riscul la maniera de a îmbrăca realitatea în haina unui ușor amuzament și vom spune că istoria Stațiunii a fost până la urmă o dramă în trei acte: actul I, EDENUL, actul II, INFERNUL și trei, EXODUL.

Actul I în regia diriguitorilor noștri, profesorii Ion Gugiuman și Constantin Martiniuc, a fost începutul romantic și momentul de vârf al Instituției la umbra liniștită a statutului de bugetari. De la 6 cercetători și tematică la alegere, Stațiunea a căpătat, în doar câțiva ani, profilul unui adevărat Institut cu peste 40 de cercetători și tot atâția tehnicieni și laboranți, fiind acoperite cu specialiști și laboratoare toate disciplinele biologice și geonomice cu posibilități de abordare interdisciplinară după o tematică ancorată în programe naționale cu fundamentare pregnant economică.

A fost epoca de boom: 140 de salariați cu 2 contabili, 2 administratori, 5 paznici; de la trăsură cu cai, ajunsese la parc auto cu autobuz, camion, cisternă, microbuz, IMS-uri și, pe deasupra, vapor și șalupe pe Lacul Bicz.

clear to me from the beginning, was just the fact that I have always hated the evocations imbued with arid statistics, embellished with minor melodramatic facts, the evocations put into the coat of sobriety, sometimes unkind, as Junimea's mentor⁷ would say, the evocations of togated sobriety in the shadow of which the megalomaniac uppishnesses and unprofitable smugnesses can easily sneak.

In the end, I have chosen the way of the symbols and, from this point of view, I believe that the history of this Institution deserves a great one. That is why I once said that on the firmament of all that was built here, it could be written: Pângărați or the Thirstiness of the Salt Mountain. Just as the salt greedy gathers every drop of water, so was the thirst for knowledge and professional fulfillment of the researchers, most of us being selected by our professors, some of them members of Romanian Academy, the last ones of the inter-war elite generation, the Golden Age of Romanian culture. Parenthetically, I confess that the emblematic title I chose is taken from a piece of Marin Sorescu's work, with who I shared the same dormitory during our studentship. The poet from Bulzești-Olt, eternally looking for metaphors, has proposed to emblazon the 40 beds room, widening very much like a stadium, with the name of Mânjoală's Bait House, alluding to Master Iancu's⁸ story, the tenacious musketeer in defence of spelling, for which was nicknamed in his epoch as Old Comma.

Ladies and gentlemen!

Turning to the point, we need to recompose, first of all, something from the history of this Alma Mater's pawn from the mountains⁹, as once I named

⁷ Junimea is a cultural and literary association founded in 1863 in Iași. The mentioned mentor is Titu Maiorescu (1840-1917), writer, philosopher, advocate, educator, one of the founder of Romanian Academy etc, a scholar of his time.

⁸ Master Iancu was the nickname of Ion Luca Caragiale (1852-1912), a Romanian acid pamphleteer, dramatist, writer etc.

⁹ This is the metaphor used in a previous published history (2015) of the *Stejarul* Station. At the beginning, the Station functioned under the patronage and financial

Glumind, se spunea: ne lipsea locomotiva și calea ferată. Peisajul avea și el ceva spectacular și pitoresc. Îmi revine în memorie imaginea lui nea Vasile Moaleș, paznicul, care întâmpina oaspeții străini cu baltagul ținut haiducește, aducând mult cu plăieșii lui Ștefan, care odinioară ținuseră în șah oastea lui Jan Sobieski.

Chiar dacă Proust era de părere că fericirea-i o eroare, și bănuim că la mijloc era mai mult o chestiune pur personală, pentru noi ea a existat, dar a fost scurtă. Organigrama ajunsă la obezitate a luat forma bumerangului în momentul când s-a trecut la regimul de autofinanțare, cu cercetare în sistem contractual; a fost începutul INFERNULUI.

Ieșisem de sub tutela Universității. Eram în epoca Băra-Andreescu când toate colectivele erau angrenate în rezolvarea unor teme contractate în majoritate cu unități economice. Mijloacele materiale deveniseră insuficiente, iar teama de a nu rezolva optim obiectivele și de a pierde beneficiarii de care atârna supraviețuirea era sursă de tensiune și aprige dispute.

Apogeul era atins la ședințele de partid și sindicat care se prelungeau până în noapte, târziu. Ne onora cu prezența și cu intervențiile de rigoare, secretarul cu propaganda al județului, Constantin Potângă, care, de la o vreme, obosit, ne-a abandonat, nu înainte însă de a ne pune, a lehamite și cu năduf, pecetea de *ultraprofesioniști*. Degenerarea, conchidea tovarășul Potângă, doctor în sociologie, avea o singură cauză: nivelul precar de conștiință politică.

