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The analysis of the flysch badlands inventory in central Istria, Croatia

Vlatko Gulam*, Davor Pollak* and László Podolszki*

* Department of Hydrogeology and Engineering Geology, Croatian Geological Survey, Sachsova 2, 10000 Zagreb, Croatia; (vlatko.gulam@hgi-cgs.hr, davor.pollak@hgi-cgs.hr, laszlo.podolszki@hgi-cgs.hr)

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ABSTRACT

The south-western part of Croatia, i.e. the area of central Istria, comprises the research area, (approximately 500 km^2). It is characterized by a flysch complex with a great number of isolated relief landforms, termed badlands. The importance of badlands (areas with sparse or no vegetation) lies in the fact that sediment production from these areas is 8000 times higher than from areas with vegetation. Here, the badland inventory presents 5568 distinguishable badlands (polygons) with a total badland area of 10.7 km^2. Spatial analysis of the badland inventory showed that erosive channel flow at the steep slope foot is the most important factor in badland formation and development for the area of central Istria.

Keywords: badland, inventory, spatial analysis, flysch complex, central Istria

1. INTRODUCTION

The long period of time necessary for the majority of the Earth's relief formation presents a problem in measuring the processes which occur during that period (HOWARD & KERBY, 1983). On a smaller scale (in area and time), the badlands as landforms can be used as case studies for research and understanding the bigger systems (WAINWRIGHT & BRAZIER, 2011) because all the exogenetic processes: weathering, denudation and deposition occur and interweave there. Changes which occur on badland relief are dynamic, and can be measured because they happen in a relatively short time span. Badlands are also very common worldwide (Mediterranean environment: Tunisia, DE PLOEY, 1974; Morocco, IMESON et al., 1982.; WAINWRIGHT & THORNES, 2003., drylands in Africa: BOARDMAN et al., 2003.; ERIKSSON, et al., 2003.; FEOLI et al., 2002.; ACHTEN et al., 2008; Chile: MAERKER et al., 2008; India: JOSHI et al., 2009; China: LIU et al., 1985). These are the main reasons for the large number of scientific papers in which badland detection, description and measurements of different processes are presented.

The term badland originates from the early French colonists in northern America who encountered terrain that was bad, or difficult to cross (WAINWRIGHT & BRAZIER, 2011). There are many definitions of badlands in the literature but they all refer to the relief with or without sparse vegetation cover, steep slope inclination, a dense hydrographic network, with or without a thin regolith, and the materials are usually unconsolidated or weakly consolidated clay rich bedrock. Marls and recent alluvium in particular can erode rapidly and they have a great denudation value. There are also some scientific papers in which the denudation values are smaller because some badlands or at least some parts of badlands can be stable for thousands of years (WISE et al., 1982; WAINWRIGHT, 1994; HOWARD, 1997; DÍAZ-HERNÁNDEZ & JULIÁ, 2006). Badlands can also be defined as areas where intensive piping, erosion and mass wasting processes combine with fluvial processes to produce a rugged, hummocky, dissected and strongly gullied topography (BRYAN & YAIR, 1982).

A large number of factors and processes have an influence on badland formation and maintaining it as a complex relief form. The analysis and research of badlands can be undertaken at a variety of different scales. Although numerous factors and processes influence badland development, most areas in which natural badland development is extensive share certain lithological and climatic characteristics (BRYAN & YAIR, 1982). Also in badland definitions sparse or no vegetation at all is one of the most important factors for the persistence of badlands and not the cause of badland formation. In recent times the anthropogenic influence is important in badland development, as in many locations the vegetation cover is disappearing due to human activity.

Badlands in central Istria are isolated relief units (in the terms of area they are smaller than 1 km^2), not like the globally known type and investigated localities (which can stretch over more than a dozen square kilometres): Dinosaur Provincial Park, Alberta, Canada (BRYAN et al. 1987) or the Henry Mountains, Utah, SAD (GILBERT, 1880; HOWARD, 1994). The small areas of badlands in central Istria (the biggest badland has an area of 0.08 km^2) suggest that an unstable chain of exogenetic processes exist in that area which dictates badland formation, development and persistence in conditions (lithological, geomorphological and climatic ones) which are characteristic for the central Istrian area. These are detailed in this paper.

In the majority of the literature which refers to the investigation of erosion in the area of central Istria, it is stressed that the aforementioned area is characterized by very intensive exogenetic processes (JURAK et al., 2002; PETRAŠ et al., 2008; ZORN, 2009a, 2009b). Here, the badlands are marked as locations with excessive erosion (JURAK & FABIĆ, 2000), with sediment production up to 8000 times higher than in locations which have some kind of vegetation cover. High sediment production from bare flysch in combination with intensive surface flows (flysch is characterized by low infiltration values and rapid runoff formation) are very common causes of backfilling of artificial accumulations, retention dams and drainage canals in traffic infrastructure.

The goal of this work is to present the badland inventory and results of spatial analysis which can help in understanding the conditions necessary for badland formation and development in the flysch area of central Istria.

2. BASIC CHARATERISTICS OF THE ISTRIAN PENINSULA

Geographical, geological and morphological characteristics of the Istrian peninsula differ from the rest of Croatia. This is the main reason why the Istrian peninsula is usually regarded as a separate unit (VRESK, 1987; VLAHOVIĆ et al., 2003.) in the scientific literature, and also why Istria is treated as a separate administrative unit.

2.1. Geographical characteristics of the Istrian peninsula

The administrative unit of Istria is located in the southwestern part of Croatia (Fig. 1) with an area of 2820 km^2.

The climate of the Istrian peninsula is also variable, particularly in big differences in arithmetic mean of annual values of precipitation. In the south-west and west these vary from 800–900 mm/year, in the middle part from 1200–1300 mm/year and in the north-east (mountainous area) from 2000–2500 mm/year (GAJIĆ-ČAPKA et al., 2003). Similar differences can also be noticed in the arithmetic mean of annual values of temperature: from 14°C in the south-west to 6°C in the north-east (ZANINOVIĆ et al., 2004). So, there are three types of climate on the Istrian peninsula (OGRIN, 2005): two types of submediterranean climate and a mediterranean one. According to Köppen, these types are: Cfb (in the central part), Cfa (in the eastern and western coastal part) and Cs (in southern coastal part). The Istrian peninsula is mainly covered by forest (61.1 %). Agricultural land 35.4 %, urban and artificial areas 3.3 % and water surfaces account for around 0.2 % of the land surface (AZO, 2006).

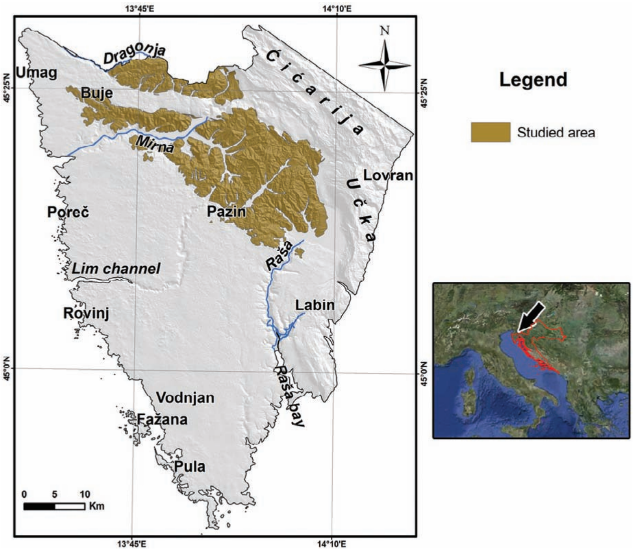

Figure 1: Research area in the central part of the Istrian peninsula (marked by brown).

2.2. Geological characteristics of the Istrian peninsula

Postsedimentation tertiary tectonics has influenced the complex structure of deposits of the Adriatic carbonate platform, but the Istrian peninsula is one of the „stratigraphic oases" where it is possible to study all major events from geological history (VELIĆ et al., 2003). From the geological aspect, the Istrian peninsula can be divided into three major regions (which also correspond to the division into historical regions according to the local population):

1) Red Istria – Jurassic-Cretaceous-Eocene plains (southern and western part of the peninsula): the term originates from the thick Quaternary deposits of terra rossa which overlie carbonate bedrock of Mesozoic and Tertiary age;
2) White Istria – Cretaceous-Eocene carbonate platform and clastic zone (mainly the massifs of Ćićarija and Učka) with characteristically imbricated structure: the term originates from the white colour of Cretaceous and Eocene weathered limestones;
3) Grey Istria – Eocene flysch basin (central Istria): the term originates from the grey colour of the marls which are interbedded with sandstones which together form the flysch complex.

Tectonic units of the Istrian peninsula can generally be divided in the Laramian tectonic unit (numbered 1 in Fig. 2) and Postlaramian tectonic units (2-5 in Fig. 2; POLŠAK & ŠIKIĆ, 1973). Here, the most important unit is unit 3 (Pazin synclinorium) and part of unit 4 (Trieste synclinorium). The Pazin synclinorium represents the tectonic unit formed from the Eocene to the Oligocene, during which time flysch sedimentation occurred in central Istria (BERGANT et al., 2003).

