GEOLOGIJA *65/2*, 129-147, Ljubljana 2022

https://doi.org/10.5474/geologija.2022.008

Review of the research and evolution of landslides in the hinterland of Koroška Bela settlement (NW Slovenia)

Pregled raziskav in nastanek plazov v zaledju naselja Koroška Bela (SZ Slovenija)

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Prejeto / Received 30. 5. 2022; Sprejeto / Accepted 22. 9. 2022; Objavljeno na spletu / Published online 30. 9. 2022

Key words: landslide, debris flow, research, monitoring, landslide evolution, Koroška Bela
Ključne besede: plaz, drobirski tok, raziskava, monitoring, nastanek plazov, Koroška Bela

Abstract

This paper gives an overview of landslide research and the activity of landslides located above the Koroška Bela settlement in Northwest Slovenia. There are several landslides in this area and they pose a direct threat to the settlement below. The settlement is very densely populated (about 2,100 inhabitants) and has well-developed industry and infrastructure. It is built on deposits from past debris flows, indicating that large slope mass movements have occurred in the past. In this regard, the hinterland of Koroška Bela has been investigated since 2006, within the framework of various research, technical and European projects. The most extensive geological and geotechnical investigations were carried out after April 2017, when part of the Čikla landslide collapsed and mobilised into a debris flow. All of the investigations which have been carried out over the years revealed that the hinterland of Koroška Bela is characterised by high landslide activity due to geological, hydrogeological and tectonic conditions. In order to protect people and their property, it is essential to implement a holistic mitigation measure which includes remediation works (drainage works, debris flow breaker, etc.) and non-structural measures (monitoring system, early warning system, risk management, etc.). Regular and continuous monitoring of all landslides is also crucial to observe the landslide dynamics and evaluate the effectiveness of structural mitigation measures.

Izvleček

Članek predstavlja pregled raziskav in aktivnosti plazov, ki se nahajajo nad naseljem Koroška Bela v severozahodni Sloveniji. Obravnavano območje je podvrženo plazovom, ki predstavljajo neposredno nevarnost za spodaj ležeče naselje. Naselje je gosto poseljeno (s približno 2.100 prebivalci) in ima dobro razvito industrijo ter infrastrukturo. Zgrajeno je na sedimentih preteklih drobirskih tokov, kar tudi dokazuje, da so se obsežni pobočni masni premiki prožili tudi v preteklosti. Zaradi naštetih dejstev na tem območju potekajo raziskave že od leta 2006, ki so se izvajale v okviru različnih raziskovalnih, tehničnih in evropskih projektov. Najobsežnejše geološke in geotehnične preiskave so bile izvedene po aprilu 2017, in sicer po sprožitvi manjšega drobirskega toka na Čikli. Vse raziskave in študije, ki so bile izvedene v vseh teh letih, so pokazale, da je zaledje Koroške Bele podvrženo aktivnim plazovom, ki so se formirali predvsem zaradi danih geoloških, hidrogeoloških in tektonskih razmer. Za zaščito ljudi in njihovega imetja je nujna celostna izvedba varovalnih ukrepov, ki bodo vključevali tako preventivne (npr. sistem za opazovanje, opozorilni sistem, načrt obvladovanja ogroženosti, itd.), kot tudi gradbene ukrepe (npr. drenažni sistem, pregrade, itd.). Prav tako je nujno izvajanje rednega in kontinuiranega spremljanja vseh aktivnih plazov v zaledju, ki bo omogočal prepoznavanje dinamike plazov in meril učinkovitost izvedenih gradbenih ukrepov.

Introduction

Catastrophic landslides are usually the result of rapid collapse of soil, rock, and fluids triggered by heavy rainfall, snowmelt, earthquakes, or anthropogenic activities (Gariano & Guzzetti, 2016; Lacroix et al., 2020). In Slovenia, landslides are fairly common and are related to active tectonics, diverse geological settings and climatic conditions. Landslides frequently occur in clastic rocks located under steep slopes composed of highly permeable carbonate rocks (Jemec Auflič et al., 2017a). An example of this is the slope morphology of the Vipava Valley, which is primarily influenced by the different lithology of the thrust units and is characterised by steep carbonate cliffs and gentle lower slopes formed in the underlying flysch (Verbovšek et al., 2017; Popit et al., 2022).

In recent decades, four major landslides have occurred in Slovenia, with a volume of approximately 1×10^6 m^3. In November 2002, the Stože debris flow formed in the catchment area above the village of Log pod Mangartom. The debris flow caused seven casualties and destroyed residential and farm buildings (Mikoš, 2020). In the same period, reactivation of the Slano Blato landslide occurred above the village of Lokavec (Fifer Bizjak & Zupančič, 2009; Mikoš et al., 2009; Maček et al., 2016) and, one year later (2001), the Strug landslide occurred above the village of Koseč (Mikoš et al., 2006). A large landslide area is also located in Rebernice in the Vipava valley, where deep-seated landslides have formed in complex geological settings (Popit et al., 2014; Popit, 2017). This area is crossed by a motorway, where investigations and remediation works are constantly carried out due to road subsidence.

These events, and the fact that alpine and perialpine regions are highly susceptible to landslides, have revealed that, on the whole, Slovenia needs to pay more attention to landslide prevention measures, to reduce the impact of landslide activity and to protect people and infrastructure (Mikoš, 2021).

This paper focuses on historical, as well as current, landslide activity on the mountain slopes above the settlement of Koroška Bela in Northwest Slovenia (Fig. 1). This territory is one of the most active landslide-prone areas in Slovenia. It attracts additional attention due to historical evidence of past debris flows in recent geological history. The first registered event occurred in the 18th century and it caused partial or complete destruction of more than 40 buildings and devastated cultivated areas in the village of Koroška Bela (Lavtižar, 1897; Zupan, 1937). The most recent event occurred in April 2017, when part of the Čikla landslide collapsed and turned into a debris flow (Jež et al., 2019a). Even though this particular debris flow did not reach the settlement, it was perceived to be an additional warning sign that slope mass movements in the hinterland of Koroška Bela are still a source of potential debris flows. The area of interest is also prone to other types of landslides, such as slides, flows, falls, and combinations thereof.

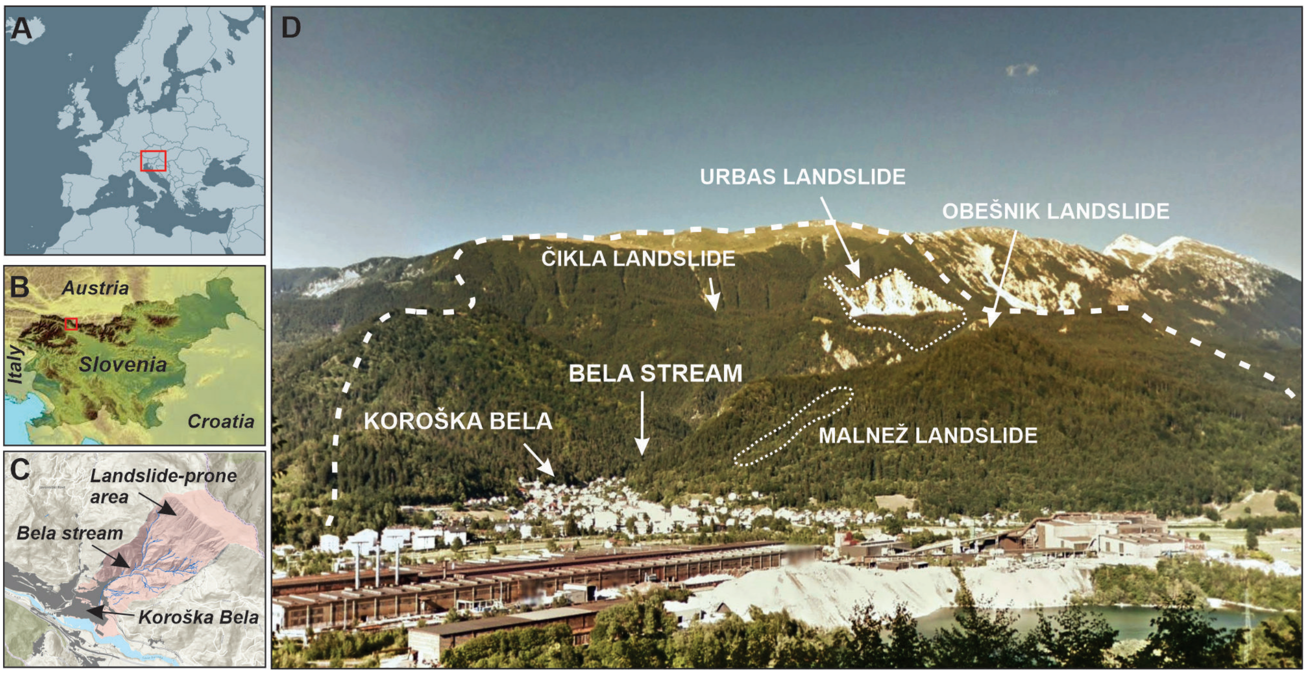

Fig. 1. Location of Koroška Bela and the extent of the landslide-prone area.

