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Longitudinal profiles of torrential channels in the Western Karavanke mountains

Vzdolžni profili hudourniških strug v Zahodnih Karavankah

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Ključne besede: hudourniki, morfometrija, prelomi, erozija, prevojne točke, Zahodne Karavanke

Abstract

From the national digital elevation model DMV 5 of the Western Karavanke longitudinal profiles of fifty-three torrents were extracted. Longitudinal profiles of torrential channels in study area have generally convex sections and do not correspond to equilibrium state. In this paper, changes in lithology across faults and other potential influences are discussed as possible cause for observed convex longitudinal profiles. Some typical cases where it has been found, that convex sections could be result of faults, are graphically showed. Also lithology of torrential stream bed could be one of main factors for convexity. This applies in particular if the torrent crosses from soft to solid rock.

Izvleček

Iz državnega digitalnega modela višin DMV 5 območja Zahodnih Karavank so bili določeni vzdolžni profili 53 hudourniških strug. Vzdolžni profili hudournikov imajo večinoma odsekoma konveksno obliko in ne ustrezajo pogojem ravnovesnega stanja. V članku so kot možni vzroki za konveksnost vzdolžnih profilov obravnavane spremembe v litologiji preko prelomov in nekateri drugi potencialni dejavniki. Grafično so prikazani posamezni značilni primeri, kjer je bilo ugotovljeno, da so lahko konveksni odseki vzdolžnih profilov hudouniških strug posledica prelomov. Prav tako se je ugotovilo, da je lahko litologija podlage dna hudouniške struge eden izmed glavnih razlogov za pojavljanje konveksnih odsekov. To velja še posebej za primere, kjer hudournik preide iz mehkih v trdne kamnine.

Introduction

Longitudinal profiles of torrential channel have been investigated by many authors (Snow & Slingerland, 1987; Hantke & Scheidegger, 1999; Rădoane et.al., 2003; Goswami et al., 2012). The most explored phenomenon related to longitudinal profiles is their form. Steady-state longitudinal stream profiles normally have a concave shape, which is not typical for torrential channels, where other shapes are often recognized. Their profiles commonly exhibit a variaton of concave, convex and flat sections, which are characteristics of morphologically-active streams with significant erosion activity.

Extreme phenomenoms like debris flows can occur in morphologically-active streams. This can result in significant damage to property and can threaten lives. Landslides, rockfalls and even snow avalanches can be triggered into the stream channel because of steep slopes and steady-state form can fail.

In this paper, we investigated torrents in the Western Karavanke on northern slopes of the Upper Sava Valley from the Završnica torrent to the East to the Trebiža torrent to the West. Our main objective was to define possible reasons for the evolution of convexity, based on longitudinal profile form of torrential streams in the study area.

In order to attain this objective, we are taking the following steps: (1) to define study area and data basis; (2) to characterize the form of the longitudinal profiles by using DMV data; (3) to study lithological settings and faults.

Steady-state longitudinal profiles of headwater torrents

The steady-state form of torrential longitudinal profiles in general has concave shape (slope decreases downstream) (HACK, 1957, RĂDOANE et al., 2003, PAZZAGLIA et al., 1998, SEIDL et. al., 1994). The torrent gradient typically decreases in the downstream direction. These characteristics are typical for morphologically non-active torrential watercourses, subject to deviations with respect to the geological structure of an area (HACK, 1957). Different empirical equations to describe steady-state form were developed. For example, FLINT (1974) described steady-state longitudinal profiles with empirical power law:

$$S = k_s A^{-\theta}$$

Where S is the local channel slope, A is the upstream contributing drainage area, and k_s and θ are the steepness index and concavity index.

A characteristic of morphologically active torrents are convex longitudinal profiles. Torrential channels are generally young morphological formations and rarely have a concave shape of their longitudinal profiles. They can be segmented into concave, convex, and flat sections, and they exhibit knickpoints (Fig. 1). The reason for these features may be tectonic activity, erosion processes, or changes in the composition of the bedrock. Such features also form where a large part of the headwater torrent runs over the bedrock, except close to the junction with the main stream where it usually flows in its own deposits. The cause may also be different erosion ability between two torrential streams which merge together. The process of establishing equilibrium in longitudinal profiles in nature can take up to several million years (STOCK & MONTGOMERY, 1999). The interpretation of a historical development of longitudinal profiles of headwater torrential streams is based on the understanding of the governing processes under which a torrential channel incises (WOHL, 1998). The bedrock and channel incision are particularly important because they can regulate how fast erosion changes expand along the torrential channel (TINKLER & WOHL, 1998). The grade of alluvial channels is determined by their hydraulic regime, whereas the grade of bedrock channels may be an independent variable, if weathering takes over erosion (HOWARD, 1980; HOWARD, 1998). In bedrock channels alluvial reaches may occur when and if transport capacity reduces due to a low channel grade.

For upper reaches of torretial channels, large grades and flow intermittency are typical. In middle reaches somewhat lower grades and more steady flow prevail, whereas in the lower reaches an inflection point or a major knickpoint at the fan apex can be present. The largest grades can also occur in middle or lower reaches at conflu-

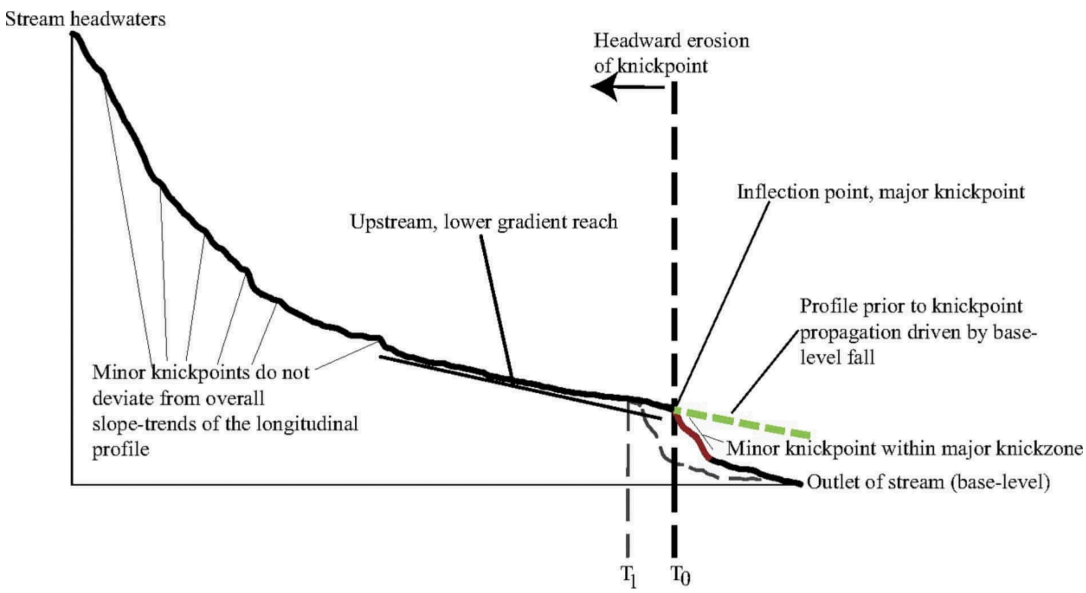

Fig. 1. Sample of a typical longitudinal profile of morphologically-active torrential channel (FOSTER & KELSEY, 2012)

ences with larger torrential streams; in this case the long-term and more pronounced incision of the main torrent prevails. These non-specific phenomena may also be affected by other erosion processes, e.g. glacial erosion.

The continuous alternation of concave and convex reaches is a sign of an unstable channel with pronounced geomorphological activity (Gavrilović, 1972). Torrential tributaries with pronounced erosion activity and sediment supply can contribute to this situation. Channels, with concave longitudinal profiles and one major knickpoint at confluence with tributary, can occur. This is a sign of an active tributary with high erosion capacity that contributes to the main stream large amounts of sediment (Gavrilović, 1972). However, this dependence is not always evident or reliable, as the main stream, due to the geological characteristics of the bedrock or a local sediment source, can have a convex form.