2.3. Geological characteristics of the research area

The research area includes almost the entire flysch complex on the Istrian peninsula. Only tectonic unit 5 is not included in the research area (the imbricated and overthrusted structure of the Ćićarija, Učka and Labin basin), although it contains flysch deposits (Fig. 2). The reason for the exclusion of this unit lies within the goal of this research: determination of the conditions necessary for badland formation and development (ie. which of the exogenetic processes is important). In unit 5, the tectonic movements are one of the main factors in relief formation and those movements are hard to measure and quantify (they appear in geological time), so unit 5 was not taken into consideration. The research area is in the central part of the Istrian peninsula (approximately 487 km^2, Fig. 1).

The research area mainly consists of deposits of Globigerina marl and flysch which have low durability and high erodibility, confirmed by JURAK et al. (2002), PETRAŠ et al. (2008) and GULAM (2012), and predetermined by the lithological, mineralogical, physical and mechanical properties of these materials. These properties of the Globigerina marl and flysch develop under a special set of conditions. The stratigraphic setting of the marl and flysch deposits of middle Istria is shown on a simplified geologic column in Fig. 3, from which it can also be seen that the base of the flysch complex and Globigerina sediments is composed of foraminiferal limestones with thin transitional sediments (marls with crabs).

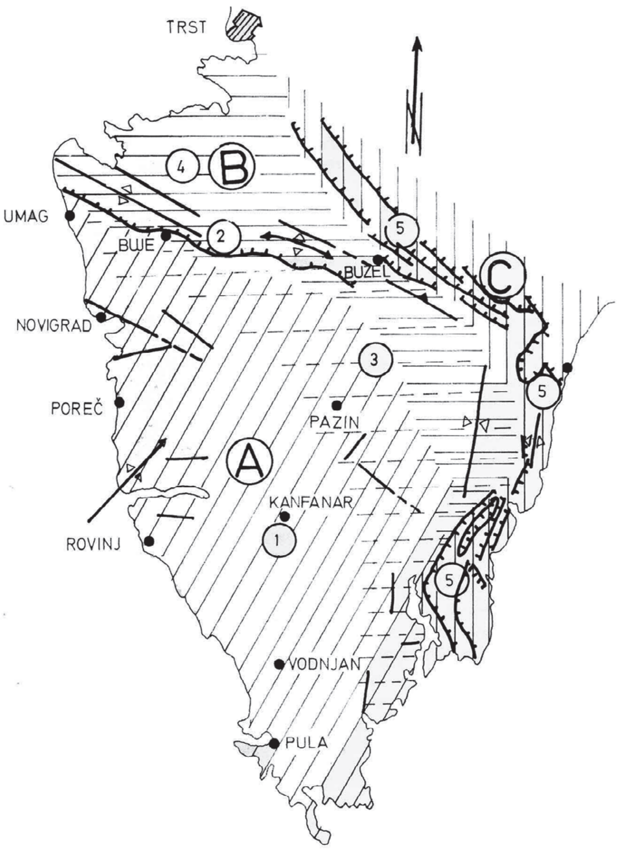

Figure 2: Tectonic units of the Istrian peninsula (according to POLŠAK & ŠIKIĆ, 1973); 1. West Istrian Jurassic - Cretaceous anticline; 2. Savudrija - Buzet anticline; 3. Pazin synclinorium; 4. Trst synclinorium; 5. Imbricated and overthrusted structure of Ćićarija, Učka and Labin basin; A – Autochton; B - Transitiona structures; C – Paraautochton.

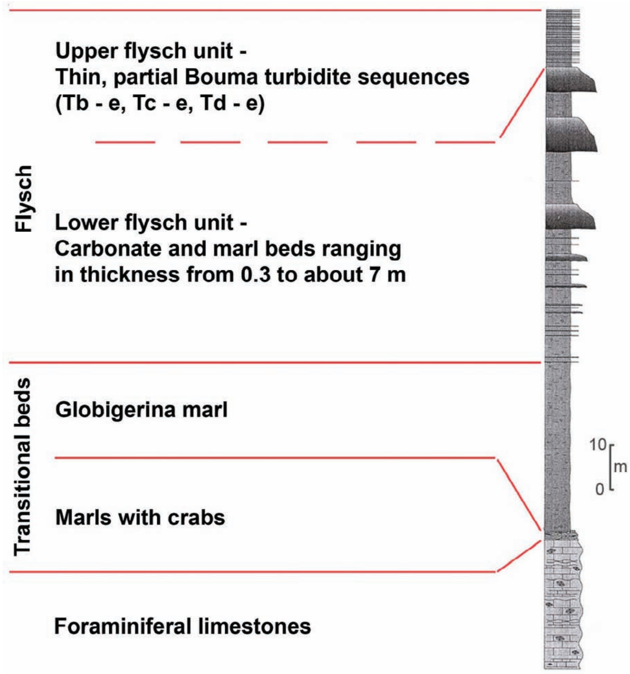

Figure 3: A simplified geological column of Kotli in central Istria (according to BERGANT et al., 2003).

The term Globigerina marl originates from the planktonic foraminifera Globigerina and contains different ratios of carbonate and siliciclastic components. The carbonate component is mainly crypto- to microcrystalline calcite, while the siliciclastic components are mainly quartz and clay which originated from the mainland (BERGANT et al., 2003). Globigerina marls are deposited in a deep sea environment as confirmed by their constituent microfauna (JURAČIĆ, 1980).

Flysch of the central Istria is superpositioned on the Globigerina marl and can be divided into the upper and lower parts (BERGANT et al., 2003), with the complex thickness of about 90-100 m (Fig. 3). The lower part of the flysch complex is composed of a rhythmical exchange of marl and carbonate sediments varying in thickness from 0.3 up to 7 m. Carbonate deposits can be conglomerates, foraminiferal breccia, arenites and siltstones. Within the lower part of the flysch complex, carbonate megalayers of various thicknesses are very common (up to couple of metres, BERGANT et al., 2003). In the upper part of the flysch complex there are deposits of carbonate-siliciclastic turbidite sediments which are thinly bedded and represent only the upper part of the Bouma turbidite sequence (Tb-e, Tc-e and Td-e, BERGANT et al., 2003), so called the undercut turbidite sequence (BERGANT et al., 2003).

3. RESULTS

3.1. Relief dissection

The relief dissection map generally indicates the areas of higher relief energy which equates to areas of potential higher

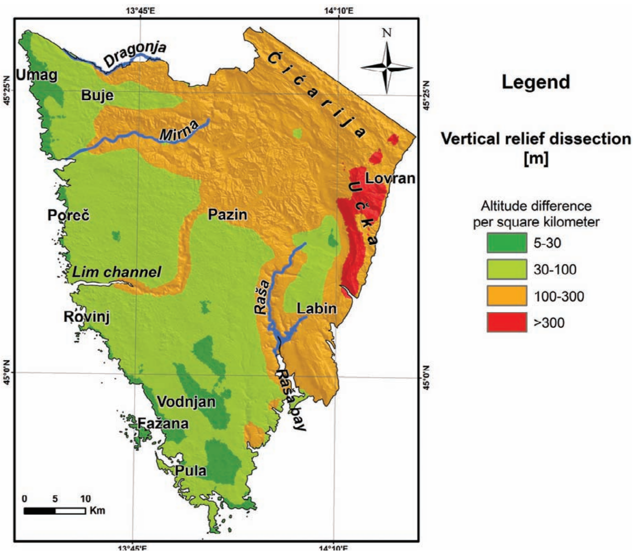

Figure 4: Map of the relief dissection of Istria.

values of denudation and vice versa (MARKOVIĆ, 1983). For some areas the value of relief dissection is determined by lithology, type and thickness of the engineering soil, tectonic activity and the type of dominant exogenetic processes.

The relief dissection map of Istria was generated using a topographic map at 1:25.000 scale. Categorization of the relief dissection was carried out according to GAMS et al. (1985) and is shown in Fig. 4. It can be concluded that the map of the relief dissection (Fig. 4) also corresponds to the potential zones of exogenetic processes intensity. The south-western part of the Istrian peninsula is mainly characterized by plains of low dissection (6.6 %) and the relief of low dissection (46.9 %). These attributes are predefined by: low erodible carbonate rocks of Jurassic and Cretaceous age and the „modest" tectonic activity in that area.

The central part of Istria, where the flysch complex deposits lie, is characterized by the relief of moderate dissection (100-300 m). Although the tectonic activity is not emphasized in this area, the relief of moderate dissection is the consequence of high erodibility and low durability of these flysch sediments. Because of these properties the central part of Istria is characterized by intense exogenetic processes. All the canyons on the Istrian peninsula (Mirna, Lim, Raša) and the mountain massive of Ćićarija occur in this category (moderate dissection). The mountain massif of Učka, in the eastern part of Istria is composed mainly of carbonates of Cretaceous age and they are in the category of relief of extensive dissection (2.8 %) which reflects the effects of tectonics.