Koroška Bela is a densely populated urban settlement in the alpine Upper Sava River valley. It is built on a typical torrential fan with an estimated area of 1.02 km^2, formed by past debris flows. Currently, it has about 2,100 inhabitants, a well-developed steel works and an important infrastructure connection between the capital of Slovenia and Northwest Slovenia.

In this respect, the landslide-prone area in the hinterland of Koroška Bela has been under investigation since 2006. The research started within the framework of various national and international projects (Fig. 2; Table 1). All of the investigations can be roughly divided into two stages: before and after the Čikla debris flow in April 2017. The first set of studies, carried out before April 2017, was primarily scientific. Their main objective was to identify and understand the characteristics and kinematics of landslides. Studies carried out after April 2017 were primarily conducted with the goal of developing and implementing mitigation measures (Fig. 2; Table 1).

Morphological and geological settings

The hilly and mountainous hinterland of Koroška Bela is a part of the Belščica slope (Karavanke mountain ridge). It covers an area of approximately 6 km^2 and extends from 520 to 2,100 m a.s.l. It is characterised by medium to steep slopes, sloping to the southwest. Since the slopes are exposed to the sun, they experience relatively large temperature oscillations. The area is characterised by very rugged terrain, dominated by concave slopes. The prevalence of concave slopes may have an indirect influence on the potential occurrence of landslides since, in these areas, the velocity of water flow usually decreases, resulting in water accumulation that increases soil water saturation and slope instability (Hengl & Reuter (2009) cited in Romer & Ferentinou (2016)). Komac (2005) also observed that a greater number of landslides in Slovenia occur in concave areas. The land use map shows that the Koroška Bela hinterland is almost completely

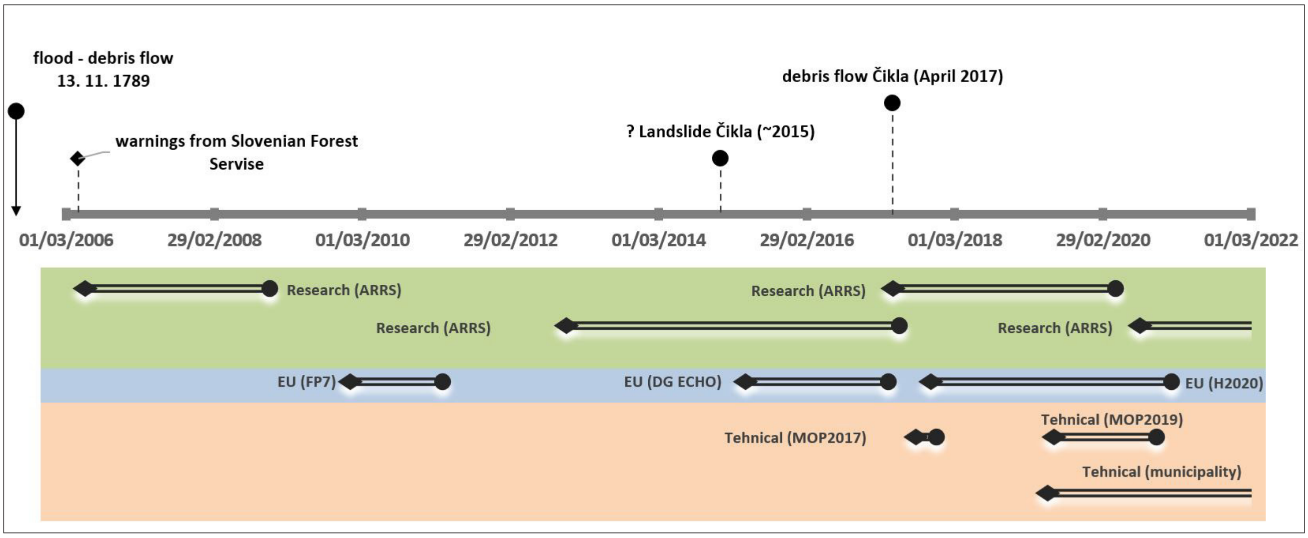

Fig. 2. Timeline of landslide activity and research since 1789. The coloured background defines the type of project (green – research projects funded by Slovenian Research Agency; blue – projects cofunded by EU Programmes; orange – technical projects funded by the Ministry of the Environment and Spatial Planning and the Municipality of Jesenice).

This paper gives an overview of landslide research above the Koroška Bela settlement. The first part consists of a detailed description of the study area, the investigations conducted and their main outcomes. The second part deals with the evaluation of recent landslide activity using multitemporal digital orthophoto imagery and digital elevation models (DEMs).

This paper summarises the extensive successive research carried out in the Koroška Bela landslide area and provides an example of good practice in landslide risk management.

vegetated and covered with forest (MKGP, 2016; Peternel, 2017). In this case, it is assumed that the forest has a rather limited protective function against slope instabilities, since most of the forest consists of larch and spruce, which are characterised by shallow root systems. Conversely, large unstable trees on steep slopes can increase the risk of triggering landslides, as windstorms may cause uprooting, toppling and falling of trees and accelerate the weathering and erosion of slopes (Jakša & Kolšek, 2009). In addition, fallen trees and other vegetation accumulate in the

Bela stream as additional unstable material that could be mobilised during torrential floods.

The Koroška Bela hinterland is defined by complex geological and tectonic conditions. For geological maps and detailed geological descriptions of the Koroška Bela hinterland, the reader is referred to previous studies (Jež et al., 2008; Peternel et al., 2017, 2018). A general, geological description of the wider Koroška Bela area has been presented by Buser (1978), Buser (1980) and Jež et al. (2008). The study area mainly consists of Upper Carboniferous and Permian clastic rocks – Permian carbonates and Triassic to Lower Jurassic carbonate rocks (Jež et al., 2008). The main slope instabilities are related to tectonic contacts between the clastic Upper Carboniferous to Permian rocks (claystone, siltstone, sandstone and conglomerate) and various Permian and Triassic carbonate and clastic rocks. (Jež et al., 2008).

Tectonically, the area belongs to the Southern Alps (Placer, 2008). It is a part of the Košuta fault zone and is dissected by numerous NW-SE faults connecting two major fault zones (the Sava and Periadriatic fault zones) (Jež et al., 2008). The rocks are heavily deformed and, therefore, very prone to rapid and deep weathering. Carbonate rocks in the uppermost parts of the Belščica slope are also subject to intense physical and chemical weathering, resulting in large quantities of talus and scree material.

Prominent morphological features in the study area are relatively long ridges interrupted by long, deep, narrow and irregular mountain watercourses (Brenčič & Poltnig, 2008; Janža et al., 2018). In general, three types of aquifers characterise the regional hydrogeological settings, which are determined by geological conditions: intergranular aquifers in clayey carbonate gravels, karst-fissured aquifers in carbonate rocks and small local aquifers, typically occurring in clastic rocks.

The morphology of the slopes, unfavourable geological and tectonic conditions, and climatic diversity contribute to the fact that the region above Koroška Bela is prone to landslides and torrents and represents the source of potential debris flows that could pose a threat to the densely populated settlement below. Landslide activity is evidenced by an irregular and hummocky terrain comprised of protrusions and depressions of various sizes, curved trees, tension cracks, erosion slumps and wetlands on the surface, as well as widespread subsidence of local roads.

The first warnings of landslide activity in the area, that attracted the attention of our research group, were reports of sliding by the Slovenian Forest Service. They reported the subsidence of a local road, the presence of curved trees and erosion flanks in the wider catchment area of the Urbas water reservoir (Fig. 2).