În același timp, freamătul nostru ajunsese până la urmă și pe ulița "Securității". Izolarea, numărul mare de mașini de scris, volumul imens de corespondență cu cercetătorii din afară, vizitele specialiștilor și studenților străini erau tot atâtea motive de neliniște, de clipe prețioase smulse somnului liniștit al celor responsabili de "unitatea de monolit" a nației.

La toate astea se adăuga apoi un oarecare nonconformism și discuțiile insinuante care se duceau pe marginea lecturilor.

it. I take the risk to apparel the reality in the amusement mantle and I would say that the history of Stejarul Station was eventually a three-act drama: act I, the Garden of EDEN, act II, the INFERNO, and act III, the EXODUS.

The first act, directed by our leading, professors Ion Gugiuman and Constantin Martiniuc, was a romantic beginning and a quiet time of the Institution in the shadow of its status of state budget receiver. From six researchers with study themes at free choice, within few years, the small Station has acquired the statute of a true Institute with more than 40 researchers and as many as technicians and assistants, all biology and geoscience disciplines taking the advantage of specialists and laboratories. Consequently, the interdisciplinary approach of themes anchored in national programmes with strong economic foundation was possible.

It was the boom epoch: 140 employees with 2 accountants, 2 administrators, 5 invigilators; from a horse carriage we got to the rolling stock with bus, truck, fuel truck, van, SUVs, and, above all, ship and motorboats on Bicaz Lake. Joking, I could say: we lacked a locomotive and the railroad for it. The landscape also had something spectacular and scenic. I remember the image of Vasile Moaleș, one of the invigilators, who welcomed the foreign guests keeping his hatchet as an outlaw, resembling a lot to the guardsmen, who had once had Jan Sobieski's¹⁰ army in check.

Even if Proust was of the opinion that the happiness is an error, and I suspect it was more of purely personal matter in it, for me it existed, but it was short. The overloaded organigram turned into a boomerang when the self-financing scheme based on research contracts began. It was the beginning of the INFERNO.

The University was not patronizing the Station anymore.

support of Alexandru Ioan Cuza University here, metaphorically named, *Alma Mater*.

¹⁰ Jan Sobieski, King of Poland and Grand Duke of Lithuania in 1674-1696, who firstly came with his army to Moldavia in 1686 trying to occupy it. The story written by Costache Negruzzi says that the 19 guardsmen of Neamț Fortress resisted for five days to the numerous Sobieski's army.

Se citeau Augustin Buzura, Alexandru Ivasiuc și Nicolaie Breban, ale căror scrieri, după cum se știe, făceau slalom printre canoanele realismului socialist; se tradusesse și se citea *Toamna Patriarhului* a lui Marquez, istoria unui dictator megaloman și paranoic. Fără îndoială, erau lucruri care se contabilizau; urmașii ohranei moldo-valahe deveniseră mai instruiți și mai subtili.

Așa se face că, în 1982, s-a hotărât aruncarea noastră în trei zări. A fost pedeapsa căzută asupra unor oameni a căror singură vină era iubirea cu patimă a meseriei și orgoliul profesional, iar pericolul invocat o simplă nălucă. Era o măsură inutilă, luată la panică și din frica de a nu se pierde niște fotolii. Precauția decidenților avea o bună doză de naivitate care nu-i onorează, dar și noi, cei ajunși în diasporă, ar trebui să trăim o oarecare jenă pentru că am primit o pedeapsă fără ca măcar să dăm un dizident.

Dezmembrarea n-a însemnat însă nici robie egipteană, nici captivitate babiloniană. Ea n-a reușit să învingă pentru că ultraprofioniștii tovarășului Potângă au continuat cu același entuziasm și cu aceeași îndârjire împlinirea profesională. Ea a sfârșit totuși cu ultimul act, EXODUL, migrarea aproape în majoritate spre *Alma mater*, atât spre universitățile de tradiție, cât și a celor nou apărute după '89.

Conferențieri sau profesori, colegii geologi-geografi, ca și biologii s-au integrat cu demnitate în elita universitară la: Institutul Agronomic și Universitatea Cuza din Iași, Universitatea Babes-Bolyai din Cluj-Napoca, Universitatea din Craiova, Universitățile Tomis din Constanța, Ștefan cel Mare din Suceava, Vasile Alecsandri din Bacău și Universitatea de Medicină și Farmacie din Tg. Mureș; mulți dintre ei s-au bucurat de aprecierea colectivelor în care s-au aflat, ajungând decani, prodecani, prorectori și chiar rectori. Aproape toți foștii cercetători de la Pângărați sunt premianți ai Academiei Române, unii de două și chiar de trei ori; unul dintre noi a avut șansa să ajungă chiar în rândul nemuritorilor.

Stimabililor!