Since they are close to their (final) stable stage, sediment potential of mature torrents is much lower than that of immature torrents. The longitudinal profiles of torrential streams usually follow the ideal parabolic curve that corresponds with the terminal grade when a torrent does not degrade nor aggrade any more under given geological settings in its catchment (Gavrilović, 1972). Even if a torrential stream exhibits a steady longitudinal profile, it is still susceptible to change. Landslides, rock falls and even avalanches can disturb the equilibrium and lead to adjustments to a new one. From a longitudinal profile of a torrential stream it is also possible to predict which reaches could undergo degradation, and which ones the aggradation of the channel. Of course, this is true for natural (unregulated) torrents. In regulated torrents, equilibrium in their longitudinal profiles is reached by e.g. transverse structures, such as check dams.

Study area

Study area belongs to the Slovenian part of Western Karavanke (Fig. 2A). Structurally, they are part of the Southern Alps. The mountain range has a distinct SE-NW orientation, with well-expressed and narrow ridge crests (Fig. 2C). Geological composition of the range is rather heterogeneous, with occurences of carbonate, clastic, volcanoclastic and volcanic rocks of different ages, and with complex tectonic structure (Jurkovšek, 1985, Buser & Cajhen, 1978). For the purpose of research, the compiled geological map and structural subdivision from Brenčič & Poltnig (2008) was used (Fig. 2B, C). Presently the area has a well-distributed network of torrrential watercourses, most of which are located in narrow valleys. Springs often have character of contact karst and emerge at the junction between permeable (eg. carbonate rocks) and impermeable rocks (eg. sandstone) (Bunčić, 2014). Activity of the Upper Sava Glacier in Quaternary also had a large impact on geomorphic characteristics of the area. The glacier formed the typical U-shaped Upper Sava Valley along the southern foot of the Western Karavanke range.

Geological background

Western Karavanke structurally belongs to the Southern Alps (Placer, 2008) and are composed of the following tectonic units (Brenčič & Poltnig, 2008, modif. from Jurkovšek, 1986, Buser & Cajhen, 1978 and Budkovič, 1999) (Fig. 2B): Paleozoic of Carnic Alps, Golica Syncline, Košuta Unit, Young Paleozoic of Jesenice Unit, Southalpine Triassic Unit. Their boundaries are mainly steep transpressive strike-slip faults. Polinski & Eisbacher (1992) investigated the origins of deformations and structure of the Karavanke, describing them as a consequence of the multi -phase oblique convergence.

The study area is characterized by the presence of wide varieties of lithological units (Fig. 2C) as a consequence of their origin in the different paleogeographical environments during geological history (Brenčič & Poltnig, 2008; Brenčič et al., 1995). The majority of faults are WNW-ESE orientated with dextral strike-slip displacement in the transpressional regime. Subordinately, there are also NE-SW directed, left-lateral strike-slip faults, and accommodating rotation of blocks between main faults. Recent morphology of Karavanke is a consequence of the on-going tectonic movements evidenced by the current seimic activities (Jamšek Rupnik, 2013), active tectonics (Polinski & Eisbacher, 1991; Nemes et al., 1997; Jamšek Rupnik, 2013; Mihevc et al., 2013) and accurate GPS measurements (Vrabec et al., 2006).

The oldest rocks in the research area are highly erodible, predominately shales of Hochwipfel beds (Lower Carboniferous) with subordinately more resistant limestone lenses. Auernig beds (Upper Carboniferous – Lower Permian) are simmilar by their lithological composition. Mas-

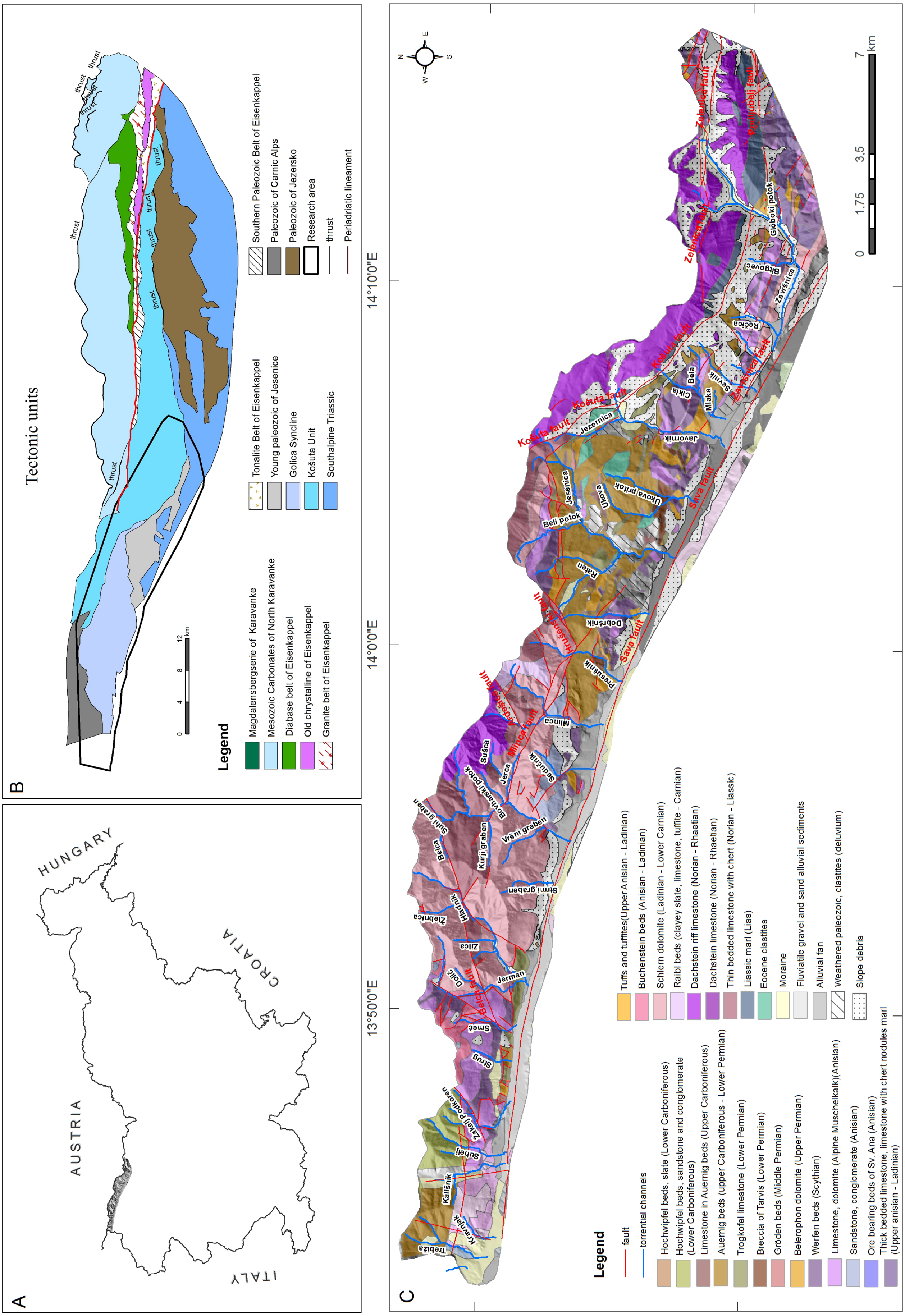

Fig. 2. Location of the Western Karavanke and the study area (modif. after Brenčič & Poltnig, 2008). A. Geographic position; B. Tectonic Units of Karavanke; C. Geological map of western Karavanke (Slovenian part).

sive Trogkofel limestones (Lower Permian) are comparably more resistant then overlying Breccia of Tarvis and Gröden sandstones (Lower and Middle Permian, respectively). Belerophon dolomites (Upper Permian) are positioned above. Lower Triassic Werfen beds are of mixed clastic – carbonate origin, less resistant compared to the overlying limestones and dolomites of the Anisian Alpine Muschelkalk. In the upper part of the Anisian and in the Ladinian, again mixed siliciclastic, volcanoclastic and carbonate rocks prevail, followed laterally and upward by more resistant Schlern dolomite (Ladinian – Lower Carnian). In the Carnian Raibl beds, there again dominate more erodible siliciclastic component, followed by predominately thin bedded dolomite and limestone succession (Upper Triassic – Jurassic), ocassionally also marlstones in Golica syncline. On the other hand, the highest peaks of the research area are composed of the highly resistant massive and thick-bedded Upper Triassic Dachstein limestones. There are also small patches of the Eocene clastites present in the area. Quarternary sediments are represented mainly by moraine, alluvial sediments and slope debris.