3.2. Badlands inventory

Worldwide, there are many methods for the detection and for sorting out the areas with excessive erosion, but generally they can be divided into two main groups:

- field mapping and
- remote sensing.

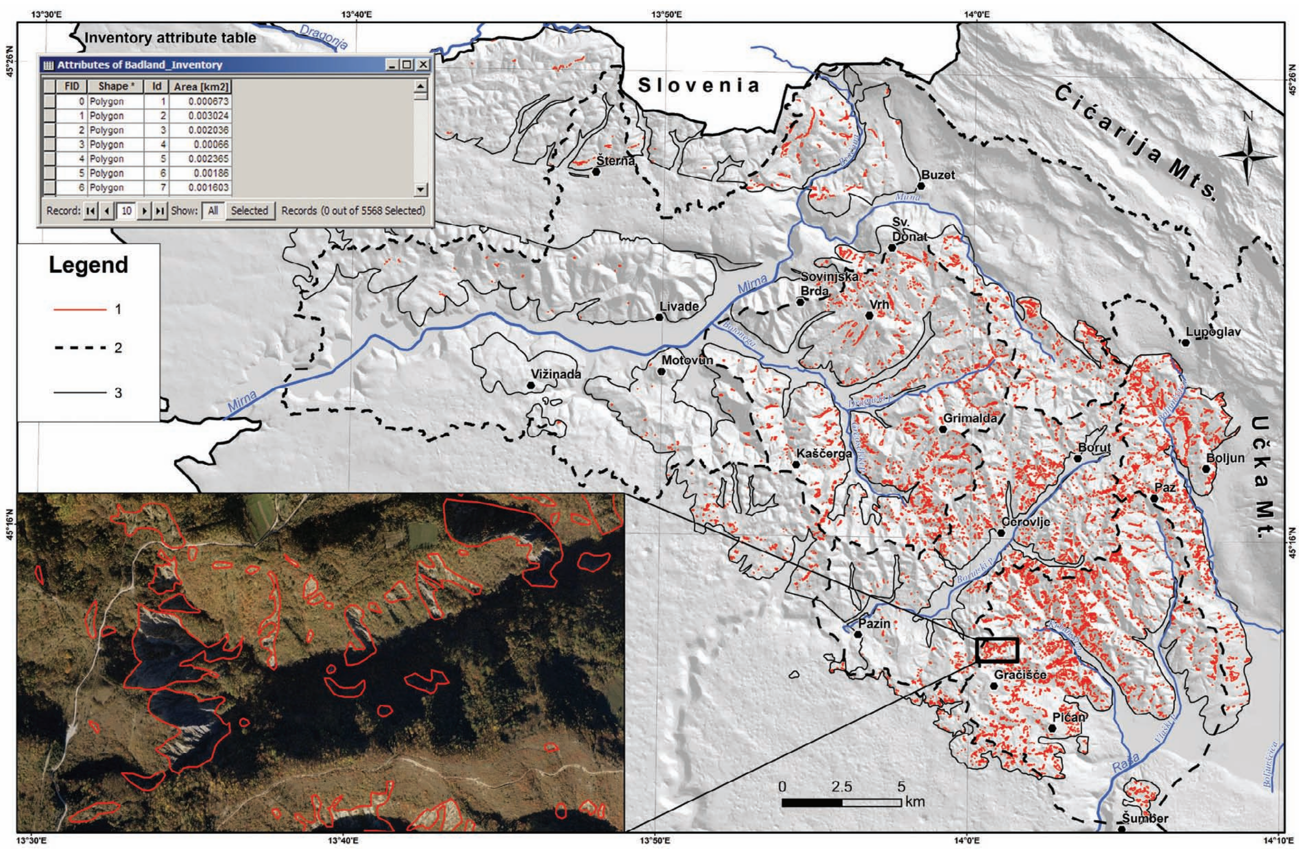

Figure 5: Badland inventory of central Istria; 1. Badland boundary, 2. Watershed boundary, 3. Studied area boundary.

The research area (Fig. 1) is almost 500 km^2 with a relatively high percentage of badlands. For example, according to JURAK & FABIĆ (2000) badlands in the catchment of the Krbunski stream constitute 6 % of the catchment area. Field mapping was impractical and expensive for the research area due to terrain configuration and the large area of interest. Therefore the logical, practical and adequate method for producing a badlands inventory in the research area, is the usage of remote sensing. The method used in this research, consisted of reviewing the orthophoto maps at 1:5.000 scale (digital orthophotos of Croatia) and marking every single badland with the unique ID and contour of badland border on the terrain surface on these photos.

The badland inventory of the middle part of Istria was used for:

1) determining the ratio of badlands in the research area,
2) determining the spatial distribution of badlands and determining the areas with the maximal and minimal ratios of badlands and
3) spatial analysis in order to determine the most important conditions/factors necessary for badland formation and development in the flysch area of central Istria.

The badland inventory (data base) contains: (i) unique ID of each badland, (ii) contour of badland border on the terrain surface (polygon) and (iii) total area of each badland. In the research area, 5568 badlands were singled out, with the sum of the total areas of badlands of 10.7 km^2, which is 2.2 % of the research area.

The research area with contour of badland border on the terrain surface (polygons) is shown in Fig. 5. Also the larger detail with the orthophoto as the background is given in Fig. 5. On that orthophoto the badlands are easily recognizable. In the upper left corner of Fig. 5 the detail of the database (from the badland inventory) is shown.

4. DISCUSSION

4.1. Chain of exogenetic processes at the badlands

The combination of exogenetic processes which takes place in the badlands needs to be explained to clarify the conditions under which badlands develop. Two very important factors for badland development in the central part of Istria are (GULAM, 2012):

1) Low durability sediments – badlands develop on the terrains where the bedrock is characterized by a very high susceptibility to periodic cycles of drying and wetting. As a result strong physical weathering occurs and the bedrock is covered with a thin, highly erodible, eluvium (10-20 cm).
2) Erosive stream – badlands in the central part of Istria are attached to gullies and valleys with very erosive periodic channel flow.

Badland development in central Istria in terms of the geological time scale is explained on the theoretical and simplified model of a flysch terrain shown in Fig. 6. Most of the flysch terrain is covered by regolith which is the consequence of chemical and physical weathering and very low bedrock durability (Fig. 6a). Periodic concentrated channel flows erode the regolith overlying the flysch sediments, since its erosivity easily surpasses the erodibility of the regolith (Fig. 6b). This process leads to gully incision (Fig. 6c). The formation of gullies redirects sheet surface waters into channel flow causing an increase in the flow rate of waters running through them. Deepening of the gullies is facilitated by this increase in water quantity, and the flanks steepen until eventually the regolith layer is detached and fresh rock is exposed – which is considered here as a badland (Fig. 6d).

Further processes which determine badland „life” are cyclical and interdependent. The main phases of this chain of exogenic processes can be schematically represented as shown in Fig. 6, (I-IV) and below:

I Fresh rock. Low durability intact rock material very prone to physical weathering is one of the basic prerequisites for badland formation.

II Weathering. In reality, fresh rock is rarely exposed at the very surface. On the steep badland slopes, fresh rock is not protected by a thick regolith layer and is exposed to physical weathering. Perpetual cyclical processes of drying and wetting of fresh rock material easily and rapidly degrades the mechanical characteristics of bedrock and form a thin layer of highly erodible material – eluvium.

III Denudation - deposition. It is important to differentiate the processes by which eluvium is transported into the bottom of the gullies (Fig. 6, III). These processes interact with slope inclination:

• Denudation

1) Sheet erosion – occurs if the slope inclination is less than the angle of internal friction of eluvium (usually less than 35°).
2) Mass movements (usually rockfalls) – result when the slope inclination is higher than the angle of internal friction of eluvium (usually more than 45°).
3) A combination of sheet erosion and mass movements – occurs if the slope inclination is near the value of the angle of internal friction of eluvium (usually between 35° and 45°).

• Deposition.

IV Erosion. Talus sediment accumulated in the central part of the gully is eroded by periodic channel flow.