Avem noi, românii, un proverb: frânghia e bine să fie lungă și vorba scurtă!

The Bâra-Andreescu¹¹ epoch began when all the collectives were involved in solving the research themes contracted mostly with economic units. The material resources had become poor and the fear of not optimally reaching the targets and losing the beneficiaries of which was depending our survival was source of tension and ardent disputes.

The apogee was attained during the communist party and trade union meetings lengthening late into the nights. The county's secretary of propaganda, Constantin Potângă, used to "grace" us with his presence and "necessary" comments, but after a while became tired and abandoned us not before to huffily wrote us off as ultra-professionals. Our degeneracy, concluded comrade Potângă, holding a PhD in sociology, had only one cause: our precarious level of political conscience.

At the same time, our effervescence was heard on the Securitate's¹² street. The seclusion, the large number of typewriters, the intense exchange of letters with foreigner scientists, the numerous visits of abroad specialists and students were just as many as reasons of suspicion and disrupted moments of quiet sleep for those responsible by the "monolithic unity" of our nation.

To all these, there was added some non-time-serving and insinuating debates on our readings. We read Augustin Buzura¹³, Alexandru Ivasiuc¹⁴, and Nicolae Breban¹⁵, whose writings, as it is known, made slalom among the canons of socialist realism; The Autumn of Patriarch of Garcia Marques, storying the life of a megalomaniac and paranoiac dictator, had been translated and read by us, then debated to length.

¹¹ Ion Bâra (1941-2007) and Ionel Andreescu (n.1933), biologists, were two of the Stations's directors.

¹² Securitate was the internal security force of communist Romania which functioned also as political police.

¹³ Augustin Buzura (1938-2017) was a Romanian proser and essayist who wrote, among others, about the conflict between the intellectual and communist system.

¹⁴ Alexandru Ivasiuc (1933-1977) was a Romanian proser and novelist. His novels are mostly concentrated on ethical and social-political debates.

¹⁵ Nicolae Breban (1934) is a Romanian writer, novelist, proser who was an opponent of Ceaușescu 's project of "cultural revolution" back in '70s.

E plin de adevăr, dar, vorba cântecului, eu nu mă pot ține pentru că mai am încă ceva de spus. Și ceea ce voi a vă spune este credința noastră că, până la urmă, sub Dealul Păru, între zidurile reci și înnegrite de vreme ale Lăpușneanului, s-a scris o carte. În ea, fiecare din noi își regăsește parte din tinerețe și din idealurile mai mult sau mai puțin împlinite.

Privesc cu ochii minții și văd că fiecare și-a scris propriul capitol sub un generic menit să-l definească. Văd titluri pestrițe, mai mult sau mai puțin inspirate, de la formulări stângace, aducând a raport de tură, și pînă la subtile sensuri kantiene, măsură a agonisiei spirituale. Văd titluri cu valoare de simbol, pline de umor, precum *Romeo și Julieta* sau *Vizirul*. Ele ascund personaje pe care "nu voi să le spui", vorba lui Caragiale, și a căror decodificare rămâne pe seama domniilor voastre.

În multe dintre pagini, unii colegi și-au mărturisit deja viața, încredințând-o posterității; lectura unora mă întristează. Mustesc de narcisism și-s atins grav de virusul amorului propriu, care, din păcate, și, după mulți, este cel mai mare lingușitor din lume. Ne-am bucura dacă la o nouă ediție, autorii ar trage puțin cu ochiul prin operele lui Montagne, La Bruyère sau Rochefoucauld.

Sub titlul *Copilul teribil al Geomorfologiei*, descopăr, apoi, pe colegul Ichim, căruia i-am zis cândva *Nicolae Labiș al Geografiei*. Cele două volume de lirică ale poetului, *Primele iubiri* și *Lupta cu inerția*, i se potrivesc. De la studiul împătimit al periglaciariului a ajuns, până la urmă, împreună cu colaboratorii, luptând cu inerția, la preocupări care au adus geomorfologia aproape de nevoile ingineresti, racordând-o la standardele exigențelor mondiale.

Îndârjirea colegului Ichim în luptă cu inerția era aidoma cu a poetului de la Mălini care se confesa :

Iertat să fie cel ce la mînie
Mi-a împlântat cuțitu' pîn' la os
Dar neuitat și neiertat să fie
Cel care-a rîs de gîndu-mi bătaios

Undoubtedly, there were things to be accounted for [by Securitate]; the followers of the Moldo-Wallachian Special Service of Information¹⁶ had become more educated and subtle.

So, in 1982, the decision to tear the Station in three parts fell on us. It was the punishment for the people who could be blamed only because of their passion and pride for profession, while the invoked threat which we would represented was a pure absurdity. It was a useless measure, taken by those who afraid of losing the comfort of their armchairs. The caution of the deciders had a good dose of naivety which did not compliment them, but we, who went to diaspora, also should be embarrassed because we were punished without even giving a dissident.