Generally, the studied torrential areas are strongly heterogeneous from the geological point of perspective.

Methodology

National digital elevation model DMV 5 (GURS, 2011-2014) was used to calculate the longitudinal profiles of the torrential channels. DMV 5 is given as x, y and z coordinates in Slovenian national grid D48/GK and organized in a grid cell with spatial resolution of 5 meters. DMV 5 was produced in years 2006 and 2007 by fusion of the results from stereophotogrammetric restitution of aerial images and resampling of the national digital elevation model DMV 12.5 (Podobnikar, 2008). Update of DMV 5 was performed in 2011 within the project of Cyclical Aerial Survey of Slovenia and ortohophoto production (GURS, 2011-2014). DMV 5 was chosen for our project over the DMV 12.5 because of better spatial resolution, although some of the past studies showed that both elevation models are useless for more precise mathematical modelling (e.g. Sodnik et al., 2009). Since this paper describes complete torrents, from springs to confluences with larger streams, good approximations of the longitudinal profiles can be obtained already by using DMV 5 (Mohorič, 2015). For the quality of the elevation model not only the spatial resolution, but also the data acquisition, height accuracy and processing of the data are important factors.

Fifty-three torrential channels situated in the Western Karavanke were analysed in the research. The analysis included the torrents whose watershed area exceeded 1.5 km^2 and are situated between torrents of Trebiža on the west and Završnica on the east.

The torrential streams were obtained within ArcGIS mapping platform (ESRI, 2013), the Environmental System Research Institute's software for data analysis in the Geographic Information Systems (GIS). Rasterised DMV 5 was used to calculate the flow direction and flow accumulation. Torrential network was produced by thresholding the flow accumulation raster as described in Parmenter & Melcher (2010). Furthermore, by vectorisation of the torrential network short reaches of potential torrential channels were obtained. Reaches that represented individual torrent were identified on the topographic map (SINERGISE, D.O.O. & MAPYX LIMITED, 2015) and manually joined into a single torrent. In order to calculate longitudinal profiles, the torrents' heights were interpolated from DMV 5. The whole methodology of the longitudinal profiles of torrential channels calculation and analysis is in detail discussed in detail in Mohorič (2015).

Fault network geometry was extracted from the geological map of the Karavanke at the scale of about 1:110.000 (Brenčič & Poltnig, 2008). For areas not covered by this map, data of the Basic Geological Map of SFRJ in the scale 1 : 100.000, sheets Beljak in Ponteba (Jurkovšek, 1986) and Celovec (Klagenfurt) (Buser & Cajhen, 1978), were used. Using GIS, we determined the points where faults cross torrential streams.

Results and discussion

Extracted longitudinal profiles of torrential channels are shown in Figs. 3 to 10. Sites where channels are crossed by transversal faults are marked as points and longitudinal faults as point clouds. Faults which cross torrential channels under torrential sediment are excluded. Short sections of convex shape occur in all analyzed stream profiles. Extreme cases, such as Sevnik torrent, exhibit almost flat longitudinal profile. Obviously, analyzed stream profiles are not equilibrated.

Influence of faults

In some cases, knickpoint with convex longitudinal profile of torrential channel occurs in areas of faults. The most significant examples where faults are oriented transverse to the direction of torrential channel are Jelenji potok at length 0,7 km, Hladnik at length 5,9 km and Suhelj at length 1,95 km (Fig. 3). Such cases may occur when faults are oriented transverse to the direction of torrential channel and separate tectonic blocks of soft rock upstream from more resistant rocks downstream. In this place, it is probably not that important if they are fractured in direction of the slope or in opposite direction of slope (on the southern parts of Karavanke slopes usually dip steeply to the south). Typically, fault zones occur in strands of several parallel faults, with observed zone widths ranging from couple of ten meters up to 300 meters. Principal fault plane usually occurs at the contact between rheological more resistant and less resistant fault-blocks, whereas the parallel and anastomosing faults (where individual fault zones/faults in the fault zone are not parallel and can be wrapped, devided and reunited again) with smaller displacements are mainly positioned in less resistant rocks.

A significant number of torrential streams at least partly run parallel to the deformed zone along the fault traces. The influence of longitudinal faults along torrents on formation of knickpoints is not observed. In a tectonically deformed zone where cataclastic sediments are present, a formation of concave, equilibrium profiles is expected. Therefore, erosion of torrential streams in cataclastic zone happens more easily. However, convex sections at some of the samples in study area most likely a result of other factors (eg. Hladnik at Fig. 3). For example, many studies have investigated the influence of tectonics on channel morphology, where channels steepen their longitudinal profiles in association with faster uplift (Kirby & Whipple, 2001; Kirby et al., 2003, Stark, 2006; Dibiase et al., 2010). Moreover, all other factors such as neotectonic movements and discontinuities caused by the different stages in the evolution of the profile, account for deviations from the general form of the profile. Due to lack of data, the tectonic structure of the study area is quite uncertain. Thus, the importance of tectonic evolution in this study has not been fully highlighted.