The relationships between the four aforementioned main phases of badland evolution over time will determine whether badlands will develop (Fig. 6e) or die out (Fig. 6f). In conditions favourable for badland progress, the deepening of the gullies takes place until the periodic channel flow reaches the erosion base. At this point, the rockwall retreat (CURRY & CHRIS, 2004; SEONG et al., 2009; ZORN, 2012) of the gullies takes place. The magnitude of badland rockwall retreat is also guided by relationships between the major processes (I to IV) described earlier. If badland slopes are in close contact with periodic channel flow, erosion will take place. But if the position of the periodic channel flow does not change over time, rockwall retreat will diminish

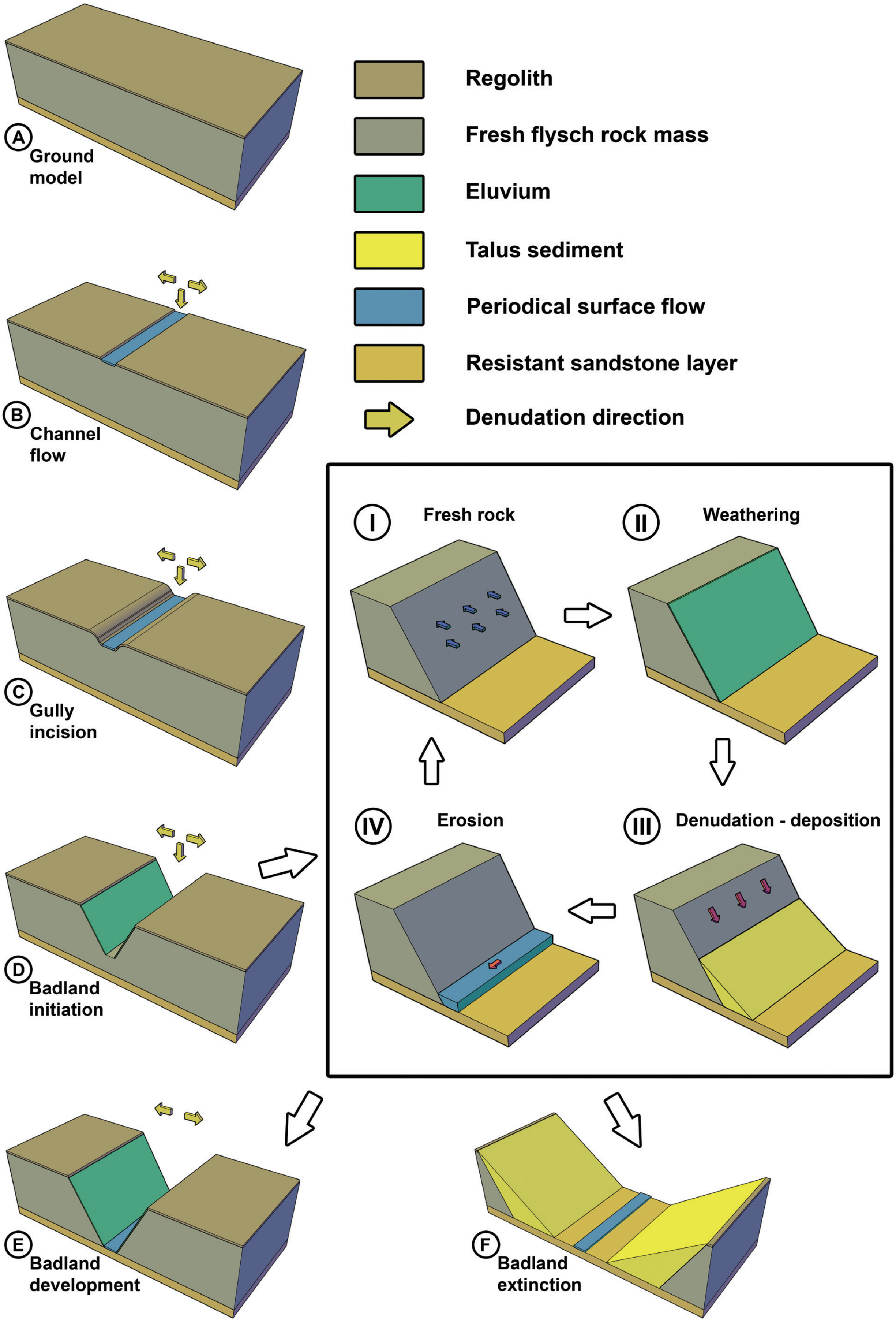

Figure 6: Badland development and the chain of exogenetic processes.

leading to badland extinction. The same will happen if the water energy drops.

The cyclical process is mainly continuous and has three constants – the same intact rock material with the same weathering potential, and the same mechanical properties of the resulting eluvium. According to these parameters, the denudation rate should be constant, but it also depends on the only variable in this cycle – climate. Climate change or climate extremes dictate both very important and periodic factors in this cycle: wetting and drying periods, and erosion of the talus sediment by periodic channel flow. It should also be noted that the equilibrium cycle can also be disturbed by a change of erosion base level (for example by endogenic movements – geological time) or by anthropogenic activity (for example in civil engineering by changing the position of the periodic channel flows caused by road buildings – engineering time).

Explanations given for Fig. 6, suggest the conclusion that the last link in the chain of exogenetic processes is the weakest – erosion by periodic channel flow (Fig. 6, IV). In middle Istria there is a periodic (or constant) channel flow of high erosivity in almost every stream order, but it is not necessary that the channel flow is in close contact with the steep flanks of valley or sediment accumulation (formed by sheet erosion or mass movements). It is clear from the discussion that the contact is necessary for the badland formation, development and reactivation, i.e. the contact is necessary for erosion and redeposition of the accumulated materials at the slope foot. The next logical question is: Which factors cause formation of this close contact? The answer is given by spatial analysis described below.

4.2. The importance of bedding inclination on badland development

Big badlands in central Istria (for example badlands in the vicinity of St. Donat or Boljun, Fig. 5 and Fig. 8) are characterized by bedding inclination between 5° and 20°. Bedding steeper than 5° influences the forming of channel flows at the badland foot, shown in theoretical model in Fig. 7.

The model presents the terrain with constant channel flow in a gully where bottom is being eroded with equal rate (Fig. 7a, f). By gully deepening (in bedrock) badlands are being formed on the flanks of the gully (rockwall) and the chain of exogenetic processes commences (Fig. 6). When the channel flow reaches resistant, none or low erodible components of the flysch deposits (for example calcarenite sediments, Fig. 7b, g), widening of the gully takes place (rockwall retreat). If the bedding is horizontal (e.g in the south-eastern part of the Ričica catchment) the rockwall retreat of the gully is equal on both flanks. If the bedding is inclined (for example badlands in vicinity of St. Donat and Boljun) the rockwall retreat of the gully takes place in one direction – in the direction of bedding inclination.

In Figs. 7c and 7h continuation of rockwall retreat is shown, while in Fig. 7c the retreat is slowing as the flow widens (a larger area of flow means lower energy of flow i.e. lower erosivity). In Fig. 7h the retreat value remains the same (as the flow energy remains the same). In Fig. 7e the end stage is presented – gully without rockwall retreat with wide flow with very low value of erosivity (or none). In Fig. 7j, on the other hand, a gully with the same level of activity is shown. On the far side (opposite side) of the flow, sediment accumulation takes place and eventually that side of the gully/valley will become inactive. The rockwall retreat continues (on the active side) until the appearance of some hindering factors stop it. Hindering factors can be: bedding inclination change to a smaller value, a greater sediment production value than flow erosivity, as a result of a larger badland area, etc.

Initial bedding inclination has a great influence on badland formation and development, i.e. on the flow concentration at the slope foot. The results of spatial analysis of slope

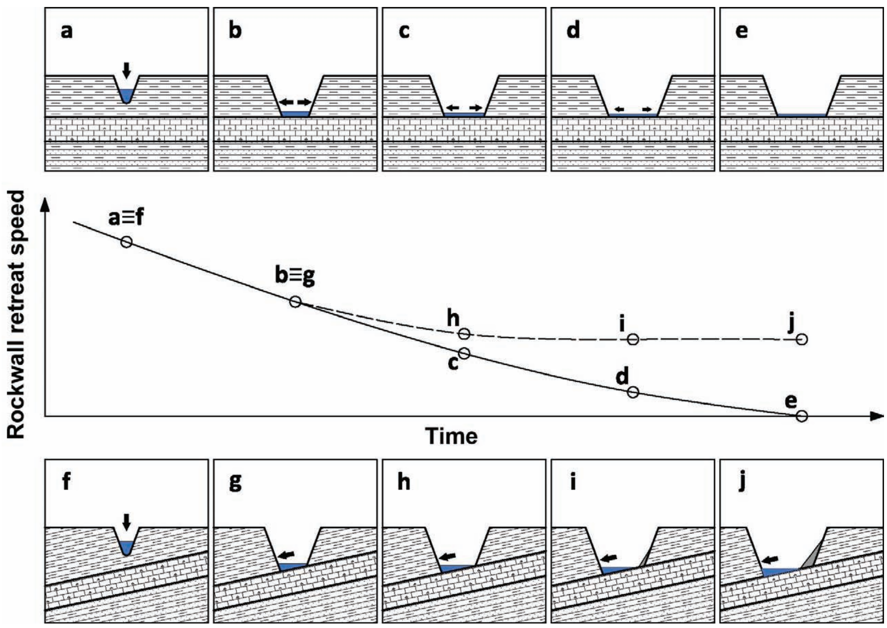

Figure 7: Rockwall retreat influenced by bedding inclination.