The Station breakdown meant neither Egyptian bondage, nor Babylonian captivity. It did not win because the comrade Potângă's ultra-professionals enthusiastically and inveterately continued their professional fulfillment. It ended, however, with the last act of the drama, the EXODUS, mostly to Alma Mater, both to universities of tradition and to the new ones that emerged after '90s.

As lecturers or professors, the geologists and geographers as well as the biologists worthily integrated in university elite, Alexandru Ioan Cuza University and Agronomic Institute of Iași, Babes-Bolyai University of Cluj-Napoca, University of Craiova, Tomis University of Constanța, Ștefan cel Mare University of Suceava, Vasile Alecsandri University of Bacău, and University of Medicine and Pharmacy of Târgu-Mureș; many of them were admired by their colleagues, some were elected as deans, vice-deans, vice-rectors or even rectors. Almost all of the former Pângărați researchers are prizemen of Romanian Academy, some two or even three times; one of us had the chance to reach even among the immortals¹⁷.

¹⁶ Special Service of Information that functioned before was replaced by Securitate (the communist political police) in 1948.

¹⁷ Here is about Dan Munteanu (1937-2016), Romanian biologist, specialized in ornitology, member of Romanian Academy

Iată-ne ajunși și la paginile bunului Nicu Bojoi, amicul nostru, cel ce a fost un dascăl și lider de excepție. Lider mai ales, pentru că avea ceva ce lipsește celor mai mulți care se înghesuie insolent spre vârful piramidei; din vocabularul său lipsea întotdeauna punitivul MERGI, optând pentru înțeleptul MERGEM.

Nu avea nimic din morga și superioritatea suverană a dascălului scorțos și grijuliu să nu devină prea amical. Deși născut în Flămânzii lui 1907, nu avea nimic din îndârjirea țăranului din celebra pictură a lui Octav Băncilă. Era calm, așezat și, în scris, îi aluneca condeiul ușor spre lirism, având slăbiciune pentru metaforă. Citiți-i *Geografia fizică a României* și veți descoperi pe Fănuș Neagu al Geografiei!

În sfârșit, dăm și de capitolul în care ne regăsim. Rândurile se înșiruie cumiți sub un titlu inconfundabil și puțin onorant: GIRUETA. Pecetea ne-a fost strecurată în biografie de bunul nostru prieten Ichim. Este un tribut al spiritului nostru conciliant, tradus adesea drept oportunism, și al sentimentalismului propriu, care, ce e drept, nu de puține ori, vămuiește adevărul

De altfel, după filozofia decanului nostru de vârstă, Conu Vasile Ionescu, noi aparținem la două lumi total opuse: Ichim, Șesului, noi, Muntelui. Șesul cu limpezimea orizontului duce la cutezanță, vecină cu imprudența, dar și la intoleranță asociată cu simțul acut al proprietății, motiv pentru care, aici, spunea Conu Vasile, hatul ajunge mai mare decât ogorul. Dimpotrivă, muntele îndeamnă la resemnare și prudență; fiecare copac poate ascunde, virtual, un dușman.

Ajunși la final stăm și ne întrebăm. În fond, ce a însemnat, până la urmă, Stațiunea Stejarul? A fost, credem, o instituție emblematică pentru ceea ce poate clădi entuziasmul și simțul responsabilității civice a unei generații, care, pe deasupra, a știut să-și adauge din mers și ceea ce nu-i oferă sistemul instructiv al acelor vremuri.

Încheind, socotim că este momentul, ca o parte din bucuria revederii noastre de astăzi, îngăduită de Providența care n-a fost prea generoasă cu mulți din colegii noștri trecuți deja în lumea umbrelor, să le-o împărtășim și lor: conului Vasile Ionescu, Nicu Bojoi, Ioniță Ichim, Ion Băra,

Honored audience!

We, the Romanians, have a proverb: the rope is good to be long and the story, short. It is true but, as a song says, I cannot hold because I still have something to say. And what I am going to tell is my belief that, in the end, in the shadow of Părului Hill, between the cold and smoky walls of Lăpușneanu, a book was written. In it, each of us retrieves a part of his youth and of his more or less fulfilled ideals.

I look with my mind's eyes and I see that everyone has written his own chapter under a title meant to define him. I see miscellaneous titles, more or less inspired, from the awkward ones, resembling the arid accounts, to subtle Kantian meanings, measure of spiritual achievements. I see symbolic titles full of humor, such as Romeo and Juliet or the Vizier. They disguise characters that I will not reveal, but you will figure out them.