Climatic conditions

The study area is characterised by an alpine climate, ranging from a low mountain to a high mountain climate (Brenčič & Poltnig, 2008). The climate is highly variable due to the effects of alternating high and low atmospheric pressure and alternating atmospheric fronts. The variable climatic conditions are also related to the great differences in altitude, the rugged terrain with deep and narrow valleys, and the slope orientation (Rakovec et al., 2000). It is typical for this part of the Karavanke Mountains that the mean annual precipitation ranges from 1,600 to 2,000 mm, while the maximum 24-hour precipitation with a 100-year return period is estimated between 180 and 210 mm (Internet 1). There are two annual precipitation peaks, with the main precipitation peak in autumn and the second in spring.

An overview of past research

An overview of all the implemented investigations is listed in Table 1. The first research started within the Target Research Project (TRP): Debris flow risk assessment in Slovenia. Within the TRP project, geological mapping of the Koroška Bela hinterland, a study of alluvial fan deposits, and modelling of debris flows using a Flo-2D model were carried out. The project results showed that the alluvial fan of Koroška Bela consists of a sequence of depositional layers related to several historic debris flows (Jež et al., 2008; Mikoš et al., 2008). Based on detailed engineering mapping of this area, the Urbas landslide was identified (for the first time), named and described as the Potoška planina landslide (Jež et al., 2008). Furthermore, the estimated magnitudes of debris flows for the Bela torrential watershed were calculated by Sodnik and Mikoš (2006), using various morphological parameters. By applying different empirical equations for the determination of the design discharge and flood volume with a 100-year return period, different debris flow magnitudes were calculated, ranging from 19,687 m^3 to 93,231 m^3 (Sodnik & Mikoš, 2006). The Bela torrential fan was classified as a transitional fan, where debris flows are possible. For debris flow modelling, a Flo 2-dimensional model was used with different numerical square grids generated from digital elevation models (Sodnik et al., 2009, 2012, 2013; Sodnik & Mikoš, 2018; Bezak et al., 2020). The calculated results showed that the estimated inundated area ranges between 118 and 145 m² and the average maximum flow depth ranges from 0.6 to 1.2 m, depending on the square grid applied.

The first monitoring at the Urbas landslide was established using a novel motion detection device that was developed within the EU funded project "Integrated Interferometry and GNSS for Precision Survey (I2GPS)" founded by the Seventh Framework Programme (FP7-GALILEO-2008-GSA-1). The device integrated interferometric synthetic aperture radar (InSAR) and global navigation satellite system (GNSS) technologies. Two compact active transponder (CAT) units (InSAR data) and a combined CAT and GNSS unit (providing 3D displacement assessments) were installed to monitor the surface displacements of the landslide and its vicinity (Komac et al., 2015). The InSAR and GNSS results showed relatively large (up to 32 mm horizontal and up to 15 mm vertical) displacements during a relatively short monitoring period (02/2011 – 08/2011), indicating a displacement of the central-upper and south-eastern parts of the landslide body (Komac et al., 2015, 2018). The Urbas landslide was further investigated and monitored within the framework of a PhD thesis (Peternel, 2017). To evaluate the kinematics of the Urbas landslide, understand the characteristics of the sliding process and assess the surface displacement rates and changes in surface topography, periodical monitoring was conducted using a variety of remote sensing and in-situ geodetic techniques (unmanned aerial vehicle (UAV) photogrammetry, terrestrial laser scanning (TLS), and tachymetric surveys) (Peternel et al., 2015, 2017a; Peternel, 2017; Peternel & Komac, 2017). The surveys revealed that the Urbas landslide is a composite landslide (Cruden & Varnes, 1996) consisting of rock falls (upper part), deep-seated landslides (main body) and debris flow source areas (lower part) (Peternel, 2017; Peternel et al., 2017a). The long-term activity of the Urbas landslide over the past 138 years has also been reconstructed using the dendrogeomorphological analysis of bent trees (Oven et al., 2019). Dendrogeomorphology has proven to be a highly useful method in the study of past slope mass movements and has recently been applied to the analysis of the debris flood magnitude in the Planica valley (Novak et al., 2020). The estimated risk and visible activity of landslides have increasingly attracted the attention of the inhabitants of Koroška Bela and the Civil protection service. For this purpose, the socio-economic impact was assessed within the framework of the EU-funded project "RECALL Resilient European Communities Against Local Landslides". In addition, a cooperative team of decision-makers, response authorities, technical experts and other stakeholders was formed to increase awareness and understanding of landslide risk in the community (Jemec Auflič et al., 2017b, 2017c, 2019). In-depth research continued within the research project "Studying landslide movements from source areas to zone of deposition using a deterministic approach (ARRS J1-8153)". As a part of the project, two additional research trenches, with depths between 3.00 and 3.95 m, were excavated on the alluvial fan where the Koroška Bela settlement has been developed; 11 samples of organic material were collected for radiocarbon dating. The main sedimentological units of the research trenches are layers of debris flow deposits interbedded with thick silty and sandy lenses, fluvial (fine-grained) deposits and flood/mudflow deposits (Jež et al., 2019b), suggesting several past depositional events. Age dating of the organic sediments revealed that most of the sediment was deposited during the Last Glacial Maximum (LGM), while two or three debris layers were found in the upper part of the fluvial succession, and these were deposited during the Holocene. The youngest deposits were attributed to the debris flow which occurred in 1789 (Jež et al., 2019b). In addition, Sodnik et al. (2017) upgraded their models by modelling debris flow source areas with a multi-model approach using field data, susceptibility and trigger modelling, implemented using LS-Rapid (Loi et al., 2020). This research project was granted as a strategically important project in the category of International Programme on Landslides (IPL) in 2017-2020.

A very important milestone, which gave additional impetus to the study of landslide areas, occurred in April 2017, when part of the Čikla landslide collapsed and mobilised as a mass flow with a significant amount of talus material and vegetation. The debris flow had an estimated volume of 5,000 m³ and was triggered by heavy rainfall, with 200 mm of precipitation falling in 48 hours (Jež et al., 2019a; Peternel et al., 2022a). This event was one of the triggers for the intensification of detailed geological, geotechnical and hydrogeological investigations of landslides in the hinterland of Koroška Bela in 2017 (Table 1). For the spatial distribution of the applied methods and the description of the engineering geological and hydrogeological results of the Urbas and Čikla landslides, the reader is referred to previous studies (Peternel et al., 2017b, 2018; Janža et al., 2018). The initial investigations were limited and provided only a rough insight into the geological and hydrogeological conditions of the observed landslides. The main outcomes were (Peternel et al., 2017b, 2018, 2019; Janža et al., 2018):

- In the hinterland of Koroška Bela there are more than 20 landslides, five of which have an area of more than 8,000 m^2: the Urbas, Čikla, Potoška planina, Malnež and Obešnik landslides. Among these, Urbas and Čikla are considered the most active.
- Landsliding mechanisms are defined by the complex lithological composition, intensive tectonic deformation and hydrogeological conditions. The rocks and sediments in the study area are heavily deformed and prone to weathering, which results in weak geomechanical properties of the bedrock.
- In the Urbas and Čikla landslides, hydrogeological conditions are very heterogeneous and cannot be characterised uniformly due to complex geological and tectonic conditions. The groundwater is recharging by a combination of infiltration of precipitation and subsurface inflow from the carbonate hinterland. In the upper parts of the landslides, groundwater occurs at the contact between slope deposits and weathered clastic rocks.
- Preliminary 3D reconstructions of the landslide body showed that the calculated volumes of the Urbas and Čikla landslides are 895,000 m^3 and 141,000 m^3, respectively. For landslide volume calculation, the GOCAD-SKUA software was used.
- The modelling results showed that the estimated potential debris flows would have catastrophic consequences in the Koroška Bela settlement. In some densely populated parts, the simulated depth of the potential debris flow exceeds 5 m, which indicates that the application of mitigation measures is inevitable.
- The results of the preliminary investigations also revealed the need for continuous near-real and real-time monitoring and additional geological (hydrogeological, geophysical), geodetic and geotechnical investigations to obtain a basis for mitigation and remediation measures.

Based on these results and the historical facts, the Municipality of Jesenice recognised the high risk and established a monitoring system for the Urbas and Čikla landslides. The monitoring network consists of extensometers, rain-gauges, piezometers, inclinometers and motion detection cameras. All the electronic geotechnical sensors are wired and powered through the base station, which also serves as an automated data logger. To store and access all measured monitoring data, the eTeren platform (https://eteren.geo-zs.si/home) was developed in 2021.