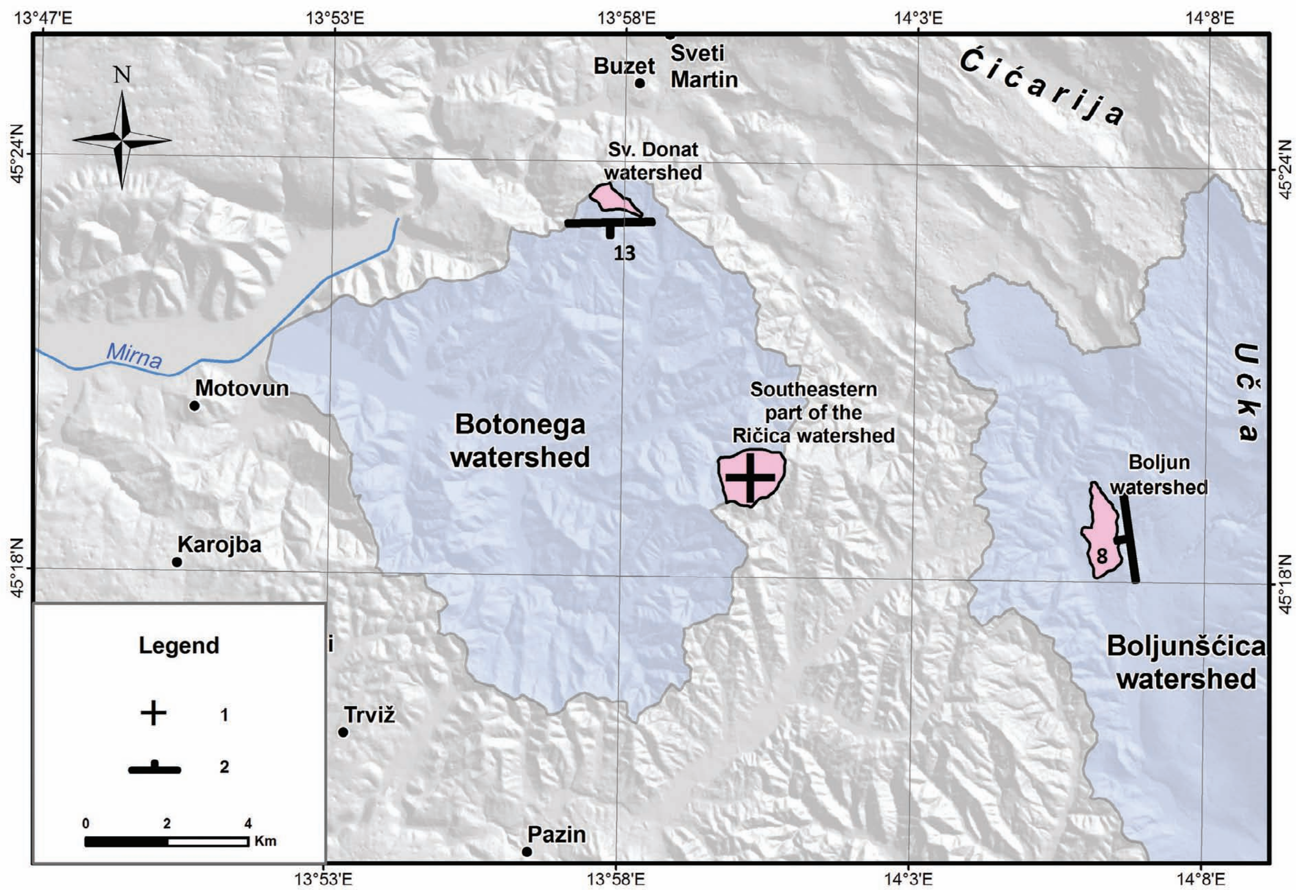

Figure 8: Spatial distribution of the analyzed locations; 1. Horizontal bedding, 2. Inclined bedding.

aspects (in badland and non-badland areas) in the south-eastern part of the Ričica catchment and in the vicinity of St. Donat and Boljun (Fig. 8) provide confirmation of this.

4.2.1. St. Donat badland catchment

St. Donat badland catchment is approximately 2.7 km south of Buzet in the centre of Grey Istria (Fig. 8). The term originates from the village of St. Donat, which is west of the badlands. St. Donat badland catchment area on which the analysis was undertaken is 0.46 km^2. The badland area in the catchment is 0.05 km^2, which is approximately 9.2 % of the catchment area. The main flow is the Kameršiač stream (its spreading is 112-292°).

According to the Basic Geological Map (1:100.000 scale), (PLENIČAR et al., 1969), the catchment consists of a flysch complex (intervals of marls and sandstones with centimetre thick beds) of Middle Eocene age ($^3E_2$). The average bedding values in the catchment is 179/13°.

The diagram in Fig. 9 clearly shows that the maximum development of the badlands aspects is almost directly opposite to the bedding azimuth in the analyzed catchment (in correspondence with discussion associated with Fig. 7), while the actual situation on the analyzed catchment is similar to that presented in Fig. 7j. The areas with vegetation approximately correspond to the bedding surfaces (Fig. 10), i.e. the maximum aspects of the areas with vegetation (Fig. 9) are in the same direction as the bedding azimuth.

The areas of blue and grey polygons in Fig. 9 are almost symmetrically divided by the arrow which represents the value of azimuth for the Kameršiač stream. This type of „butterfly" distribution (in which the values of aspect for badland and non-badland areas of the catchment are shown), is very common for the catchment areas of central Istria when the whole catchment is characterized by uniform bedding values. This conclusion is also confirmed by the example of the Boljun badland catchment analysis which is in the south-eastern part of flysch basin in Boljunščica catchment (Fig. 8).

4.2.2. Boljun badland catchment

The Boljun badland catchment is in the north-western part of Boljunšćica catchment area (Fig. 8). The name originates from the village of Boljun which is south-east of the badlands. Boljun badland catchment area on which the analysis was undertaken is 1.33 km^2. The badlands in the catchment cover 0.16 km^2, which is approximately 12.0 % of the catchment area. The main flow is the western confluent of the Boljunšćica stream with an approximate north – south direction of flow.

According to the Basic Geological Map (1:100.000 scale) (ŠIKIĆ et al., 1969) the catchment consists of flysch complex (intervals of marls and sandstones) of Middle and Upper Eocene age ($E_{2,3}$). Average bedding value on catchment is 262/8°.

The „butterfly" distribution in Fig. 11 is very similar to Fig. 9. The maximum of the badlands aspect is opposite to the bedding azimuth and to the maximum aspect of slopes with vegetation (non-badland area). This also confirms the discussion concerning Fig. 7, i.e. confirms the fact that badlands on the catchments with uniform bedding are developing on the flanks which are opposite to the bedding azimuth.

Boljun badland catchment in 3D is shown in Fig. 12 and it clearly shows that non-badland areas correspond approximately to bedding planes and that most of those areas are on the left side of the main flow in the catchment. These slopes are characterized by lower slope inclination and a higher area of spreading.

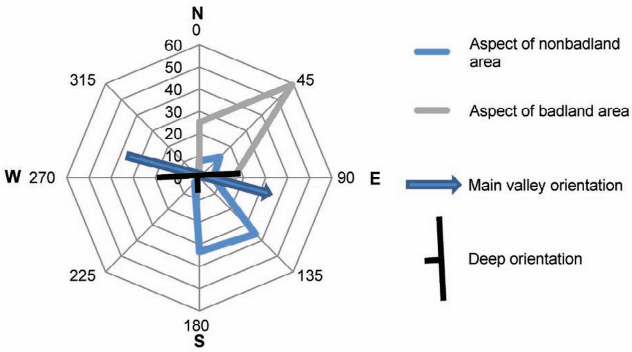

Figure 9: Analysis of slope aspect and badlands and their connection with the average value of bedding in St. Donat badland catchment.

4.2.3. South-eastern part of the Ričica catchment area

The Ričica catchment area is part of the southern part of the Botonega catchment (Fig. 8) with an area of 1.75 km^2. The badland area in the catchment is 0.13 km^2, which is approximately 7.4 % of the catchment area. The main flow is the Ričica stream (spreading is 130-310°).

The Ričica catchment is in the central part of the flysch synclinorium and it is characterized by horizontal bedding. This is also the reason for the somewhat different badland aspect distribution in relation to the non-badland area, shown in Fig. 13 by the blue arrow (presenting the flow of the highest order in that catchment area) as a division of the grey polygon into two parts, almost equal in area. This means that badlands form equally on each slope which is confirmed by the high overlapping of non-badland area (areas with vegetation, blue polygon) and badland area (grey polygon).