In many pages, some of my colleagues have already confessed their lives, entrusting them to posterity; reading some of them make me sad. They abound of narcissism and are seriously touched by amour-propre, which, unfortunately, is, after many, the biggest adulator from the world. We would be glad if for a new edition, the authors would steal a glance to the writings of Montagne, La Bruyère or Rochefoucauld.

Under the title The formidable child of Geomorphology, I discover my colleague Ioniță Ichim¹⁸ whom I named once Nicolae Labiș¹⁹ of Geography. Two poetry volumes, The first loves and The fight with the inertia, written by Labiș match him. From the impassioned study of the periglacial environments, he finally arrived, together with his collaborators, fighting with inertia, to the preoccupation that brought the geomorphology close to the engineering needs, joining it to the standards of worldwide exigencies.

¹⁸ Ioniță Ichim (1940-2007) was a geomorphologist who published more than 150 articles and 12 books, being for a while (1990-1995) the director of the *Stejarul* Station as it survived after its three part breakdowns.

¹⁹ Nicolae Labiș (1935-1956) was a Romanian dissident poet born in Mălini (Suceava) who suspectly died in an accident. He was considered by one of his reviewers, "the mace of a generation".

Costică Măzăreanu, Giovanni Lupașcu, Pusi și Costică Rujinski, Florin Mihăilescu, Sorin Mărieș și Veronica Saucenițeanu. Bunii noștri colegi, fiți liniștiți! De câte ori vom ridica pocalul în sănătatea noastră, ne vom gândi și la voi. În curând va veni și vremea cununiei noastre cu eternitatea; va fi prima dată când nu vom întârzia.

The devotion of my colleague Ichim in his struggle with inertia was as the poet from Mălini confessed:

*Forgiven be the angered one
That stuck his knife deep to my bone
But unforgettable and unforgivable be the one
Who laughed by my chivalrous thought²⁰*

Here we come to the pages dedicated to my good friend Nicu Bojo²¹, the one who was a great educator and leader. As a leader he had something lacking to most of those insolently crawling toward the top of the pyramid. The punitive YOU DO lacks from his vocabulary, being replaced with the wise WE DO.

*He had nothing from the pomposity and arrogance of a stiffed educator paying attention not to be too friendly. Although he was born in Flămânzi village where the peasants revolted in 1907, he had nothing from their grimness admirable portrayed by Octav Băncilă²². He was calm, sober, and a disposition to metaphor in his writings can be found. Read, *The Physiscal geography of Romania* written by him and you will find Fănuș Neagu²³!*

Finally, we arrive to the chapter where I found myself. The lines unobtrusively flow under an unmistakable and unflattering title: the WEATHER VANE. My good friend Ichim put this seal on my biography. It was meant to depict my conciliatory spirit, often taken as opportunism, and my own sentimentality which, admittedly, times and often, bends the immediate truth.

Moreover, according to the philosophy of the oldest of us, Master Vasile Ionescu²⁴, we belonged to totally opposed worlds: Ichim to the Plain, myself to the Mountain. The clearing of the plain horizon

²⁰ The tetrastich is rhymed in Romanian language.

²¹ Ion (Nicu) Bojoi (1936-1998) was a geographer, professor and Rector of Ștefan cel Mare University of Suceava.

²² Octav Băncilă (1872-1944) was a Romanian realist painter who portrayed the peasant's revolts from 1907.

²³ Fănuș Neagu (1932-2011) was a Romanian writer, novelist, and dramatist

²⁴ Vasile Ionescu (1914-1992), was a Romanian biologist, author of an important monograph, *The vertebrates from Romania* (1968), Academy of Romania Publishing House, among others.

bring to audacity, neighboring with incaution, and also to implacability associated with an acute sense of property, which is why here, as Master Vasile said, the field margin gets bigger than the field itself. On the contrary, the mountain urges to resignation and caution; every tree can hide eventually an enemy.

Coming to the end I can't help to ask: after all, what did the Stejarul Station mean? It was, I think, an emblematic institution for what could be built by the enthusiasm and the sense of civic responsibility of a generation that, above all, knew how to add along the way what did not received from the instructional system of those times.

Concluding, I think it is the time that part of the joy for our gathering, allowed by Providence that was not too generous with the colleagues already in the shadow world, to share with them: Master Vasile Ionescu, Nicu Bojoi, Ioniță Ichim, Ion Băra, Costică Măzăreanu, Giovanni Lupașcu, Pusi and Costică Rujinski, Florin Mihăilescu, Sorin Mărieș, and Veronica Saucenițeanu²⁵. Our good colleagues, be peaceful! Whenever we'll pick up the goblet in our health, we'll think of you as well. The time of our marriage with the eternity will come soon. It will be the first time we won't be late!