In 2019, additional geological, geotechnical and geodetic investigations were carried out in the frame of the project funded by the Ministry of the Environment and Spatial Planning. The main purposes of this project were the engineering, geological and hydrogeological characterisation of landslides and the implementation of the stability analyses and feasibility studies of mitigation and remediation measures (Table 1). The Geological Survey of Slovenia (GeoZS), which led the project, also involved the Faculty of Civil and Geodetic Engineering (University of Ljubljana) and experts from the Italian Geological Survey (ISPRA) were called in as external consultants. Within the framework of the project, the following main outcomes were drawn (Bezak et al., 2020, 2021; Peternel et al., 2020a, 2020b, 2022a):

- The preliminary results of real-time landslide monitoring showed that the dynamics of the Urbas and Čikla landslides represent a combination of steadily sliding mass behaviour as well as episodic, rapid displacements corresponding to increased rainfall.
- Improved 3D reconstruction of the landslides resulted in the following estimated volumes: Urbas: 1,578,700 m^3, Čikla: 330,500 m^3, Malnež: 173,750 m^3, Obešnik: 301,780 m^3. For landslide volume calculation, the GOCAD-SKUA software was used.
- The study confirmed that the Urbas and Čikla landslides are a source area for debris flows and pose a direct risk to the settlement of Koroška Bela.
- Observations of the Malnež, Obešnik and Potoška planina landslides, which were first identified in 2017, showed that their current state and dynamics pose a significantly lower direct risk to the settlement. Nevertheless, monitoring should be continued and improved.
- The field investigation of the Bela stream and its tributaries revealed that more than

Table 1. An overview of past landslide risk research projects in the Koroška Bela area. The coloured background is defined by the type of project (green – research projects funded by the Slovenian Research Agency; blue – projects cofunded by EU Programmes; orange – technical projects funded by the Ministry of the Environment and Spatial Planning/Municipality of Jesenice).

	Duration		Type of project	Project	Type of research	Location	Research papers
1.	01/06/2006	30/11/2008	ARRS	Debris flow risk assessment in Slovenia	- tranch (Koroška Bela): 2 - geological map of the hinterland of KB - debris flow modelling using the Flo-2D	Hinterland of Koroška Bela; alluvial fan	Sodnik & Mikoš, 2006; Mikoš et al., 2008; Jež et al., 2008
2.	01/01/2010	31/03/2011	EU: FP7	I2GPS – Integrated Interferometry and GNSS for Precision Survey	- 1st monitoring of surface dispalcements using InSAR and GNSS	Urbas	Komac et al., 2012a; 2012b; 2015; 2018
3.	01/12/2012	31/05/2017	ARRS	Dynamics of the slope mass movements in the Potoška planina with analyses of results of remote sensing and terrestric surveys techniques and in-situ measurements	Lower part: - Tachymetric m.: 7 - UAV photogrammetry: 7 Upper part: - TLS: 2 - UAV photogrammetry: 2	Urbas	Peternel et al., 2015; 2017a; Peternel & Komac, 2017; Peter-nel, 2017
4.	04/05/2015	04/04/2017	EU: DG ECHO	RECALL Resilient European Communities Against Local Landslides	Cooperative team Monitoring using crackmeter method	Urbas	Jemec Auflič et al., 2017b; 2017c; 2019
5.	01/05/2017	30/04/2020	ARRS	Studying landslide movements from source areas to zone of deposition using a deterministic approach.	tranch (Koroška Bela): 2 Gephysical m.: vertical electrical sounding (VES)	Urbas, Čikla, Koroška Bela	Sodnik et al., 2017, Jež et al., 2019a; 2019b
6.	21/08/2017	30/11/2017	MOP2017	Implementation of urgent engineering geological, hydrogeological, geophysical, geomechanical and geodetic surveys to determine the objective degree of risk to the population from slope mass movements in the Potoska Planina area and prepare expert documentation prposing mitigation measures.	- geological mapping of the hinterland of Koroška Bela; - engineering-geological (EG) mapping of landslides Urbas and Čikla; - hydrogeological (HG) mapping + in-situ investigations; - 9 boreholes (2 inclinometers; 2 piezometers); - 2 tranches (1 Urbas, 1 Čikla); - seismic Refraction Tomography (SRT): 4 cross-sections (3 Urbas, 1 Čikla); - electrical resistivity tomography (ERT): 4 cross-sections (3 Urbas, 1 Čikla); - light detection and ranging (LiDAR)	Urbas, Čikla	Peternel et al., 2017b; Peternel et al., 2018; Janža et al., 2018
7.	04/07/2019	20/11/2020	MOP2019	Detailed geological-geotechnical and hydrogeological characterization of large landslides in the hinterland of Koroška Bela settlement for the stability analyses and for a feasibility study of mitigation measures	- update EG map; - EG mapping: Malnež, Obešnik; - mapping of Bela stream; -17 boreholes (9 inclinometers; 8 piezometers); - in-situ geotehnical investigations (presiometer. 26; SPT: 4) - in-situ HG investigations (slug t.: 1; pumping t.: 11; tracking t.: 2) - geophysical m. (SRT:~1.200 m; ERT:~2.400 m; GPR: 270 m); - inclinomteric m.: 0 + 4/6 mesurements - tachymetric m.: 4 (dec/19; apr/20; sept/20; jun/21) - UAV photogrammetry (Urbas): 2 (sept/19; avg/20) - tranches (Koroška Bela): 2	Urbas, PP, Čikla, Malnež, Obešnik:	Peternel et al., 2020a; 2020b; 2022 Bezak et al., 2020; 2021; Koren et al., 2022
8.	01/09/2020	31/08/2022	ARRS	Deep-seated landslide prediction modelling based on a combination of physical modelling and a data-driven approach	- continues monitoring; - landslide dynamic modelling; - landslide prediction modelling.	Urbas, Čikla	Peternel et al., 2020; 2022a; 2022b
9.	01/11/2017	31/01/2021	EU: H2020	GIMS: Geodetic Integrated Monitoring System	GNSS antenna: 7	Urbas	Šegina et al., 2020
10.	02/06/2019	ongoing	municipality Jesenice	Establishment and maintenance of monitoring system at Urbas and Čikla landslides	- raingauges - ekstenziometers - web camera - motion detection camera	Urbas, Čikla	reports (GeoZS ar-chive)

15,000 m^3 of material was deposited in the Bela and Čikla watercourses as a result of previous debris flow events. Potential torrential floods could mobilise the debris material deposited along the Čikla and Bela streams.

- The existing check dams do not have sufficient capacity to fulfil the sediment and debris flow management needed in the area.
- It is essential to implement holistic remediation measures to protect the population and infrastructure. Primarily, remediation measures must be taken on the Čikla and Urbas landslides and the torrents below.
- In the future, periodic and continuous monitoring of all landslides is essential in order to observe landslide dynamics and to verify the effectiveness of potential remediation measures.
- Future impacts of climate change should also be considered when designing mitigation measures. The analysis of the impact of future climate change shows that the negative impact of total and effective rainfall, air temperature, evapotranspiration and runoff from the Bela stream catchment is expected to increase, compared to the previous period.

In parallel, near real-time monitoring of the Urbas landslide was improved with the GNSS system developed in the frame of EU project GIMS: Geodetic Integrated Monitoring System (No. 776335). The system provides a continuous, simultaneous and accurate monitoring of surface displacement at multiple locations across the Urbas landslide (Šegina et al., 2020; Peternel et al., 2022b). The availability of the remote data and the ease of installation of the GNSS units proved that the system is very suitable for monitoring landslide areas that are difficult to access. For this reason, the Čikla landslide was also equipped with the GNSS unit to monitor the displacement of a large boulder located in the active part of the Čikla landslide.

Currently, the main ongoing activities are carried out within the Postdoctoral Research Project (ARRS, Z1-2638). The main objective of the project is to investigate landslide triggering parameters (rainfall, groundwater level, etc.) and to develop a landslide prediction model based on quantitative methods using data collected through continuous monitoring of landslide displacements. The results of the study, carried out on the Urbas landslide, showed that the dynamics of a landslide vary, depending on local geological and hydrogeological conditions. Consequently, certain parts of the landslide are at different evolutionary states and respond differently to the same external triggers (Peternel et al., 2022b).