The south-eastern part of the Ričica catchment in 3D is shown in Fig. 14. It is clearly visible that badlands develop and form on both flanks of the main valleys. The terrain is

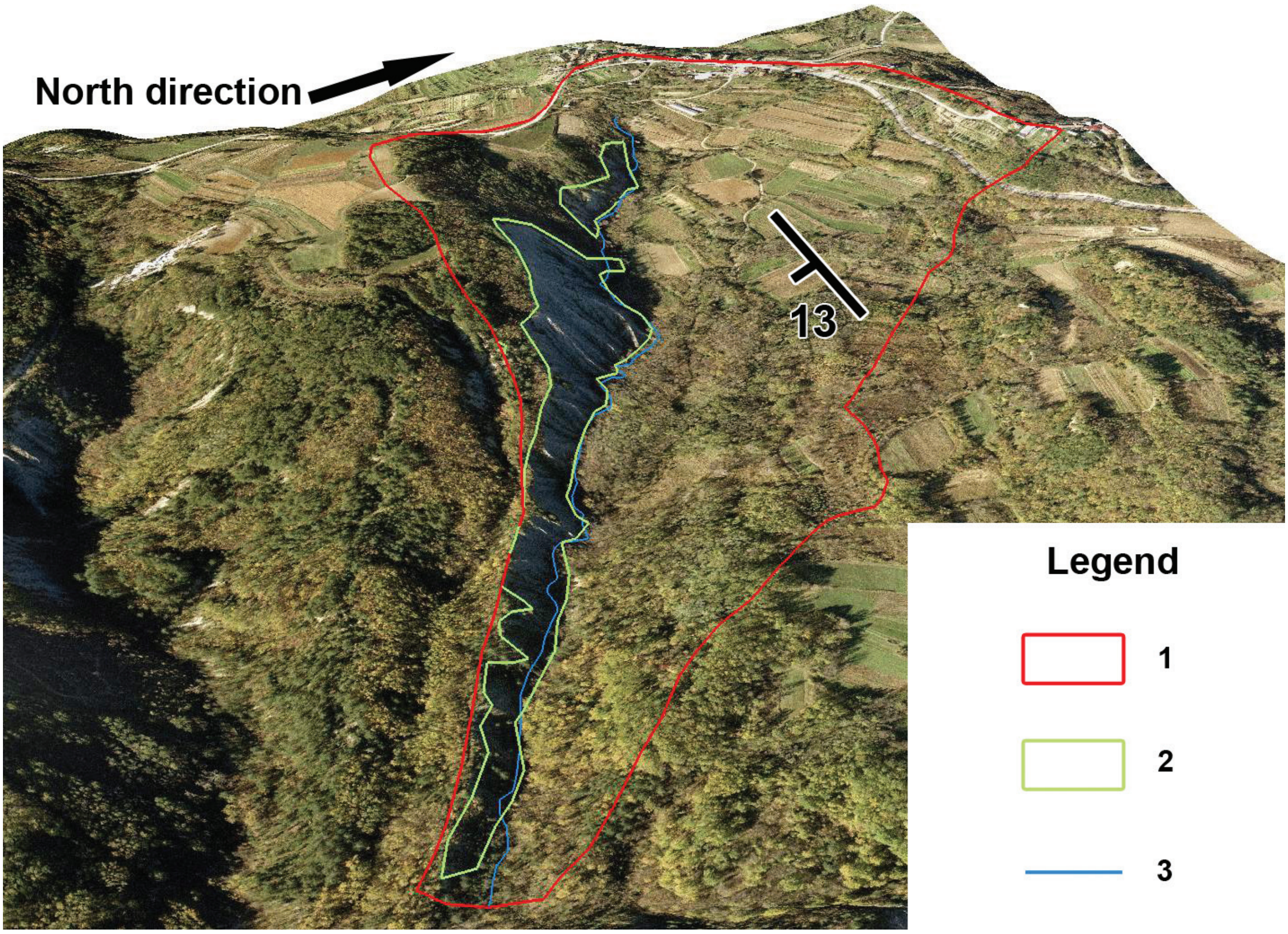

Figure 10: St. Donat badland catchment in 3D; 1. Watershed boundary, 2. Badland boundary, 3. Main stream

similar to that presented in Fig. 7a–7e, i.e. the horizontal bedding predefines approximately equal development of badlands on each slope of each valley.

4.3. The influence of the valley cross section morphology on badland development

After the badland inventory was prepared and visually analyzed, some general conclusions were reached: there is regularity in the ratio of badlands in some smaller catchments to periodic channel flows (also for some larger constant flows). The ratio of badlands in some areas is increasing as the distance from the mouth of the river is growing, i.e. as the erosion base is becoming more distant. This conclusion is confirmed by simple spatial analysis in which the connection between the badland ratios on some parts of the analyzed catchment (segment) and the distance of the centroid of that part of the analyzed catchment (segment) from the mouth of the catchment is observed. These segments are formed by the principle of concentric clips where the centre is the mouth of the catchment. The spatial analysis for the Botonega catchment is shown below (Fig. 15).

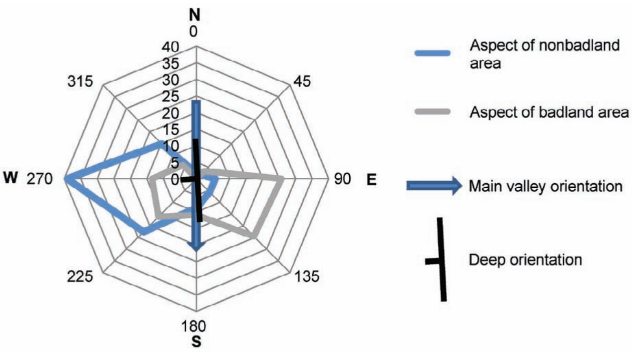

Figure 11: Analysis of slope aspect and badlands and their connection with the average value of bedding in the Boljun badland catchment.

4.4. Botonega catchment area

The Botonega catchment represents the left tributary of the Mirna river and has an area of 104.6 km^2 with the height difference of 485 m. The highest elevation in the catchment area is 500 m while the lowest is 15 m above sea level. The catchment is fan shaped with Botonega as the main flow and also as the flow of the highest order (6th order defined by the contour lines at 1:25.000 scale according to the methodology suggested by STRAHLER, 1957). The badland area in the catchment is 2.0 %.

The central valley (the Botonega river valley) corresponds with the axis of the flysch basin which is bath shaped

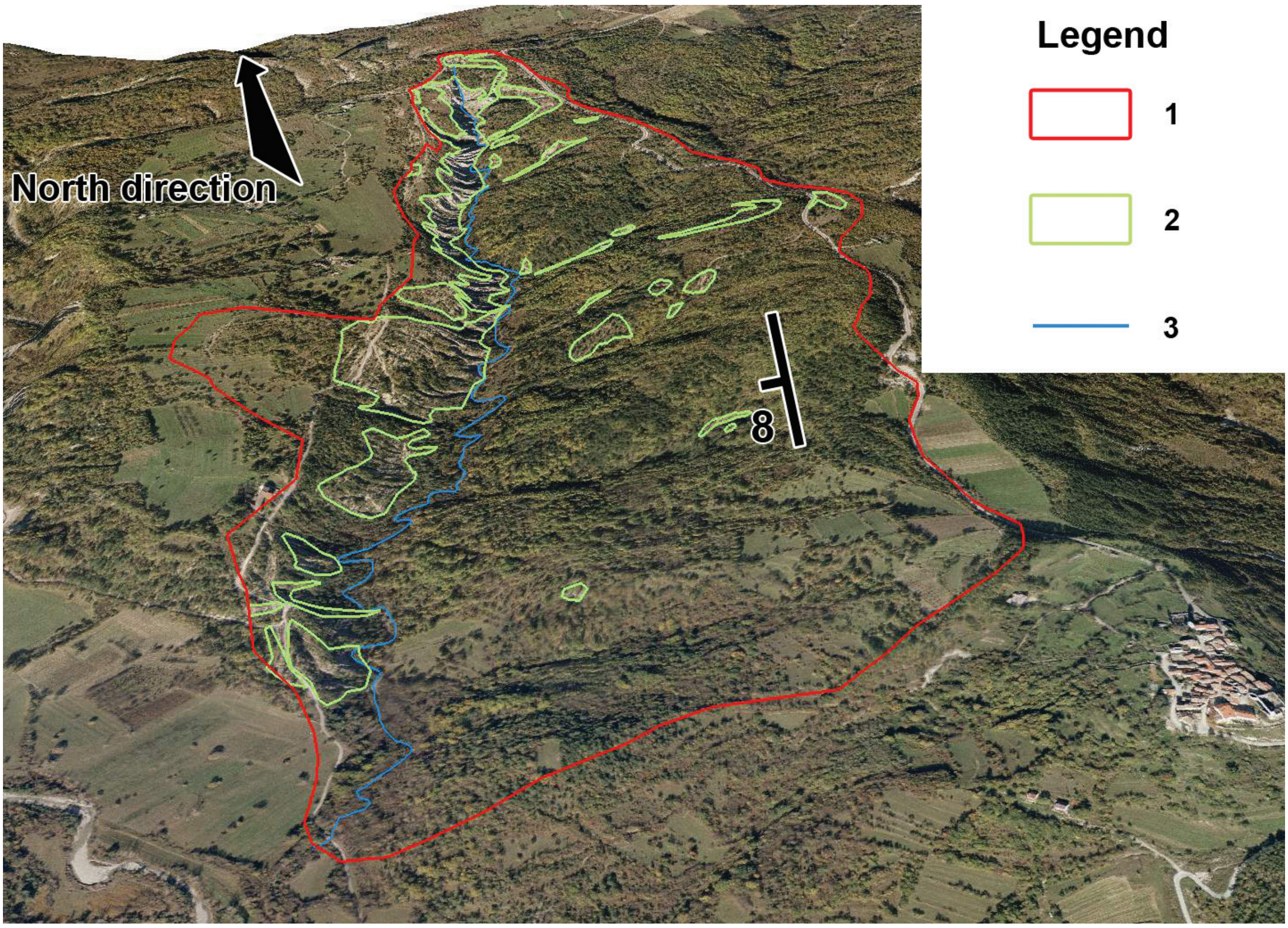

Figure 12: Boljun badland catchment in 3D; 1. Watershed boundary, 2. Badland boundary, 3. Main stream

and stretches from the north-west to south-east. According to the Basic Geological Map (1:100.000 scale, (sheets: Trieste, PLENIČAR et al., 1969; Ilirska Bistrica, ŠIKIĆ et al., 1972; Rovinj, POLŠAK & ŠIKIĆ, 1969; Labin, ŠIKIĆ et al., 1969)), flysch deposits cover approximately 86 % of the catchment area and the rest is alluvium (11 %) and carbonate deposits (3 %).