(Traducere - Crina MICLĂUȘ, Alexandru Ioan Cuza
University of Iași, October 2016)

²⁵ All these people were researchers at *Stejarul* Station from Pângărați

Symposium

National Symposium on Geomorphology, 33rd Edition, Iași, Romania, May 11-14, 2017

The 33rd edition of Romanian Geomorphology Symposium was held in Iași, between 11 and 14 May 2017. Organized by the Department of Geography of "Alexandru Ioan Cuza" University of Iași, the symposium represented a new opportunity for many scientists to present and to discuss their new results in many geomorphologic fields: tectonic geomorphology, fluvial geomorphology, slope processes, mountain geomorphology (glacial and periglacial), coastal geomorphology, soil erosion, geomorphometry, paleogeomorphology, dendrogeomorphology, geomorphosites, hazards and associated risks.

During the two days of indoor sessions (kindly hosted by "Mihai Eminescu" Central University Library Iași), were presented 19 oral and 25 posters. For the first time, this edition hosted five invited speakers, well known scientists in our field: Prof. (retired) Ian Evans from Durham University (United Kingdom); Prof. Jean Poesen from Leuven University (Belgium), Doctor Honoris Causa of "Alexandru Ioan Cuza" University of Iași; Prof. Dan Bălțeanu, member of the Romanian Academy, Head of the Institute of Geography (Romania), Prof. Mauro Soldati, the actual President of International Association of Geomorphologists, from Modena and Reggio Emilia University (Italy), and Prof. Paolo Tarolli from Padova University (Italy). The oral sessions were plenary grouped in 6 slots of 4-8 presentations, and the poster session (a very animated session), organized on the evening of 12 May, reached 25 posters, presented especially by younger geomorphologists. Overall, more than 60 participants have attended the symposium sessions. They have represented many academic centers from Romania (Bucharest, Cluj-Napoca, Timișoara, Iași, Suceava, and

Constanța) and from other European countries (Belgium, Bulgaria, Italy, and United Kingdom).

The fieldtrips were organized in the afternoon of the third day and in the fourth one. They included two routes in Central Moldavian Plateau and Jijia Hills. The main topics were slope processes, land degradation, anthropic lakes and sediments, and threatened cultural heritages.

Many of the themes discussed during the symposium were already published in the first volume of the "Proceedings of the Romanian Geomorphology Symposium" edited by Mihai Niculiță and Mihai Ciprian Mărgărint (<http://www.geo.uaic.ro/sng2017/>). The volume includes two introductive articles about Romanian Association of Geomorphologists and "Mihai Eminescu" Central University Library Iasi, 33 papers presented during the symposium sessions, and 6 papers dedicated to the main objectives visited during the fieldtrips.

According to the Statute of Romanian Association of Geomorphologists, this event was the occasion for the election of the president and the council members. The new leading structure of Romanian Association of Geomorphologists is: the President of our association – Dr. Mihai Alexandru Micu (Institute of Geography, Romanian Academy); the Vice-Presidents: Prof. Maria Rădoane, Prof. Petru Urdea, Prof. Mircea Voiculescu, Lect. Olimpiu Pop, and Assoc. Prof. Mihai Ciprian Mărgărint; Secretary General, Prof. Alfred Vespremeanu-Stroe; Council Members: Prof. Iuliana Armaș; Dr. Marta Jurchescu; Prof. Sandu Boengiu; Assoc. Prof. Nicolae Cruceru; Prof. Dan Dumitriu; Lect. Mihai Niculiță; Lect. Florin Tătui.



(Ciprian Mihai MĂRGĂRINT, Mihai NICULIȚĂ, Department of Geography, Faculty of Geography and Geology, "Alexandru Ioan Cuza" University of Iași, November 2017)

Symposium

SEDIBUD Workshop, 11th Edition, Baru, Romania, September 5-8, 2017

On 5-8 September 2017, an IAG SEDIBUD (Sediment Budgets in Cold Environments) Workshop was held for the first time in Romania, at the Research Base of the Babeş-Bolyai University, located in Baru (Hunedoara County). The 11th SEDIBUD Workshop entitled „*Relationships between climate change, vegetation cover and sediment fluxes in high latitude/high altitude cold environments*” was organized by the following institutions: International Association of Geomorphologists (IAG), SEDIBUD Working Group, Babeş-Bolyai University, West University of Timișoara and Romanian Association of Geomorphologists.

The conference started with a welcome cocktail and icebreaker on 5 September. The conference was attended by about 30 scientists from France, Norway, Czech Republic, Poland, South Africa, Italy, Bulgaria and Romania. Besides the scientific program, a SEDIBUD business meeting took part on 6 September, after the poster session.

Twenty-one papers dealing with sediment fluxes in cold environments, denudation rates of high mountains, rock glaciers as part of periglacial debris transport system, snow avalanches reconstructions using tree-ring analyses, permafrost occurrence in mid-latitude mountains and the dynamics of slope processes in mountain areas were presented within three sections. The time span for

each oral presentation was limited to 20 minutes, but profound discussions were encouraged by the organizers after each presentation.