Long term evaluation of landslide activity using orthophotos and LiDAR-derived DEMs

Since the in-situ landslide monitoring provides spatially limited information, remote sensing data, such as digital orthophotography and laser scanning data, have been used to provide an overview of landslide activity across the entire area. The landslide activity was estimated through analysis/review of orthorectified aerial photography (digital orthophotos or DOFs) with a resolution 0.50 m, taken between 1994 and 2020, and digital elevation models (DEMs) with a resolution of 1 m, taken in 2014 and 2017. An overview of the spatial data used is presented in Table 2. The analysis provided the first information on landslide activity in the entire Koroška Bela hinterland, which encompasses a total area

Table 2. An overview of orthophotos used and DEMs derived from LiDAR.

Type of spatial data	Number of the acquisition	Date of acquisition	Resolution	Availability
DOF	1	27. 7. 1994 (C26) 12. 9. 1999 (D26)	0.5	Public
	2	22. 7. 2006 (C26) 20. 7. 2006 (D26)	0.5	Public
	3	11. 8. 2011	0.5	Public
	4	5. 7. 2015	0.5	Public
	5	24. 8. 2017	0.5	Public
	6	28. 7. 2020	0.5	Public
DEMs	1	2014	1.0	Public
	2	14. 11. 2017	1.0	Upon request

of 7 km². It also enabled the evaluation of the kinematics of landslides for the period when the monitoring system was not yet in place.

First, a visual interpretation of six DOFs was used to obtain information on visible landslide changes over time. Particular attention was paid to changes that might indicate landslide activity, such as disturbed or absent vegetation cover, deformation of the local roads and a growing erosion surface. The observed features were manually digitised and compared to all available orthophotos. Based on this comparison, the intensity of change was classified into three classes: low, medium and high change intensity (Fig. 3). Then, all observed changes were characterised by the type of phenomenon (landslide or deforestation), and verified by field investigations. The field investigations revealed that some large areas were the result of deforestation and were excluded from further analysis.

Based on the results of the change intensity assessment and field investigations, we identified three landslide active areas that have been analysed in more detail (Fig. 3):

- Active area 1: The lower part of the Urbas landslide, which has the potential to mobilise into a debris flow (see section 2.1).
- Active area 2: Local road crossing the main body of the Urbas landslide (see section 2.2).
- Active area 3: Pre and post-Čikla debris flow (see section 2.3).

In addition to DOF analysis, elevation and volumetric changes resulting from landslide activity have also been estimated by comparing two successive DEMs. Elevations from the earlier DEM were subtracted from the latter on a cell-by-cell basis, at 1 m resolution. Decreases in elevation represent erosion zones (red colour), while increases in elevation indicate accumulation zones (Fig. 4). It should be noted that this method only indicates changes in surface elevation and volume and does not provide any insight into the overall mass balance of the area.

The elevation difference calculated for the entire Koroška Bela hinterland between 2014 and 2017 shows that 43,616 m³ of material accumulated and 107,283 m³ eroded during this period, indicating that the Koroška Bela hinterland is a predominantly erosive area. The erosion is mostly limited to the carbonate slopes, while accumulation occurs in the form of scree deposits under steep slopes. Carbonates on the Belščica slope are prone to extensive planar erosion, which is mainly concentrated in gullies, indicating most of the torrential transport and removal of the available, mechanically weathered top layer of rock. Similar processes are anticipated on carbonate slopes of the Alničje ridge. The most intensive erosion and accumulation of material occurred in the Čikla landslide, where a typical sequence of downslope erosion, followed by accumulation (at the foot of the landslide) can be observed.

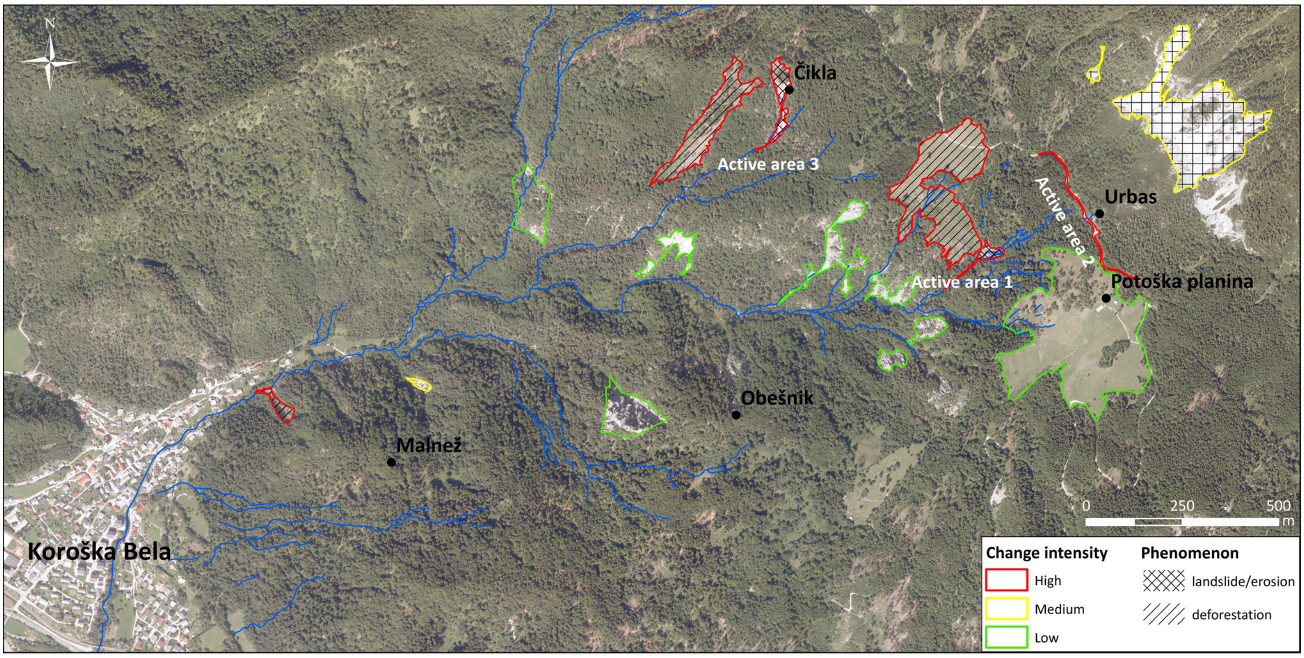

Fig. 3. Assessment of change intensity by visual interpretation and comparison of multitemporal orthophotos. The highest change intensity due to landslides was observed in the areas crossed by the Bela stream and its tributaries.