Spatial analysis for the area of the Botonega catchment were undertaken as described in Section 4.3 (Fig. 15). Segments are defined at 1 km intervals.

Fig. 16 shows the correlation between the distance of the centroid of each segment from the mouth of the catchment and the badland ratio of each segment. This correlation confirms the visual analysis and it can be described with a linear function (with a very high factor of determination – 0.85). Graduation of the red colour (Fig. 15) shows this linear distribution, i.e. light red marks the segments with low badland ratios and vice versa (dark red marks the segments with high badland ratios).

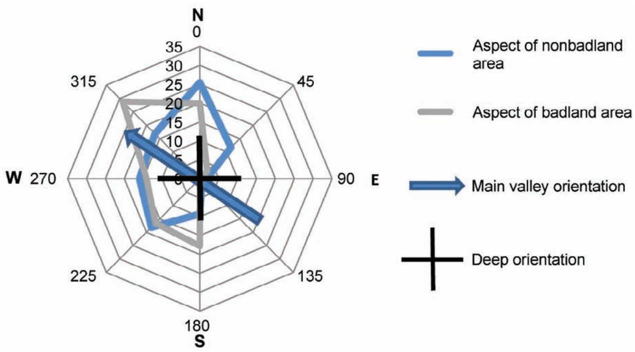

Figure 13: Analysis of slope aspect and badlands and their connection with the average value of bedding in the south-eastern part of the Ričica catchment.

To clarify, the very high value of the factor of determination means it is necessary to take into consideration the described chain of exogenetic processes (Fig. 6). The flow concentration at the steep slopes foot, as one of the most important links in the chain, can be predefined by the shape of the valley cross section. If the cross section is U shaped there is a very high probability that the channel flow in the centre of the valley will not be in close contact with flanks (rockwall). The situation is reversed if the cross section is V shaped, then there is a very high probability that the cannel flow is in a close contact with the steep flanks of the valley (rockwall).

If the valley cross sections for each segment on the branch of the hydrographic network marked with thicker blue line (Fig. 15) are analyzed there will be 12 profile positions and 12 values. This branch is approximately in the centre of the Botonega catchment area and it stretches from the river mouth to the final segment. The cross sections for each profile position were made and analyzed (Fig. 17a & 17b) and four characteristic cross sections are also shown in Fig. 15. On the cross sections, the vertical scale is enlarged by x 20 to emphasise the shape of the cross section.

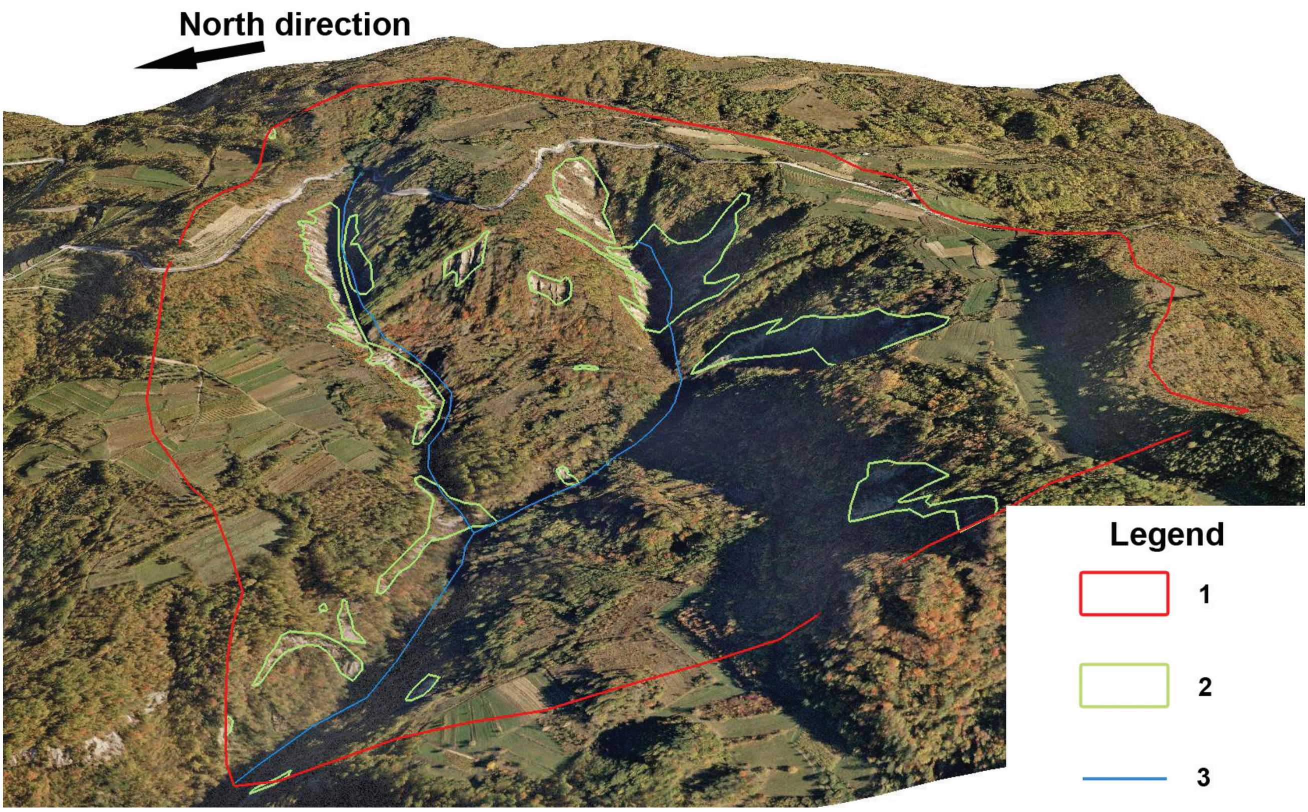

Figure 14: South-eastern part of the Ričica catchment badlands in 3D presentation; 1. Watershed boundary, 2. Badland boundary, 3. Main stream

