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Landslide events in Slovenia 2023: causes and consequences

Mateja Jemec Auflič[(1)]*, Jernej Jež[(1)], Ela Šegina[(1)], Tina Peternel[(1)], Andrej Novak[(1)], Špela Kumelj[(1)], Domen Turk[(1)]

1) Geological Survey of Slovenia, Dimičeva ulica 14, 1000 Ljubljana, mateja.jemec-auflic@geo-zs.si

Abstract Between August 3 and 6, 2023, Slovenia was hit by a natural disaster of national scale. Extreme rainfall with a return period of up to 250 years led to flooding and triggered several thousand landslides. Most landslides were recorded in the area north of Kamnik, in the area of Zgornja Savinjska dolina and in the wider Koroška region between Črna na Koroškem and Dravograd, as well as in the area of Poljanska dolina. At the Geological Survey of Slovenia (GeoZS), field data on landslides and related phenomena were mainly collected during intervention visits, which we carried out in coordination with the civil protection headquarters. Due to the large amounts of water, the landslides mostly turned into mud or debris flows, with material deposited on the foothills some 10, 50, 100, sometimes even more than 100 meters away from their original location. We estimate that around 10,000 slope mass movements were triggered during the event, with extremely high densities in some areas.

Keywords landslides, slope mass movements, extreme rainfall event, Slovenia

Introduction

Due to geological structures, relief and climatic conditions, Slovenia is very susceptible to the occurrence of various types of landslides. The most common of these are shallow landslides, which are usually triggered by rainfall. The scale and magnitude of the landslides are of a magnitude that has never been observed in the history of the Geological Survey of Slovenia. At the time of the event, we identified a number of landslides, the extent of the events and the causes of creep during the intervention visits and assessed the possibilities of further movements and provided for possible temporary intervention reinforcements. During the intervention visits, we determined the type of slope mass movements, the extent of the events and the causes of creep, as well as assessing the potential for further movements and planning possible temporary intervention measures. In most cases, the rock surface is covered by clastic sediments of varying thickness. In Koroška, weathering of metamorphic and magmatic rock can also be observed. Less frequent were wedge-shaped rockslides, where material slide along deep structural discontinuities in the slope. In some exceptional cases, landslides occurred for very unusual geological grounds, where they would not otherwise be expected. To assess the damage caused by the landslide in August, we also prepared expert bases on the basis of which we estimated that around 10,000 landslides occurred during this period. The recent disaster, which caused enormous damage and also fatalities (Fig. 1), is clear proof that Slovenia is highly susceptible to landslides. This undoubtedly underlines the need for the inclusion and implementation of preventive measures to cope with natural disasters.

In order to coordinate flood recovery as efficiently as possible, a Flood Recovery Coordination Working Group was established in August 2023, as well as the Post-Flood and Landslide Reconstruction Office. Technical offices are being established to speed up the implementation of recovery and to ensure coordinated implementation between the different bodies responsible for the various measures. The Reconstruction Council advises the Government on the formulation of disaster recovery measures and the development of disaster resilience.

This paper examines the rainfall conditions during the event and the nature of the slope mass movements.

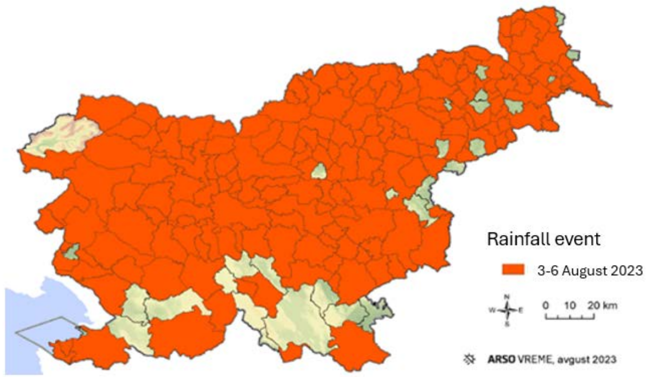

Figure 1 Municipalities that reported damage after flood event (181 out of 212 municipalities).

What causes landslides?

Extreme rainfall

The natural disaster that occurred in August 2023 was a consequence of a set of meteorological circumstances. Conditions typical of winter or autumn time occurred in the mid-summer when, in addition, the Mediterranean Sea was extremely warm, affecting the amount of water vapour in the air and thus the amount of precipitation. Already in July 2023, the amount of precipitation was at least 100 % exceeding the long-term average in the entire country. Such conditions resulted in extremely high soil saturation.