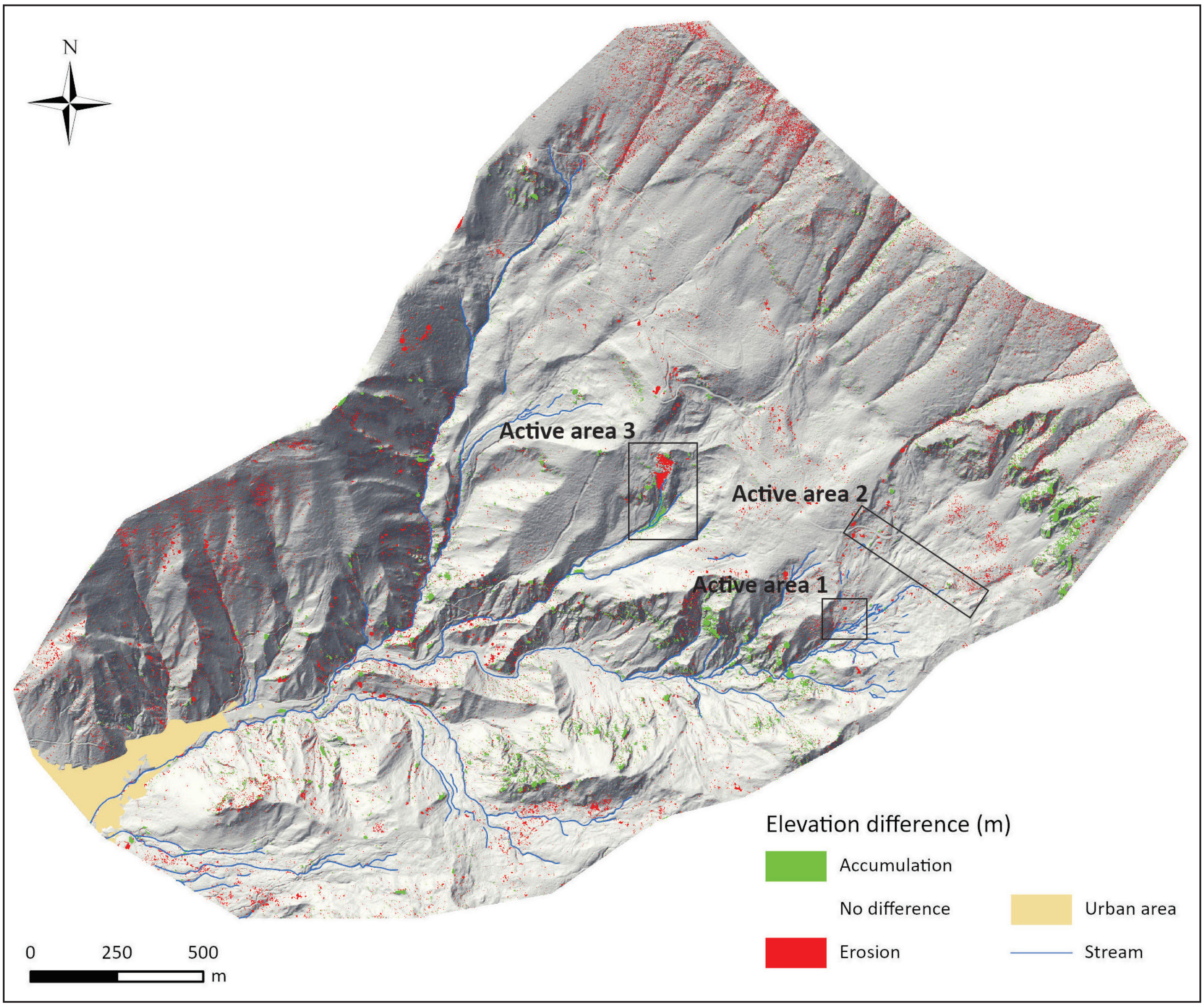

Fig. 4. Spatial extent and temporal change of elevation changes of active areas based on the series of DEM analyses.

Active area 1: Čikla landslide

Čikla landslide activity can already be seen by comparing the 2011 and 2015 DOFs (Fig. 5A and 5B), which shows that part of the Čikla landslide collapsed before 2017. Although the exact date and trigger mechanism of this event are unknown, the erosion of about 1,200 m^2 can be seen from the 2015 DOF.

Another event occurred on the night of April 28–29, 2017, when part of the Čikla landslide body collapsed and mobilised a large amount of debris and vegetation into a mass flow. The sliding material flowed several hundred metres along the Čikla stream. The triggering of this event was attributed to heavy rainfall. The nearby meteorological station (Javorniški Rovt) measured 204 mm of precipitation in 48 hours.

DOF analysis indicates that about 5,500 m^2 of the area was affected by debris flow, representing 21 % of the total Čikla landslide area, determined by detailed engineering geological mapping (Peternel et al., 2020). DEMs analysis indicates that approximately 1,214 m^2 was affected by significant erosion. The volume of eroded surface material was approximately 4,700 m^3 and the surface had subsided an average of 2 m (up to 6 m in peak areas) (Fig. 6, area 1). The lower part of the Čikla landslide is characterised by an accumulation of material, with an average increase of 2.0 m and a maximum increase of 2.5 m. The estimated volume of accumulated material is about 1,700 m^3 (Fig. 6, area 2). The deficit of material was either deposited further down the slope outside the observed area or it was removed by the torrent.

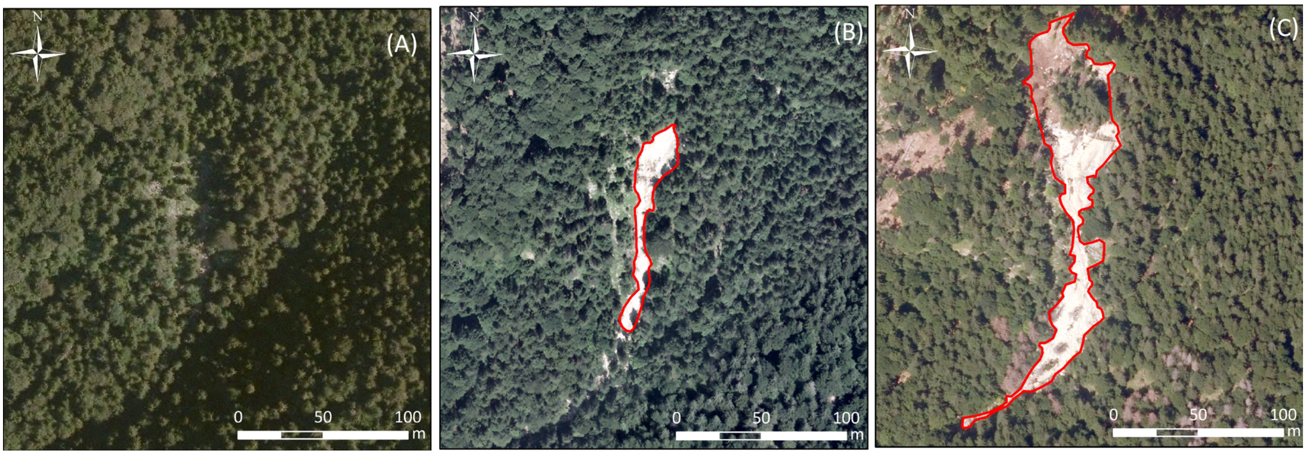

Fig. 5. Digital orthophotos of the Čikla landslide from 2011 (A), 2015 (B) and 2017 (C). Red line represents the manually digitalised boundary of the Čikla debris flow.

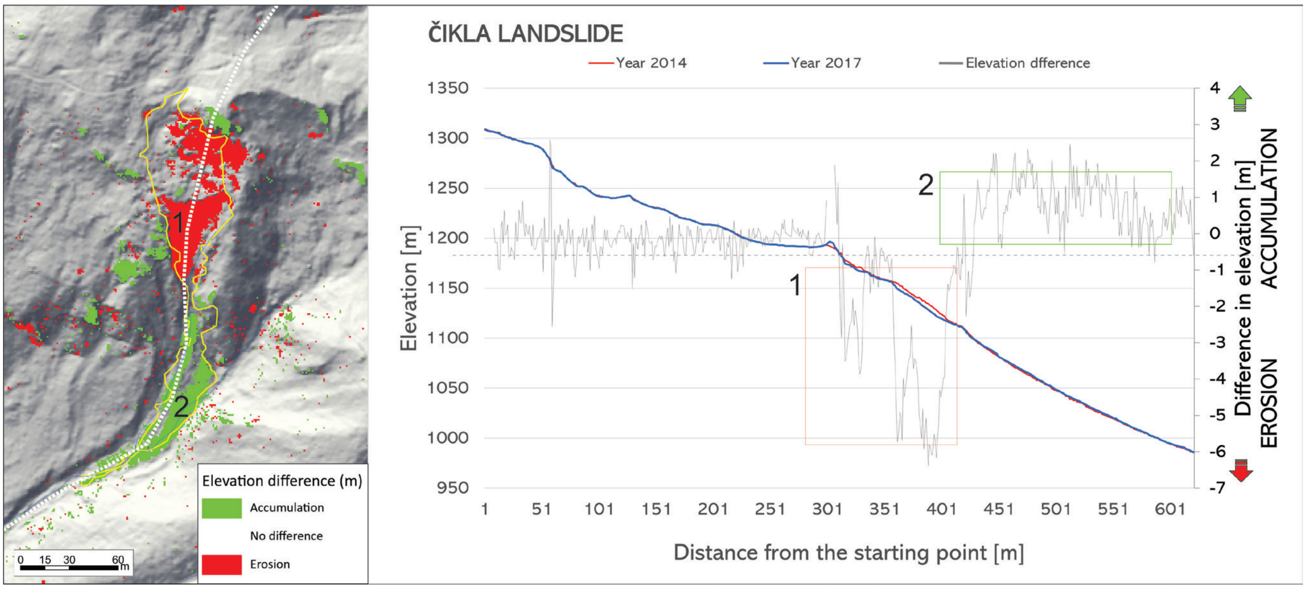

Fig. 6. Surface elevation difference (z-axis) between two LiDAR-derived DEMs from 2014 and 2017. Cross-section shows elevation differences along the Čikla landslide. The yellow line indicates Čikla debris flow (Fig. 5C).