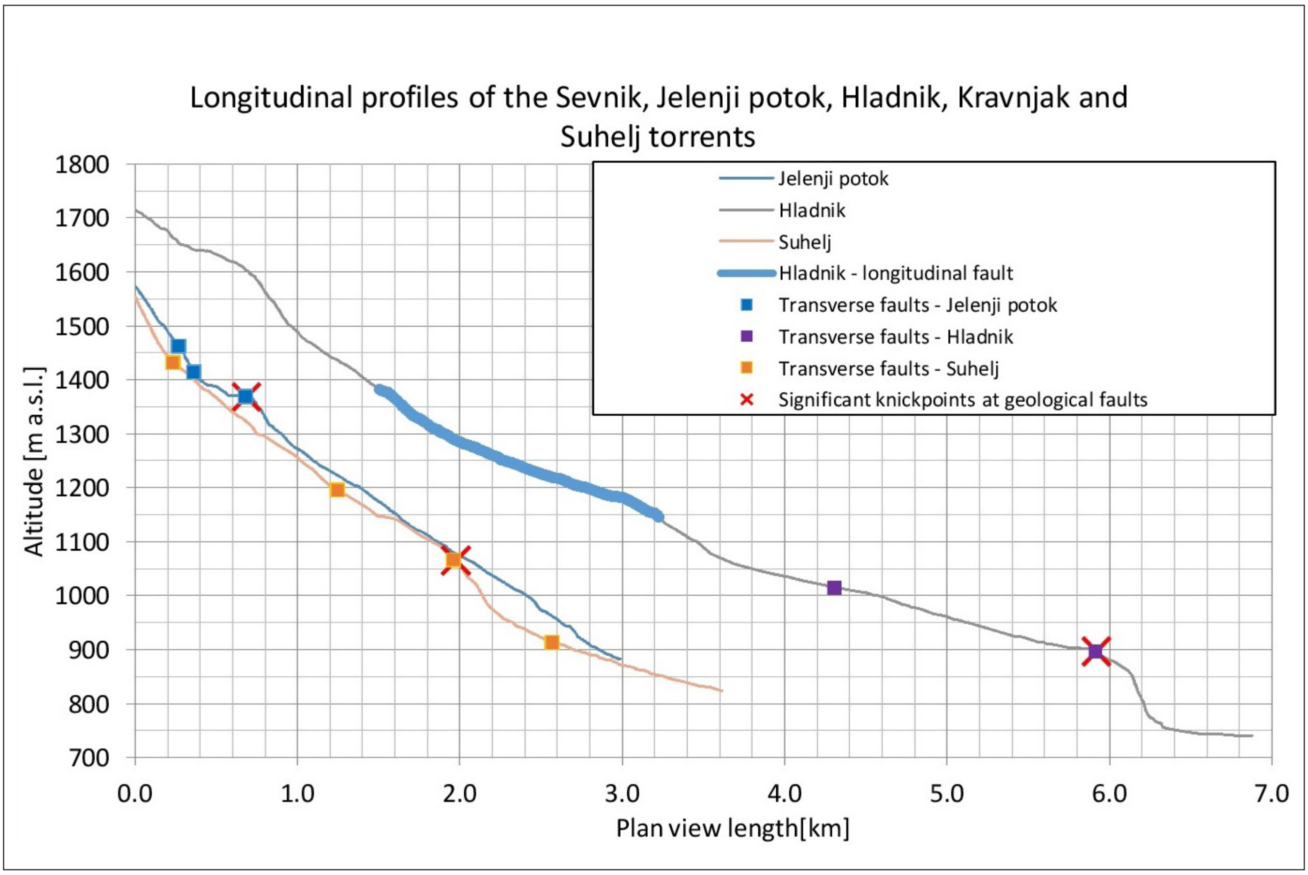

Fig. 3. Longitudinal profiles of the Sevnik, Jelenji potok, Hladnik, Kravnjak and Suhelj torrents with significant knickpoints at geological faults.

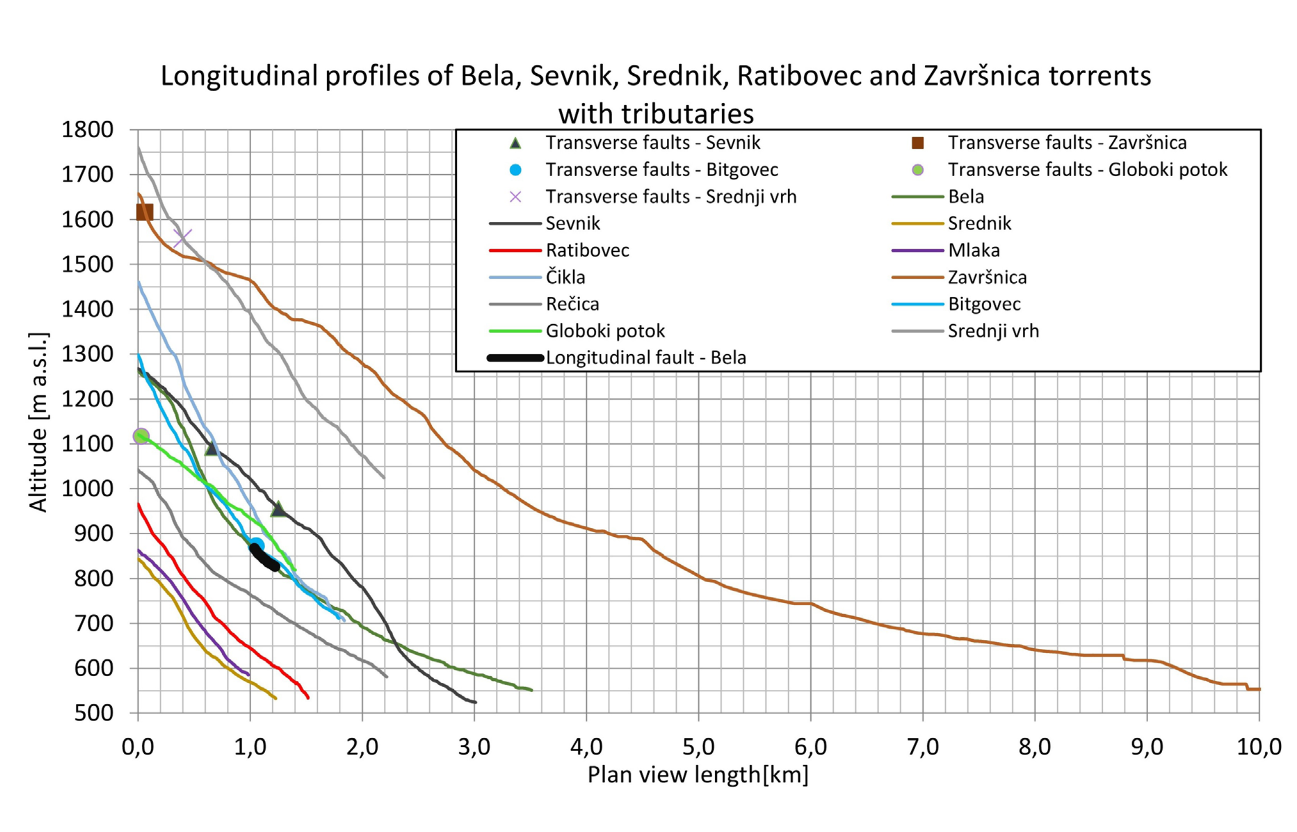

Fig. 4. Longitudinal profiles of the Bela, Sevnik, Srednik, Ratibovec, and Završnica torrents.