The majority of the participants were young PhD students or post-doctoral geomorphologists, encouraged to participate at this workshop by the free conference registration. Two travel grants have been awarded by the IAG for the best applications of two PhD students.

All the participants to the conference joined the one-day scientific field trip organized in the western part of the Parâng Mountains (Southern Carpathians). Since the visited region was profoundly shaped by the Pleistocene glaciers, the field application inspected the late Pleistocene glacial features within the upper sector of the Mija Valley. The excursion allowed the participants to see several periglacial landforms and to discuss about mountain permafrost monitoring in Southern Carpathians. Associated landforms of present-day geomorphic activity (rockfalls, snow avalanches, rock avalanches, debris flows, periglacial activity etc.) in the alpine area between Parângu Mic and Cârja were visited by the participants.

After the 9th IAG conference in New Delhi (6-11.11.2017), the SEDIBUD working group (2005-2017) has formally ended its scientific activity within IAG which means that the 11th SEDIBUD workshop was the last one organized by this working group.



(Alexandru Lucian Onaca, West University of Timișoara, October 2017)

Symposium

International Conference on Geomorphology, 9th Edition, New-Delhi, India, November 6-11, 2017

The 9th International Conference on Geomorphology (ICG) was organized by the Indian Institute of Geomorphologists in New Delhi at Vigyan Bhawan from the 6th to the 11th of November, 2017. The main theme was *Geomorphology and Society* and it included 39 scientific sessions and a special session for young geomorphologists. In addition there were two pre-conference, six post-conference and a mid-conference field trip that focused on different topics ranging from scientific to cultural. The ICG was attended by 477 delegates from 44 countries and registered 740 abstracts out of which 477 were approved for oral presentation and 263 for poster presentation.

The Romanian delegation was formed out of 9 delegates from 3 institutions: Institute of Geography, Romanian Academy, Bucharest (Dan Bălteanu, Mihai Micu) University of Bucharest (Iuliana Armaş, Luminiţa Preoteasa, Alfred Vespremeanu-Stroe, and Florin Zăinescu) and West University of Timisoara (Brigitte Magori, Flavius Sîrbu, and Petru Urdea).

There were a total of 10 papers submitted by Romanian authors in eight different sessions, out of which six were presented orally and four as poster. In addition to this there were four more papers which had three more Romanian co-authors.

Besides the scientific part the ICG had an important administrative part which consisted, among others, in two Executive Committee meetings that decided on a number of aspects on which the IAG/AIG will focus on the next four years.

The most important of these decisions was the election of the new Executive Committee of the IAG/AIG (2017-2021) which will be presided by Prof. Mauro Soldati and that will have a representative from Romania (Secretary General Mihai Micu). Other decisions from the Executive Committee established the new and also the continuing Working Groups. For the next years two regional conferences are planned. The first one is schedule to take place in Greece in 2019 and the second one in Iran in 2020. The next ICG will be hosted by Coimbra, Portugal and will be organized in 2021 by the University of Coimbra with the focal theme *Geomorphology and global Change*.



(Flavius Sîrbu, West University of Timișoara, October 2017)

Symposium

École d'été doctorale francophone

Méthodes dendrochronologiques, d'analyse des palynomorphes et documentaires utilisées dans la reconstitution des changements climatiques et environnementaux Baru, Roumanie, 10-14 Septembre, 2017

L'école d'été doctorale francophone intitulée « Méthodes dendrochronologiques, d'analyse des palynomorphes et documentaires utilisées dans la reconstitution des changements climatiques et environnementaux » a été organisée par l'École Doctorale Géographie et Laboratoire de Dendrochronologie de l'Université Babeş-Bolyai (UBB), en collaboration avec l'Agence Universitaire de la Francophonie (AUF) et L'Association Roumaine des Géomorphologues (AGR), entre 10-14 septembre 2017, à la Station de Recherche à Baru (département Hunedoara, Roumanie). L'école d'été a réuni 19 participants, dont 10 doctorants, 3 chercheurs post-doctorants et 6 intervenants provenant des universités et des laboratoires de recherche de Bulgarie, France et Roumanie. La Station de Recherche de l'UBB a offert un cadre approprié de rassemblement et d'échange de connaissances et d'idées entre doctorants et chercheurs ayant un intérêt particulier pour la reconstitution diachronique des conditions climatiques et environnementales dans divers milieux montagneux et littoraux. Lors des interventions et des discussions l'accent a été mis sur l'application des méthodes dendrochronologiques (dendrogéomorphologie et dendroclimatologie), d'analyse des palynomorphes et des documents cartographiques historiques, pour reconstituer la variabilité climatique et les changements environnementaux. Un regard critique a été porté sur les possibilités que chacune de ces méthodes offre, mais aussi sur leurs limites dans la reconstitution spatio-temporelle des événements perturbateurs.