Active area 2: The lower part of the Urbas landslide

Based on previous research (Peternel, 2017; Peternel et al., 2017a; Šegina et al., 2020) and field investigations, the lower part of the Urbas landslide is considered the most active landslide in the area of concern. It is crossed by the Bela stream, which has formed gully-type morphology. The sliding mass consists of tectonically deformed and weathered clastic rocks, covered by a relatively thick cover of carbonate gravel and boulders. The Bela stream causes significant erosion and increases the possibility of downstream mobilisation of the sliding mass. The area is characterised by bare, rugged ground with fallen trees, strong gully erosion and flank ridges.

The DOF analysis clearly indicates that erosion progressively increases during the year. The estimated extent of this area was determined by manual digitalisation of the available DOFs and is represented in Table 3 and Figure 7. No erosion was observed in the 1999 DOF, while the 2020 DOF was overexposed in this area, so digitisation was not possible.

Most activity was observed between 2015 and 2017, when the extent of the erosion area increased by about 1,200 m^2 (or 400 m^2 per year) which is twice as large as in previous years. The DOF analysis also shows that, after this event, the Bela torrent channel became enlarged due to the active erosion of the Bela stream. The wider area was also subjected to deforestation of its slopes, which could also increase erosion.

Table 3. Estimated extent of the lower part of the Urbas landslide.

Orthophoto	1999	2006	2011	2015	2017	2020
Area (m²)	no evidenced activity	90	320	1,060	2,300	no data – overexposed image

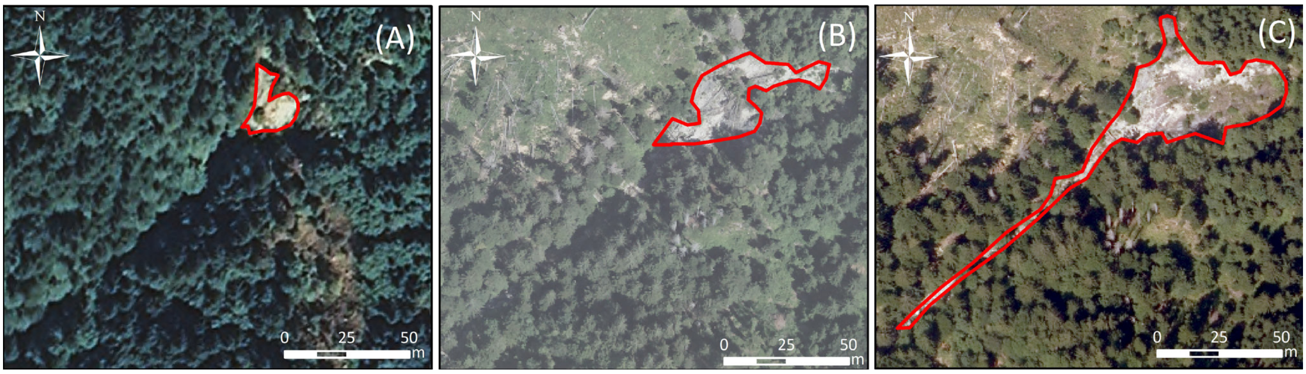

Fig. 7. Digital orthophotos of the lower part of the Urbas landslide from 2006 (A), 2015 (B) and 2017 (C). Red line represents the manually digitalised boundary of the Čikla debris flow.

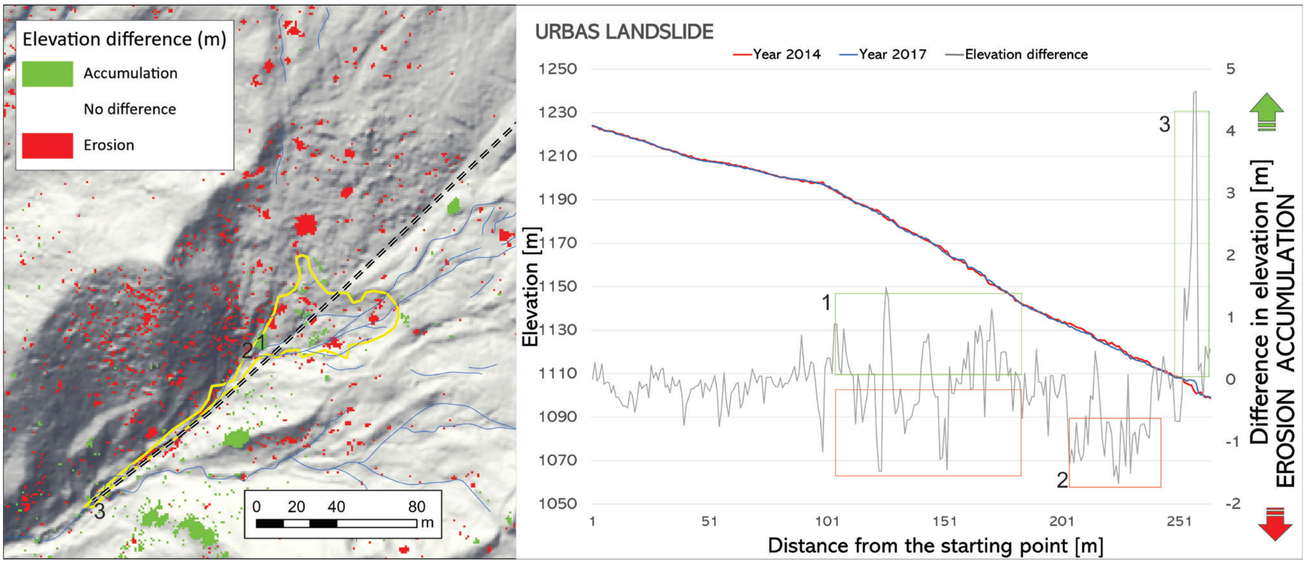

Fig. 8. Surface elevation difference (z-axis) between two LiDAR-derived DEMs from 2014 and 2017. The cross-section shows elevation differences along the Urbas landslide. The yellow line indicates the lower part of Urbas (Fig. 7C).

DEMs analysis shows that approximately 87 m² of the lower part of the Urbas landslide has been affected by erosion, while 12 m² was characterised by accumulation. The volume of eroded surface material was approximately 273 m³ and the surface had subsided between 2 and 5 m (Fig. 8, area 1 and area 2). The Bela torrent channel is characterised by an accumulation of material, with a maximum increase of 2 m. The estimated volume of accumulated material is about 24 m³ (Fig. 8, area 3). The deficit of material was either deposited further down the slope, outside the analysed area, or had been transported away by the torrent.

Active area 3: Subsidence of the local road

The strong landslide activity also affects the local road that crosses the main body of the Urbas landslide, which consists of decomposed siltstone and claystone. Above the road, near the Urbas spring, a minor scarp was formed (Fig. 9). Manual measurements of the minor scarp indicate that it has been opening at a rate of 0.5 to 0.8 m per year. This area consists of clastic rocks with very low permeability, which is reflected in the occurrence of springs charged from the carbonate hinterland. The Urbas spring is partly captured and used to supply water to nearby mountain huts but the rest of the surface water flows uncontrolled along the landslide and across the road. Local geological and hydrogeological conditions are reflected in continuous subsidence and occasional road collapses. The increased water flow causes intense road erosion and often makes it impassable, particularly during periods of intense or prolonged rainfall.

For this reason, the road has been reconstructed several times by adjusting the road level to the terrain, which can be observed on cross sections in Figure 10. Cross section 3 also indicates strong subsidence of the road level, ranging from 0.7 m (for the period from 1999 to 2017) to 11.0 m (for the period from 1999 to 2017) (Fig. 10). Road reconstruction was carried out by backfilling with gravel material and log cribs. Backfilling material represents an additional weight that accelerates sliding. Due to subsidence, the road level was later relocated by cutting into the slope. No appropriate drainage system has ever been implemented.