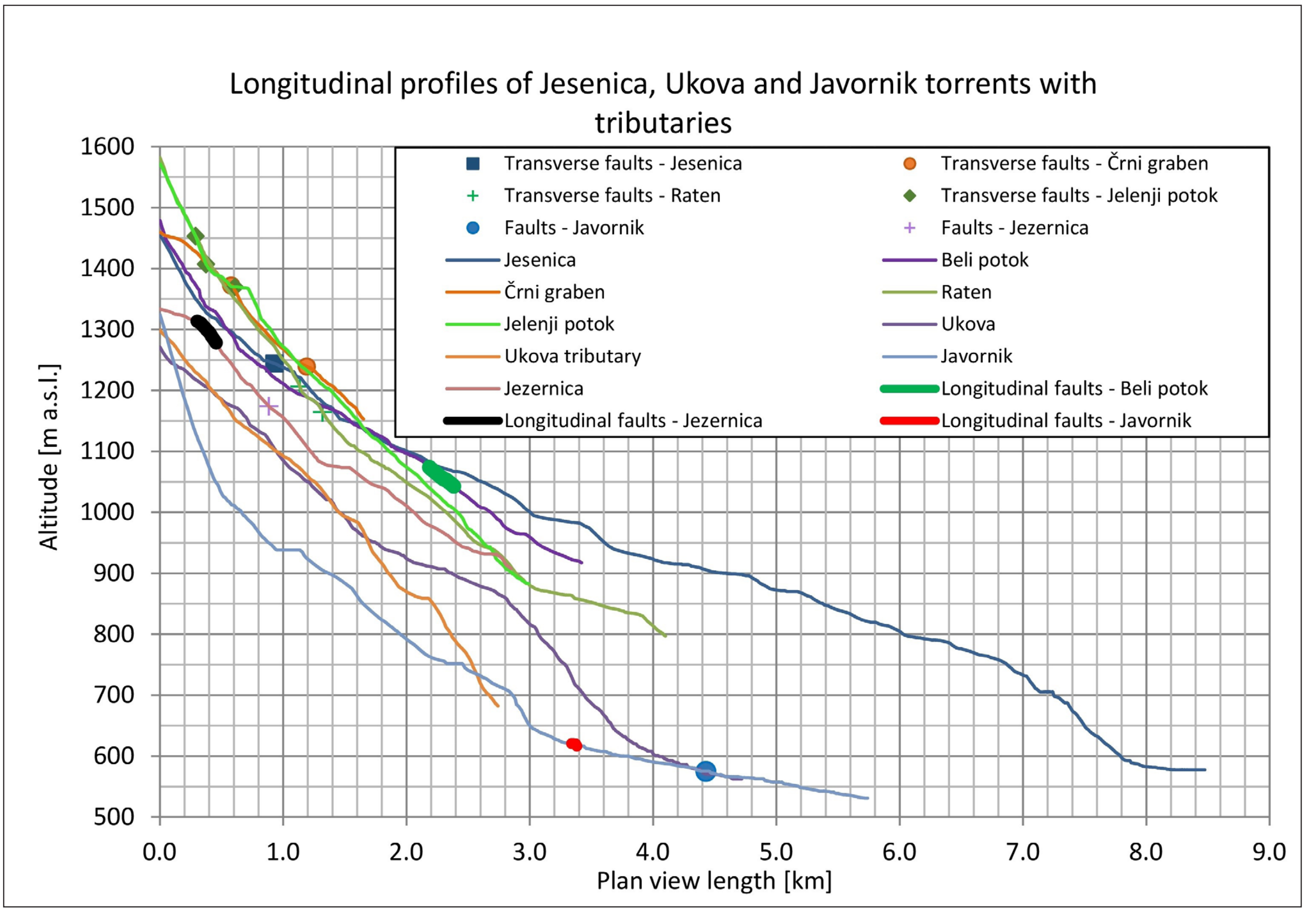

Fig. 5. Longitudinal profiles of the Jesenica, Ukova and Javornik torrents – with their tributaries.

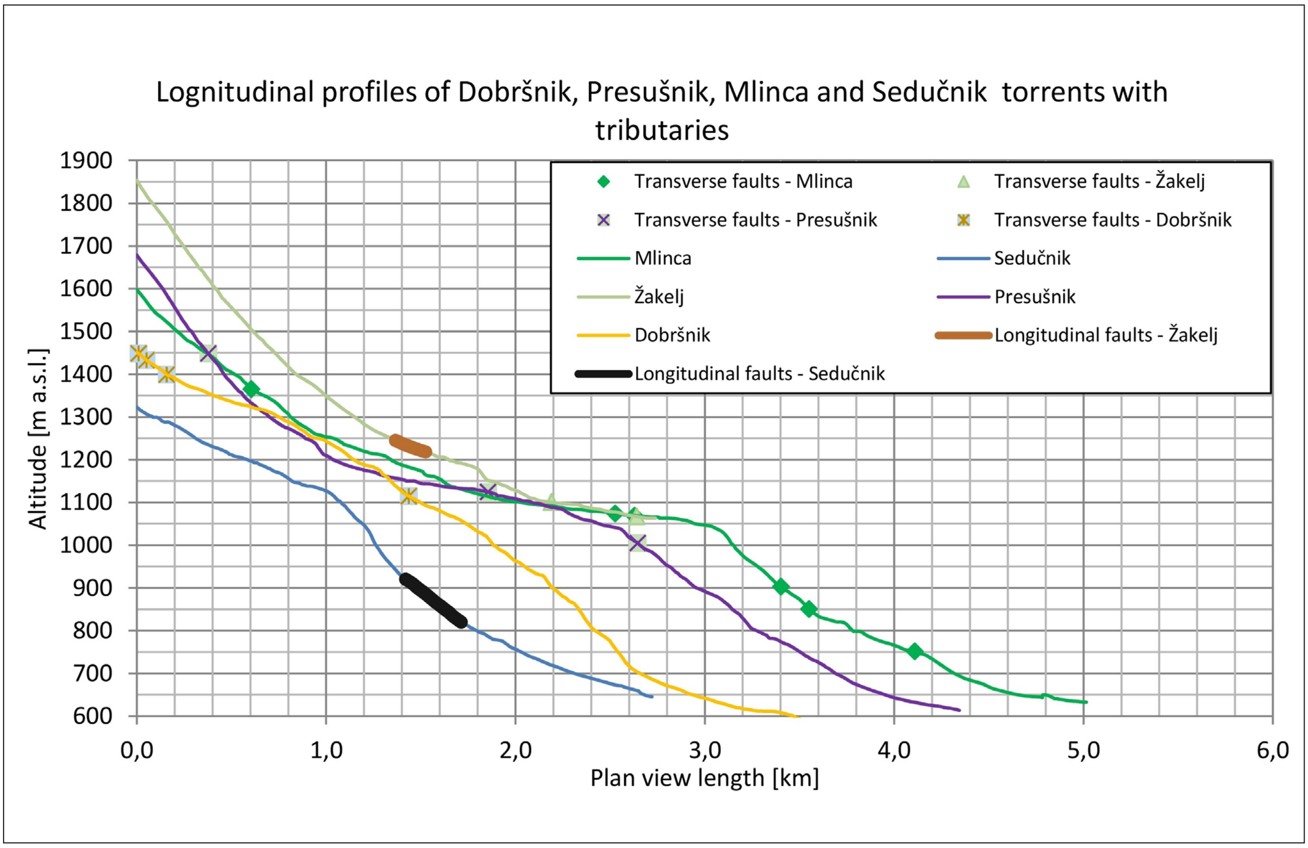

Fig. 6. Longitudinal profiles of the Dobršnik, Presušnik, Mlinca in Sedučnik torrents – with their tributaries.

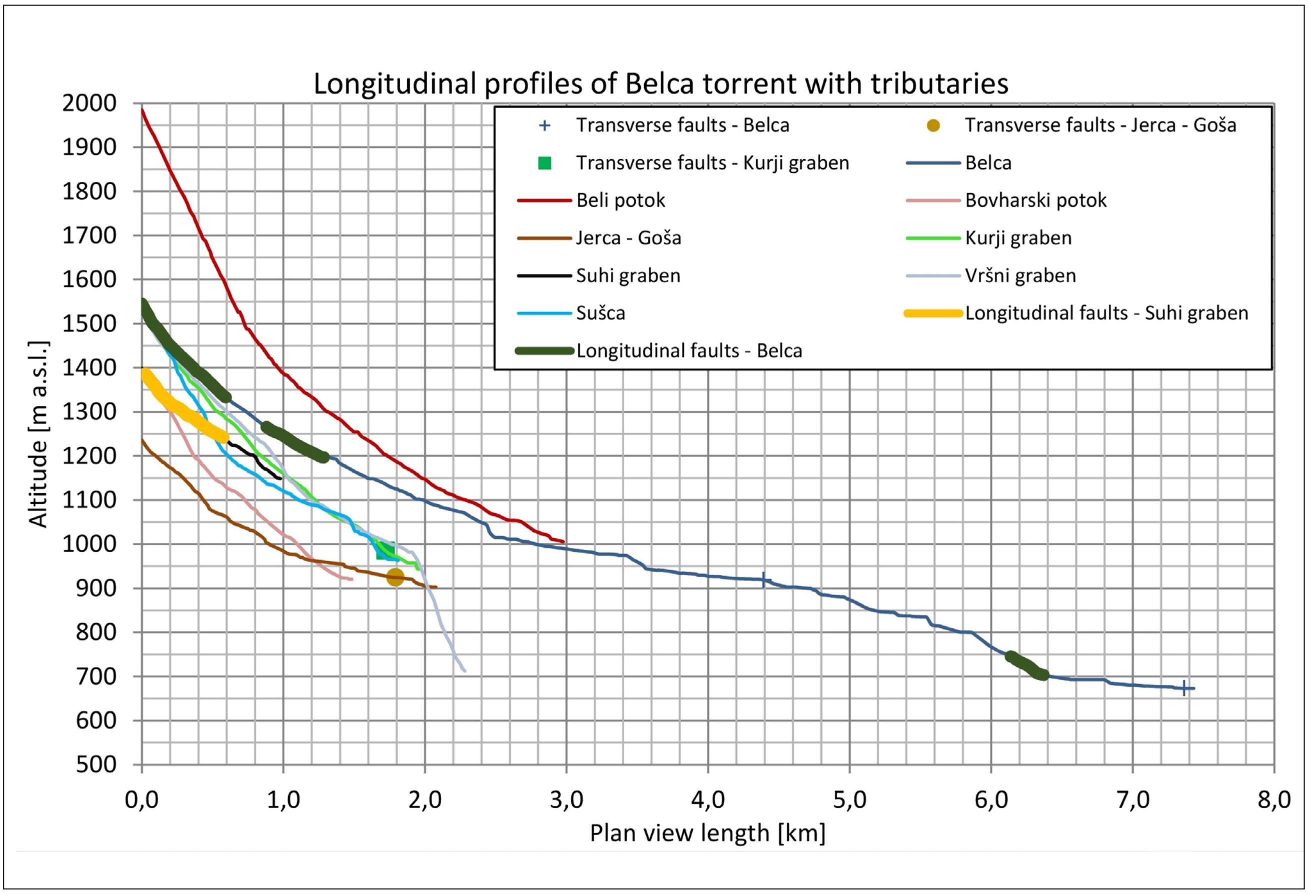

Fig. 7. Longitudinal profiles of the Belca torrent – with its tributaries.