Les débats se sont articulés principalement autour de 4 thématiques :

1. Histoire holocène des changements hydrologiques et du couvert végétal reconstituée en utilisant l'analyse des palynomorphes (pollens, thécamibiens) préservés dans les milieux tourbeux.
2. Activité morphodynamique dans les milieux forestiers montagneux retracée à partir des enregistrements préservés dans les cernes des arbres ;
3. Variabilité climatique en haute montagne reconstituée par l'approche dendroclimatique ;
4. Historique des influences anthropiques dans le milieu littoral reconstitué par l'analyse combinée des documents cartographiques historiques, des photographies aériennes et des méthodes dendrochronologiques.

La première journée a été entièrement dédiée aux présentations des intervenants et aux discussions concernant l'objet d'étude, les principes de base et les domaines d'application spécifiques à chacune des méthodes de reconstitution environnementale mises en discussion.

Une sortie sur le terrain a été ensuite organisée dans les Carpates Méridionales, dans le Massif du Parâng (dans un couloir d'avalanche situé sur le versant sud-ouest au-dessous du sommet Parângul Mic, à 2074 m altitude), ayant comme objectif principal de reconstituer la fréquence des avalanches de neige et d'évaluer les effets de celles-ci sur la forêt. Le site d'étude a offert la possibilité de reconstituer les événements passés qui ont perturbé la forêt d'épicéas (*Picea abies* (L.) Karst.) au long de ce couloir fréquemment affecté par les

avalanches de neige. Sur le terrain, les doctorants se sont familiarisés avec les techniques de collecte d'information concernant les arbres perturbés par les avalanches de neige (localisation dans le couloir, position sociale, type de dommage visible sur les troncs ou branches, position de l'échantillonnage sur le tronc etc.). Ils ont eu l'occasion aussi de tester, en conditions réelles, diverses stratégies d'échantillonnage et d'utiliser les instruments spécifiques pour la collecte de données (GPS, clinomètre, télémètre, tarière Pressler etc.).

De retour à la station de recherche, les participants ont travaillé sur la préparation et l'analyse des échantillons de bois (carottes et rondelles), ainsi que sur l'interprétation des résultats. Trois équipes ont travaillé simultanément et indépendamment dans l'analyse des échantillons. Pour la reconstitution dendrogéomorphologique visant le site d'étude du Parâng, une équipe a analysé les carottes, tandis qu'une autre équipe a utilisé uniquement des rondelles des épicéas provenant du même site. La troisième équipe a exploré les possibilités de reconstituer les années-événements utilisant des rondelles des pins de Bosnie (*Pinus heldreichii*) provenant de 3 couloirs d'avalanches du Massif du Pirin (Bulgarie). Ces couloirs d'avalanches ont été étudiés en juillet 2017, lors de la mission de terrain effectuée dans le cadre du projet de recherche conjoint « *Zonage des aléas géomorphologiques dans les espaces touristiques des massifs du Parâng (Roumanie) et du Pirin (Bulgarie)* » financé par l'Agence Universitaire de la

Francophonie (AUF) et Fonds de Recherche Scientifique (FRS) de Bulgarie.

L'analyse des échantillons a suivi la méthodologie classique, commençant par le comptage des cernes sous microscope, ensuite les mesures de l'épaisseur des cernes utilisant le système LINTAB 5 composé d'un stéréomicroscope et d'une table de comptage connectés à un ordinateur équipé du logiciel TSAP^{Win} Scientific, ensemble conçu par RINNTECH. L'analyse des échantillons et des données collectées sur le terrain a donné la possibilité aux doctorants d'obtenir une fréquence minimale des événements avalancheux le long des couloirs étudiés. Les résultats obtenus par chaque équipe ont été présentés lors de la réunion finale du quatrième jour et on fait l'objet des discussions entre doctorants, chercheurs et intervenants.

L'objectif éducationnel de l'école d'été a été atteint pleinement : rassembler des doctorants, des chercheurs post-doctorants et des intervenants provenant de domaines de recherche différents, mais ayant tous un intérêt particulier pour la reconstitution des conditions environnementales et climatiques du passé. Les doctorants participants ont été encouragés à appliquer des approches dendrochronologiques et palynologiques dans leurs recherches futures pour les reconstitutions climatiques et environnementales. La réunion a aussi donné l'occasion aux doctorants et chercheurs de créer des réseaux et d'entamer des collaborations futures pour la recherche scientifique interdisciplinaire.

Miscellanea



(Olimpiu POP, Babeş-Bolyai University of Cluj Napoca, October 2017)