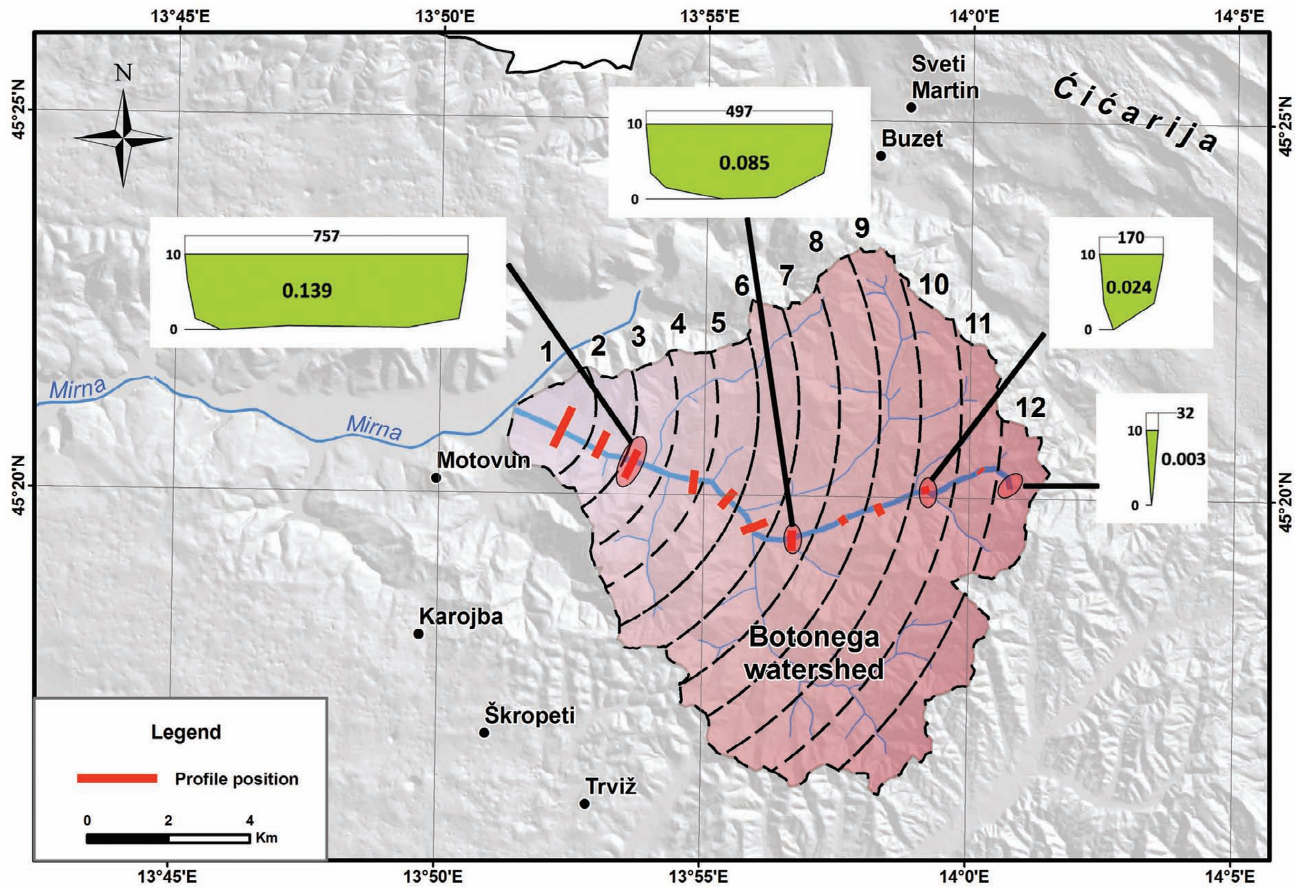

Figure 15: Spatial analysis for the area of the Botonega catchment with 1 km segments and characteristic valley cross sections.

The total height of each cross section is 10 m. In these cases the values which can determine the cross section shape are their width and area. The width is expressed in km and represents the distance between the two highest points of each cross section. The area of exaggerated cross section is expressed in km^2 and it is defined by a horizontal line which connects the two highest points of the cross section and the profile line, (the area defined in this way is shown on four examples of exaggerated cross sections by a green colour in Fig. 15).

From the values shown in Fig. 17, it is clearly visible that the badland ratio in the segments is reducing as the width and the area of cross section increases. Both correlations result in very high factors of determination, approximately 0.76. The logical conclusion is that the cross section shape of the valley is very important in badland formation

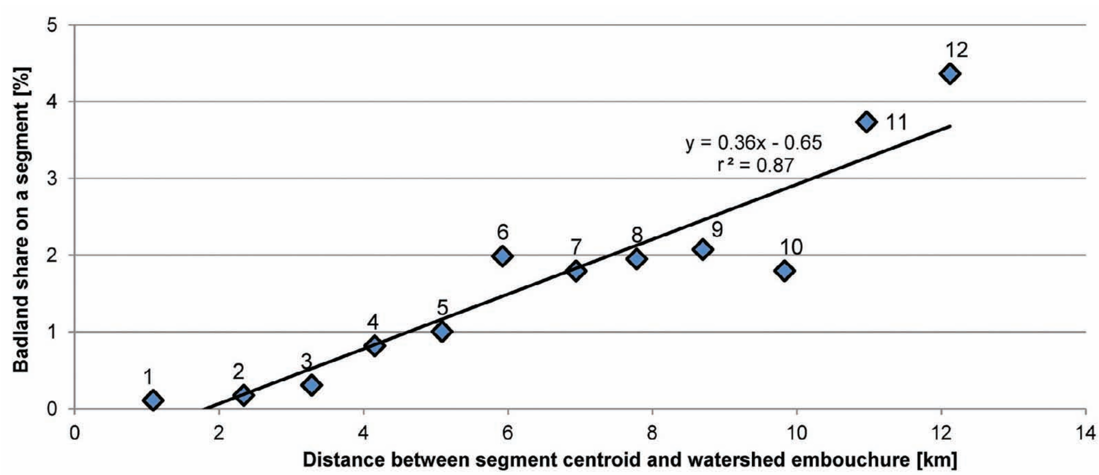

Figure 16: Correlation between the distance of each segment centroid from the mouth of the catchment and the badland ratio on each segment.

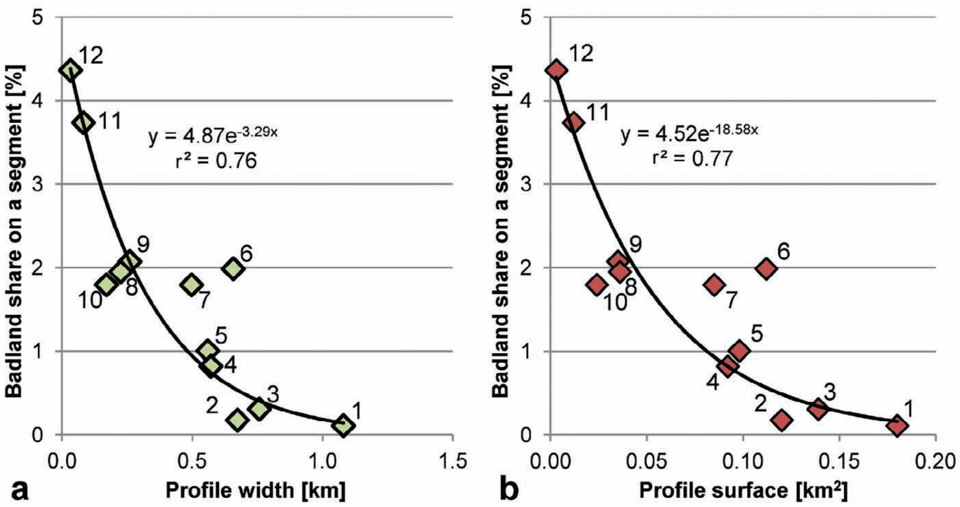

Figure 17: Analysis of 12 profile positions: a) correlation of the width of cross section and badland ratio for each segment b) correlation of the area of cross section and badland ratio for each segment.

and development as it is in direct connection with the channel flow concentration at the foot of steep valley flanks (rockwall).

5. CONCLUSION

The area of central Istria is characterized by low tectonic activity but the relief dissection is moderate i.e. relief energy values are also moderate. This is the result of very intense exogenetic processes which are predefined by the combination of existing specific lithology and climate.

As the product of these specific set of conditions the badlands in central Istria are very common isolated morphological landforms. A badland inventory of the research area, based on orthophoto pictures, contains 5568 identified badlands (polygons). Badlands in the research area are isolated landforms, and therefore very small, since the biggest has an area of 0.08 km^2. Badland area overall in the research area is 10.7 km^2, which is 2.2 % of the total research area. Badlands of central Istria are also characterized by some sparse vegetation.

Generally, on all badlands of central Istria there is strongly connected chain of exogenetic processes. In the chain of exogenetic processes most of exogenetic processes take place: weathering, denudation (erosion and mass movements on slopes), deposition or accumulation.

The research results prove that the last link in the chain of exogenetic processes – erosion of the channel flow is the most important one, the link that defines the badland initiation, development and formation, i.e. close contact of the channel flow with the accumulated material at the badland slope foot is the most important factor in badland development and formation.

As an argument for these statements, spatial analysis was undertaken on bedding orientation and cross section shape of the valley. Analyses proved that both factors can influence the erosion by the channel flow, i.e. can dictate the concentration of channel flow at slope foot and conditions under which badlands can be formed.

Bedding orientation was analyzed at three locations: the south-eastern part or the Ričica catchment area, St. Donat badland catchment and Boljun badland catchment. The analysis showed that in the catchments with horizontal bedding (south-eastern part or the Ričica catchment) badlands are equally developed on each slope, while on the catchments with inclined bedding (St. Donat badland catchment and Boljun badland catchment) badlands are developed on slopes which have the opposite aspect to bedding inclination.

Analyses of the cross section shape of the valley were undertaken on the Botonega catchment where the ratio of badland increases from the mouth of the catchment towards the south-east border. The area of the cross section of the valley in that direction (north-west to south-east) is reduced, i.e. the valley width is smaller. This means that the cross section of the valley changes in shape from a U shape (higher order of valleys closer to the river mouth) to V shape (lower order of valleys more distant from the river mouth). The V shape of the valley influences the concentration of the channel flow at the slope foot which contributes to the badland formation and development.

Based on the present research, it can be concluded that close contact of the channel flow with the accumulated material at the badland slope foot is frequently the most important factor in maintaining an erosively active badland rockwall. Therefore such situations, at locations of interest, should be artificially controlled or regulated if we wish to preserve fertile soil material and enable conservation of vegetation.

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