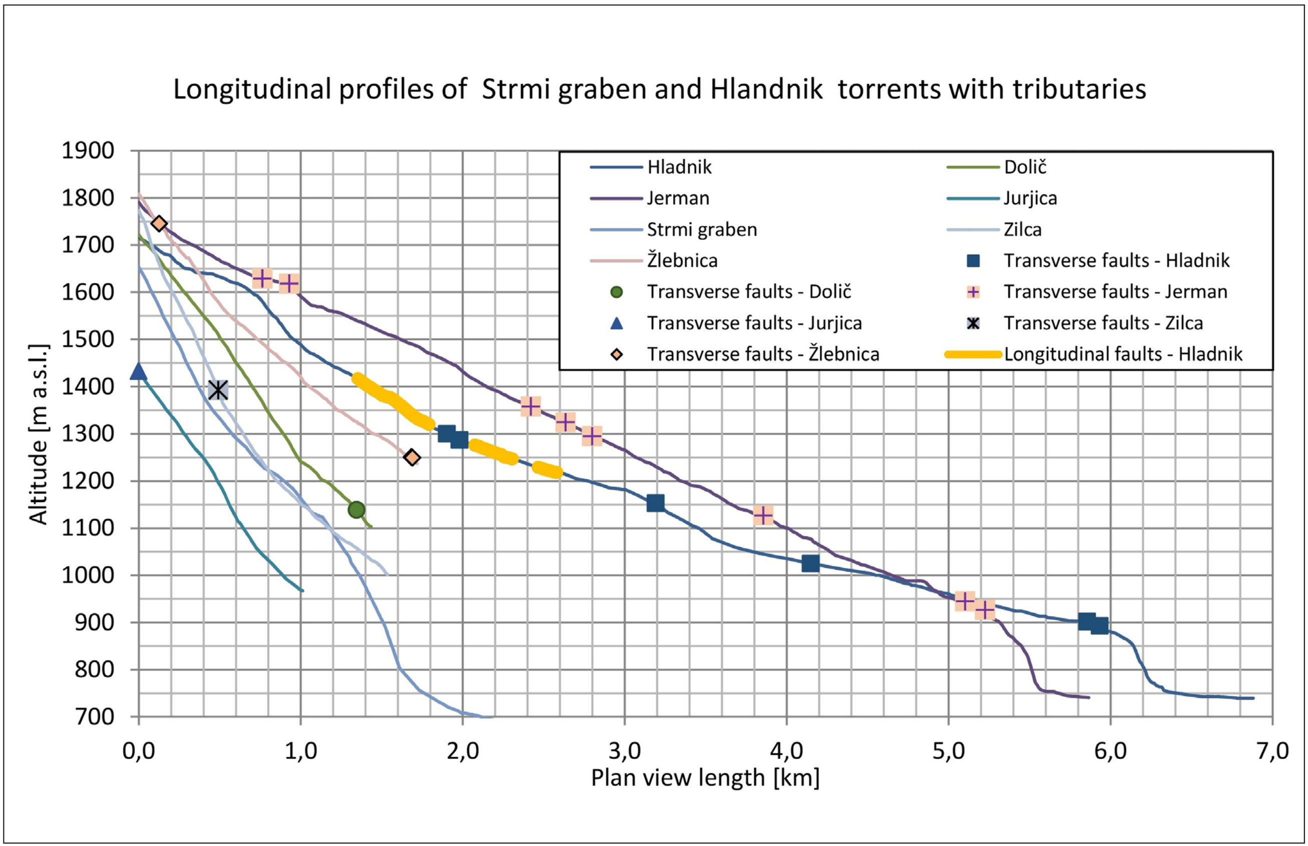

Fig. 8. Longitudinal profiles of the Strmi graben in Hladnik torrents – with their tributaries.

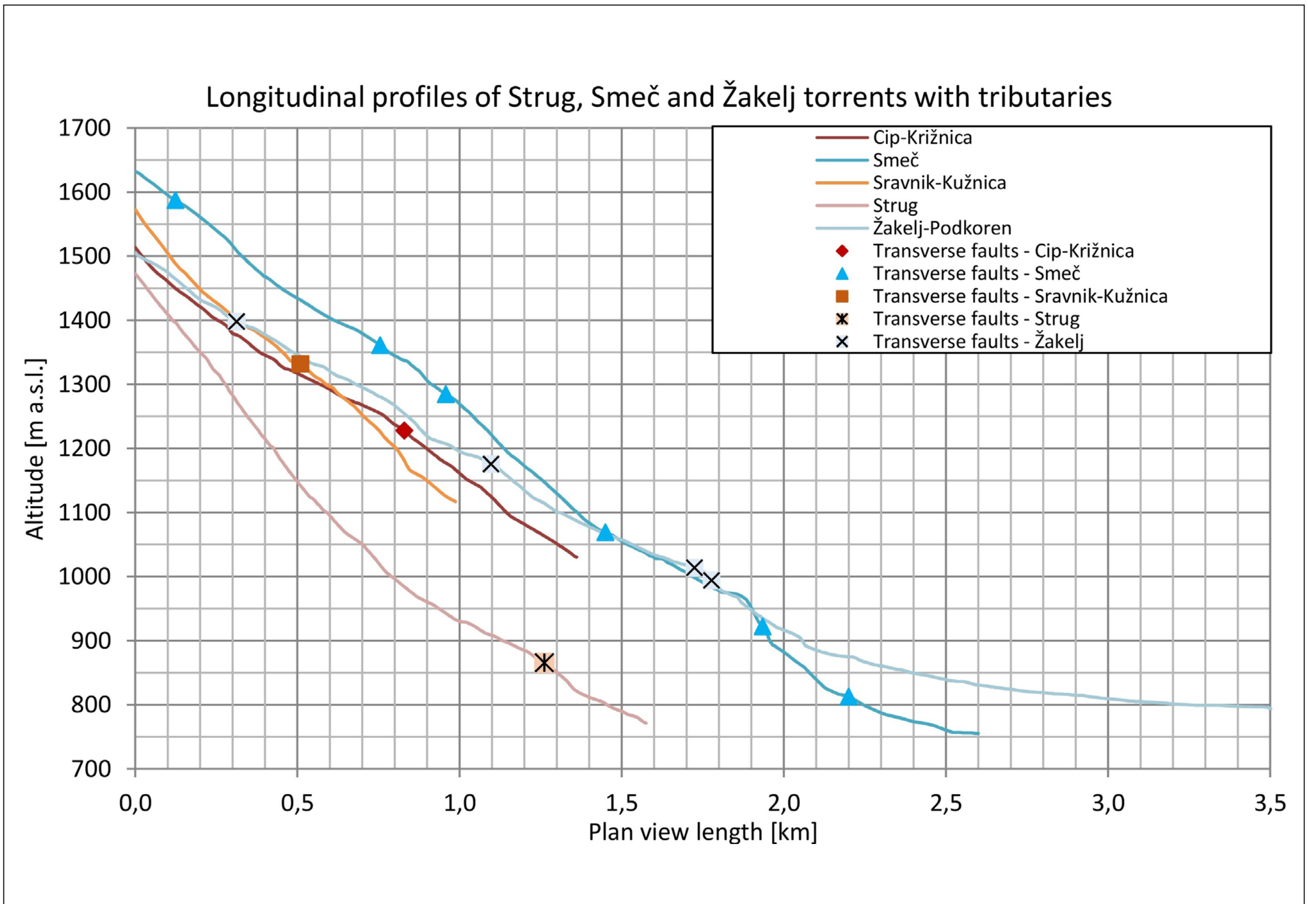

Fig. 9. Longitudinal profiles of the Strug, Smeč and Žakelj torrents – with their tributaries.