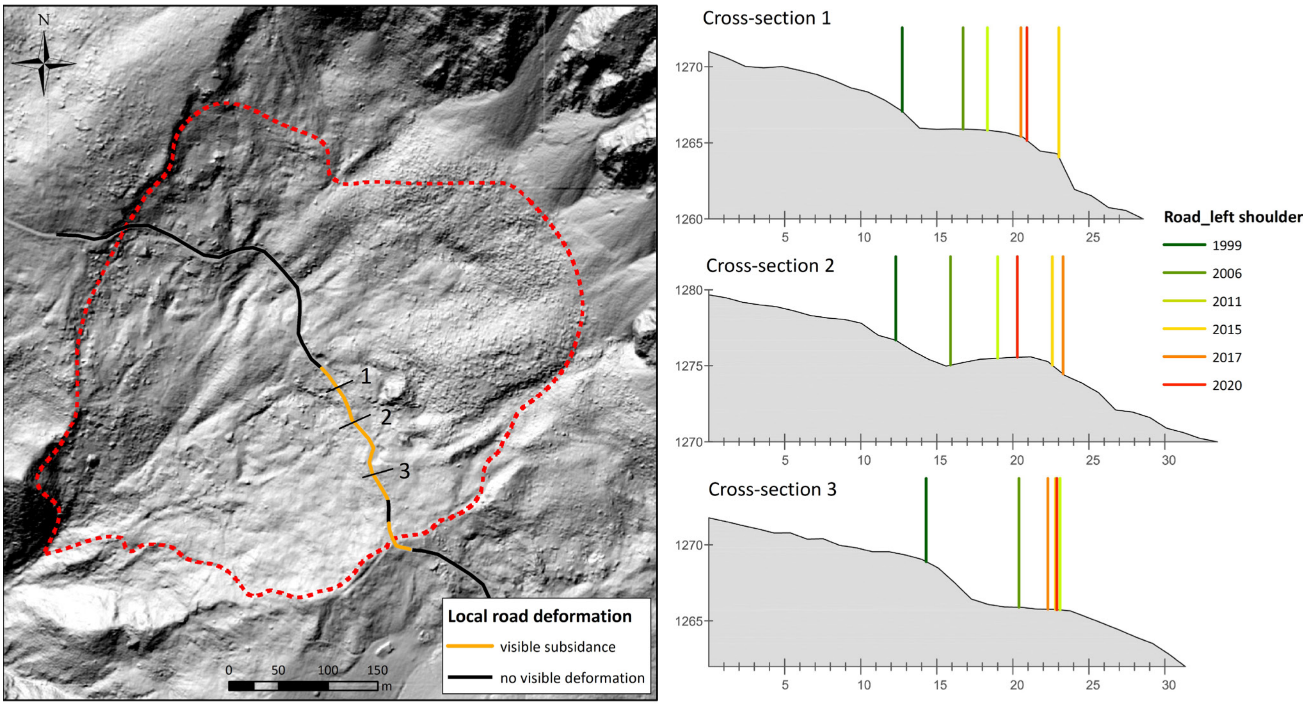

Fig. 9. Longitudinal tension crack above the local road representing a minor scarp.

Fig. 10. Position of local road that crosses the Urbas landslide. Cross-sections represent the position of the road's left shoulder, which has been manually digitalised in orthophotos.

Discussion

Archival DOFs and LiDAR-derived DEMs were used to show the long-term evolution of landslide activity. This approach has been successfully applied in landslide mapping and characterisation by several researchers (Prokešova et al., 2010; Jaboyedoff et al., 2012; Bühler et al., 2012; Kenner et al., 2014; Popit et al., 2014; Đomlija et al., 2019; Görüm, 2019).

Our case review of the available archival data enabled the observation of landslide activity, even for the period when no monitoring system had been established. This approach turned out to be very useful when observing landslide activity for the entire hinterland of Koroška Bela, especially for the remote areas that have not yet been investigated in detail. The results were further validated using the data from the existing monitoring system.

Analysis of the changes of the Čikla landslide surface provides us with useful information about the extent and volume assessment of the debris flow that occurred in April 2017. At that time, no detailed investigations had been conducted and there was no monitoring system for the Čikla landslide. The detailed geological and hydrogeological investigations conducted after April 2017 showed that the Čikla landslide covers an area of 26,000 m^2 and its volume was estimated to be about 330,500 m^3 (Peternel et al., 2017b, 2018, 2020a, 2022a). To date, the Čikla landslide has also been investigated by drilling five boreholes. Two were installed with piezometers and three with inclinometers. The depth of the boreholes was about 40 m. Boreholes and inclinometers indicate that the maximum shear surface occurs at a depth of 28 m, while the average sliding surface is about 23 m deep (Peternel et al. 2018, 2020a). Groundwater level appears at the contact between the debris deposits and the weathered bedrock. The 2017 debris flow occurred in the central part of the Čikla landslide, beneath a large carbonate block that is tectonically deformed and structurally lies within the clastic Carboniferous rocks (Fig. 6, zone 2).

In contrast to Čikla, the Urbas landslide has been the subject of several studies in the past (Jež et al., 2008; Komac et al., 2015; Auflič et al., 2017; Peternel, 2017; Peternel et al., 2017a). For example, the lower part of the Urbas landslide was investigated in detail between December 2012 and April 2016, using UAV photogrammetry and tachymetric measurements. Comparisons of the national orthophotos allows the calculation of the extent of erosion over a long period of time, while the high-resolution DOFs and the DEMs derived from UAV photogrammetry provide accurate displacement vectors and elevation changes. Surface displacement patterns for the entire monitoring period (December 2012 to April 2016) were analysed based on the sum of displacement vectors for all observation periods. The determined displacements ranged from 0.9 to 19.0 m, with a clear SW directional orientation (Peternel 2017, Peternel et al. 2017a). No geotechnical in-situ investigations (inclinometers or piezometers) were conducted in the lower part of the Urbas landslide due to difficult access and rugged morphology. Although these results only indicate changes at the surface and do not provide information on the depth of sliding surface, they contribute to a better understanding of landslide behaviour and kinematics.

Reviewing the available archival orthophotos, we also observed the deformation of the local road that crosses the main body of the Urbas landslide. Digitised road shoulders provided information about the continuous subsidence and collapse of the road. Nearby boreholes along the road indicated that the road crosses the landslide area with a depth of sliding surface ranging between 8 and 15 m (Peternel et al., 2018). Monitoring of the surface displacements using GNSS also indicates the constant displacements of the landslide main body. The GNSS antenna located below the road, and measuring the surface displacements in real-time, showed displacements of 37 mm over a period of one year (Šegina et al., 2020).

Conclusions

In this paper we summarise all conducted and on-going research and the main findings related to the landslide prone areas above the settlement of Koroška Bela. For the first time, we have also revealed the evolution of landslide activity over the last 25 years. According to investigations so far, the following main outcomes are defined:

- The main landslides detected in the Koroška Bela hinterland are the Čikla, Urbas, Potoška Planina, Malnež and Obešnik landslides. All landslides are characterised by high activity due to intense rainfall events, long-term precipitation and/or groundwater table change. In addition, the moderate-high seismicity of the area could be another predisposing factor contributing to the occurrence of threatening landslides.

- Under the above conditions, the potential risk induced by the mass movements on the town of Koroška Bela can be generally assessed as follows:
  - very high risk due to the occurrence of fast-moving landslides (i.e. debris flows) that have already affected the urban area in the past and might happen in the future;
  - moderate to high risk derived by the slow-moving landslides detected in the slopes up-hill of Koroška Bela, some of them (i.e. the Malnež landslide) potentially threatening the eastern part of the town.
- Even though a lot of knowledge and information has been gained, there are still unknowns that need to be resolved and improvements that have to be implemented. There is still a need for further geological and geotechnical investigations for: i) the improvement of the geological model of the study area, ii) integration with the equipment already installed and, iii) set-up of an integrated monitoring system for the control of slope deformations acting in the landslide areas in the Karavanke mountains.
- Implementation of direct and indirect feasible, effective and sustainable landslide mitigation strategies aimed at reducing the landslide risk in the Koroška Bela settlement.
- Due to the estimated risk, there was a need to set up a continuous and flexible monitoring system that could serve as a basis for a local landslide warning system. With the aid of landslide monitoring, early landslide activity can be detected and landslide impacts can be reduced. In this stage we set up customised dashboards that allowed access to all real-time monitoring sensors. In this way, GeoZS emergency services and stakeholders can access daily updated data, presented on a webpage, at any time. In future, we plan to upgrade the local warning system with email alerts sent to registered users when determined threshold values are exceeded.
- This study is a step forward in landslide management in Slovenia. Several activities that have been implemented within the framework of different projects have enabled the establishment of connections between national and local authorities, scientific and technical experts, and Civil Protection and residents of Koroška Bela.

Acknowledgements

This research was funded by the Slovenian Research Agency through grants Z1-2638, J1-8153, P1-0419, P1-0011, P1-0020 and P2-0180. Additional financial support was provided by the Ministry of the Environment and Spatial Planning, and the Municipality of Jesenice.

The authors would also like to thank the reviewers and the editor for their constructive comments, which helped to improve the manuscript.

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