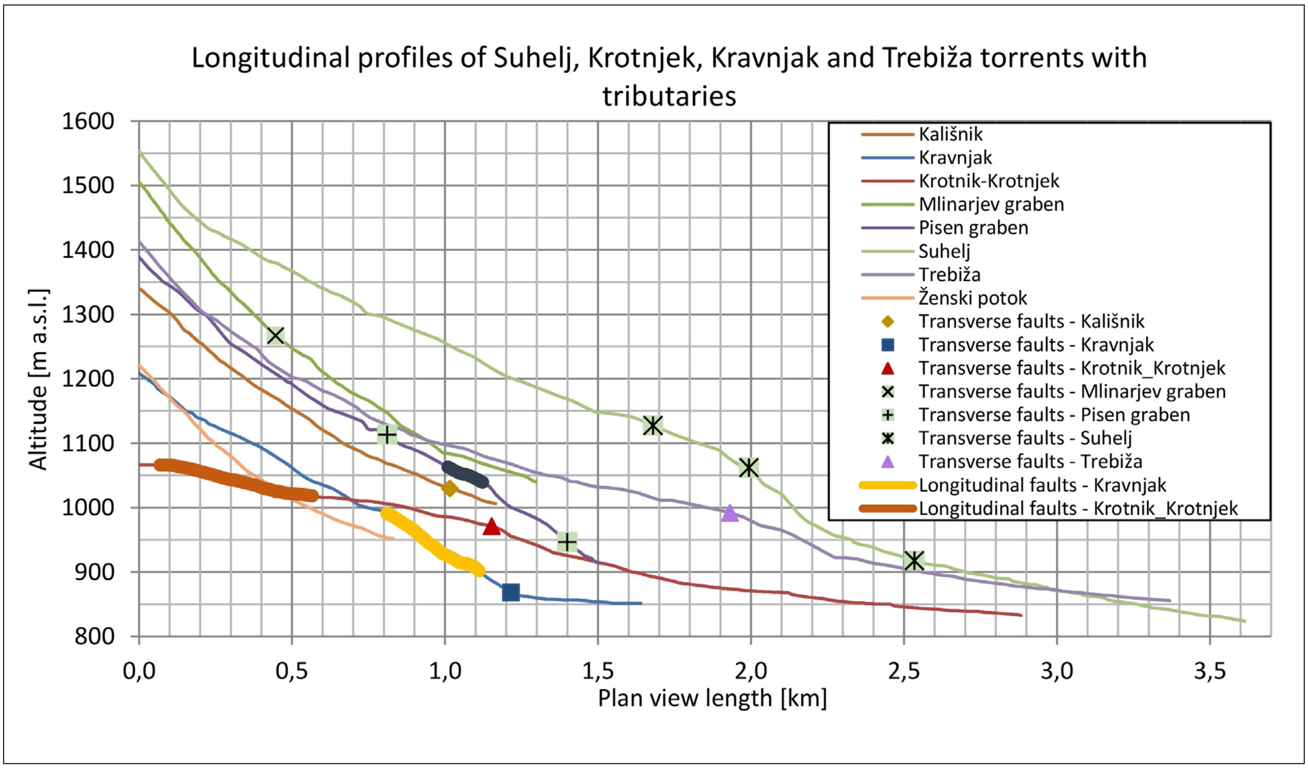

Fig. 10. Longitudinal profiles of the Suhelj, Krotnjek, Kravnjak and Trebiža torrents – with their tributaries.

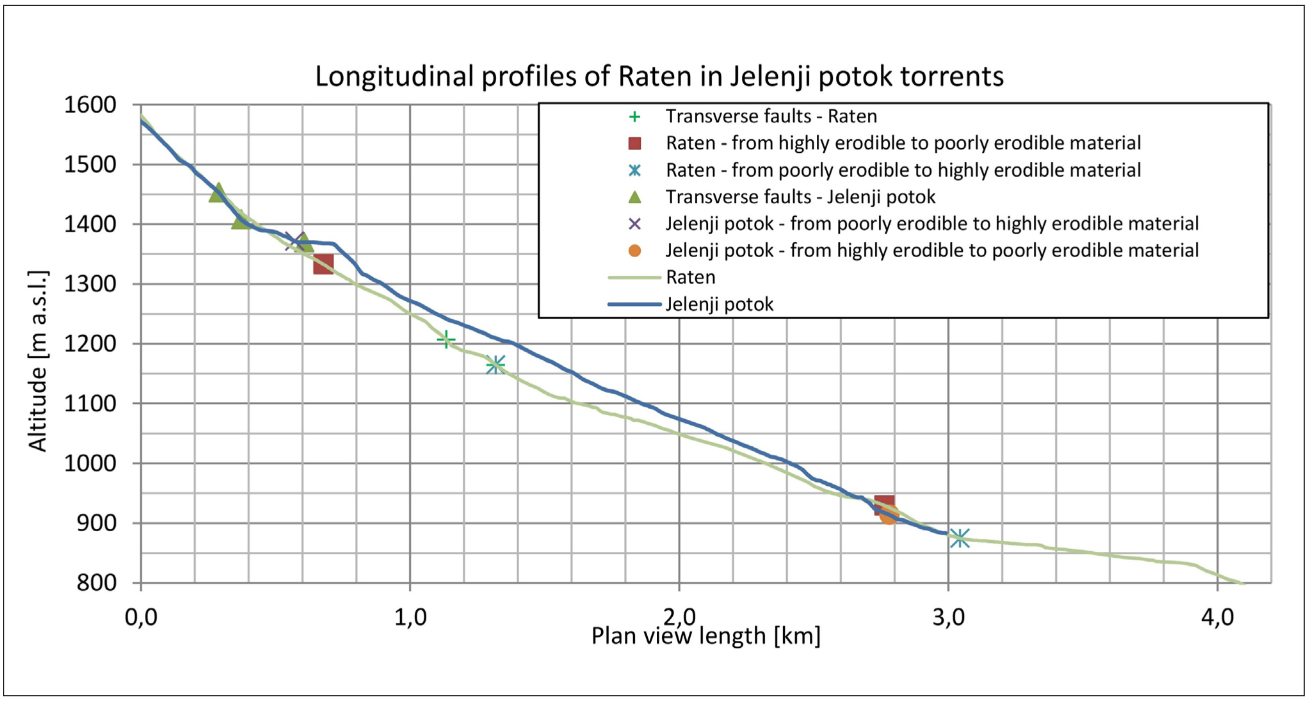

Fig. 11. Longitudinal profile of Jelenji potok with significant knickpoints at contact of highly erodible and poorly erodible material and contrary.

Impact of lithology on torrential stream bed

Due to the varying resistance of rocks to erosion, bedrock lithology presents an important factor influencing the stream profile shape. Additionally, when bedrock is impermeable the enhanced surface water runoff will mechanically erode soils. Orientation of various tectonic and non-tectonic structures may also significantly influence the rate of erosion. For example erosion tends to be stronger parallel to bedding in sedimentary rocks (Perron & Royden, 2012).

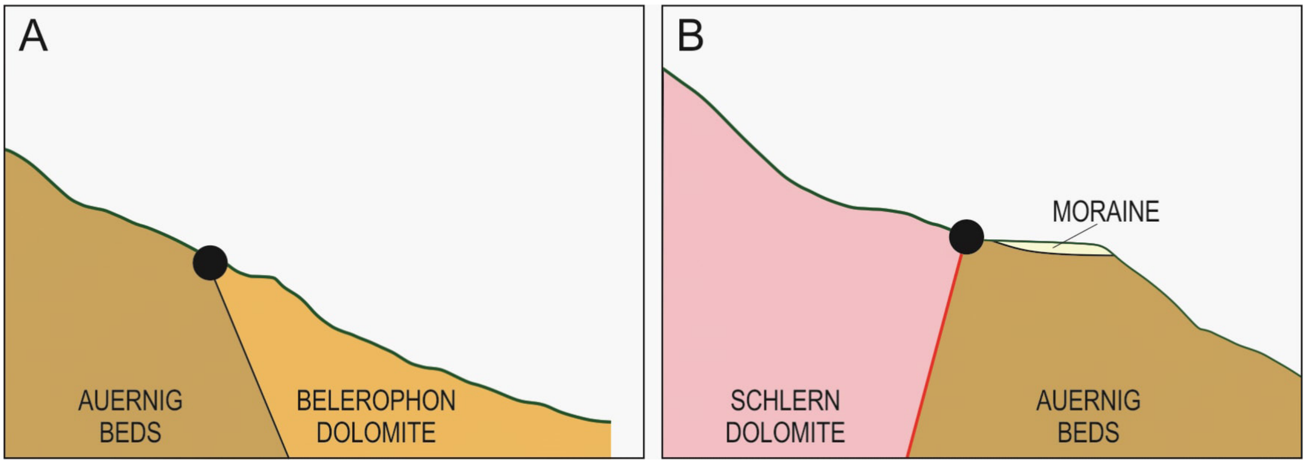

Fig. 12. Convexity and concavity between different erodible rocks, example of Jelenji potok. A – torrential streams flow from highly erodable to poorly erodable rocks; B - torrential stream from poorly erodible to highly erodible rocks.

Engineering geological classification categorizes Slovenian rocks into three groups (Ribičič et al., 2003). Highly erodible rocks of the first group comprise of soils and soft rocks (carbonate clastic rocks, marlstone, rocks composed of clay and silt fractions). The second group includes moderately erodable rocks with a thin weathered cover (clastic, pyroclastic and metamorphic rocks), whereas the third group comprises poorly erodible massive carbonates and igneous rocks. In general, torrential streams form concave shapes but in nature the concave and convex forms often exchange. Frequently the longitudinal profile of torrent is transformed at the contact between soft and solid rocks or at the contacts between clastic rocks and carbonates respectively. It is harder for torrents to erode carbonate rocks therefore in the case of contact from soft to solid rocks the longitudinal profile is converted from concave to convex shape. This can be clearly seen from Fig. 11 and Fig. 12A where torrential streams flow from highly erodable (clastic sediments, fine grained clastic rocks, mixed clastic rocks with sandstone and breccia) to poorly erodable rocks (massive carbonates, thick bedded and massive carbonates). On the contrary, the longitudinal profiles of torrent in the Fig. 12B form concave shape.

Figure 13 shows the accumulated length of headwater torrents per rock erosivity class based on Erosion map and lithological properties (Ribičič et al., 2003). From the Figure 13 it can be seen that the majority (87.4 %) of investigated torrential streams in the Western Karavanke are cutting into highly erodable rocks (137.54 km), whereas the total length of torrents in poorly erodable rocks is 19.83 km. These results correspond to concavity of the longitudinal profiles in more easily erodible sedimentary rocks. Moreover, the impact of lithological background is reflected a great number of torrential streams that were determined on the research area of 1.5 km^2.

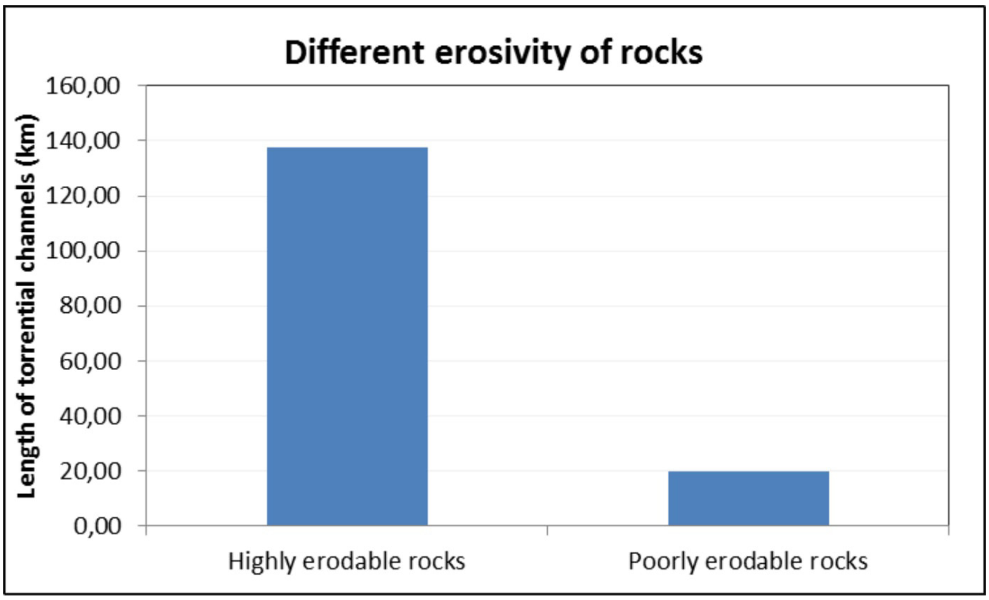

Fig. 13. Cumulative length of investigated torrents per erosivity class of the bedrock

Conclusions

In this paper, fifty-three longitudinal profiles of torrential channels in the Upper Sava Valley on the slopes of the Western Karavanke are discussed. ArcGIS mapping (ESRI, 2013) was used to obtain longitudinal sections of torrential channels from DMV 5. In general, accuracy of longitudinal profiles provided from DMV 5 does not correspond to more detailed mathematical modeling, but for describing complete torrents (from springs to confulences with larger streams) and for detecting main forms the accuracy of calculated profiles is sufficient.

For the Western Karavanke, a rather heterogenous geological composition and a large number of faults are typical. Highly and poorly erodable rocks of stream bed often change along torrential channels. Majority of torrential channels in the study area are cutting into highly erodable rocks, consequently torrential watercourses are located in narrow valeys. Frequently faults occur longitudinal or transverse to torrential channel.

From the research that has been carried out, it is possible to conclude that the longitudinal profiles of torrential channels do not correspond to equilibrium longitudinal profile. A lot of convex sections are presented. According to the availability of data it was found, that (1) transverse faults could be the reason for some knickpoints while longitudinal faults provide conditions for the formation of concave, equilibrium stream channel, and (2) at the contact between solid and soft rocks convex reaches with knickpoints occur.

Also, other factors could be the reason for convexity with knickpoints but were not presented in this article. Additionaly, the erosion of Quaternary glaciations of the Upper Sava Glacier could have influenced the longitudinal profiles of torrential stream channels. Existing data about those glaciations are poor and glaciations were consequently not included in this study. Exceptionally, other reasons like the low erosion ability of lower order torrential streams, higher erosion capacity of the main torrential stream against the tributary torrential stream and as well human influence could have impact on convex longitudinal profiles with knickpoints. Knickpoints are the result of local conditions which affected formation of torrential channels and normally do not have a single reason for their formation.

Authors are aware that present study does not reflects the entire "story" of longitudinal profiles of torrential channels in the Western Karavanke Mountains. More research that will include detailed field surveys is still necessary before obtaining a more certain answer on the evolution of longitudinal profiles of torrential channels. Further in-depth analysis using higher resolution data, alongside palaeoenvironmental work, will greatly benefit our understanding of geological and tectonic controls upon longitudinal profile of torrent stream evolution.

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