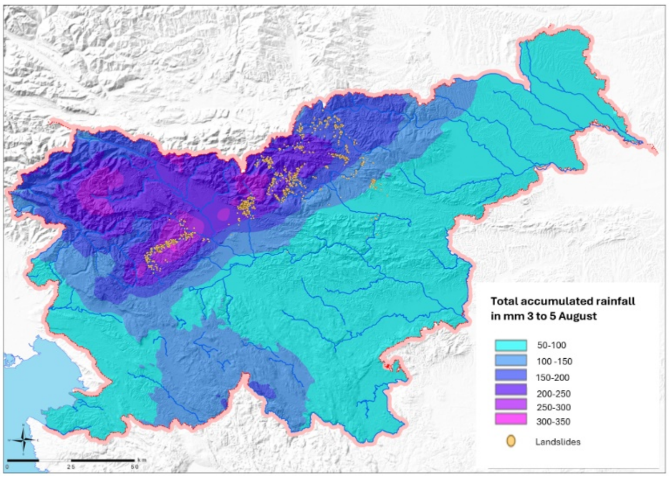

Figure 2 Total accumulated rainfall during rainfall event from 3 to 5 August 2023. Location of mapped landslides from orthophoto images (DOF).

Figure 3 A-The extent of available DOF data. B- Visual digitization of landslides from DOF.

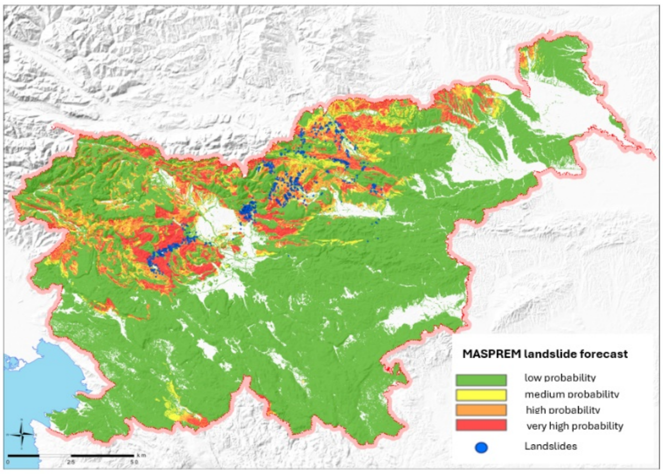

Figure 4 National landslide forecast system with total event accumulated rainfall.

On the days between August 3 and 6 at some measuring points, the monthly average amount of precipitation fell within a few hours. On August 4, the record values of daily precipitation were measured at several measuring stations. The estimated return period of extreme rainfall was 250 years or even more (Slovenian Environmental Agency 2023). High soil saturation as a result of a high amount of precipitation in July in combination with intense precipitations at the beginning of August induced massive disruptions in slope stability across the entire territory of Slovenia.

The actual conditions in a limited area are to be captured by the accessible method (remote sensing, field inspection etc.). In our case, in the most affected parts of the country, interventive aerial photography was performed right after the event on 7 and 8 August 2023. Systematic landslide digitization was carried out on a part of a photographed area. Digitization of landslides from DOF was performed using the method of manual visual interpretation (Scaioni et al. 2014). A total of 2142 landslides have been evidenced on 1620 km² (Fig 3 A, B).

In order to estimate the total landslide damage on the national scale we used landslide forecasting system (Jemec Auflič et al. 2016; Peternel et al. 2022) that integrates environmental (geologic, geomorphologic and hydrologic) and weather conditions on a national level. The classes has been recalculated for the total amount of precipitation received between August 3 and August 5, 2023. The resulting area was classified into four classes of landslide vulnerability: small, medium, high and very high susceptible to landslides based on the rainfall received between 3 and 5 August. A total area is attributed to each susceptibility class (Fig 4).

Most landslides were recorded in the area north of Kamnik, in the area of Zgornja Savinjska dolina and in the wider region of Koroška, between Črna na Koroškem and Dravograd, as well as in the area of Poljanska dolina. The Geological Survey of Slovenia collected field data on landslides and related phenomena mainly during intervention visits, which we carried out in coordination with the Civil Protection Headquarters. During the intervention visits, we determined the type of slope mass movements, the extent of the events and the causes of the creep processes, assessed the potential for further movements and planned possible first and temporary intervention measures.

Consequences of landslides

We estimate that up to 10,000 slope mass movements were triggered in Slovenia during the event, with exceptionally high densities in some areas. (Fig. 5). The affected areas of the individual landslides, i.e. the areas of material deposition, show that these was extreme event that differ from the previously known landslide phenomena in these areas. In very few cases was the landslide deposited in the immediate vicinity of the source areas (Fig. 5). Due to the large amounts of water, the landslides often mobilised into mud or debris flows (Fig. 6), whose material was deposited on the foothills 10, 50, 100, sometimes even more than 100 meters away from their original location. As a result, facilities and infrastructure were also affected and threatened, sometimes far from the primary areas of origin of the phenomena (Fig. 6 A and B).

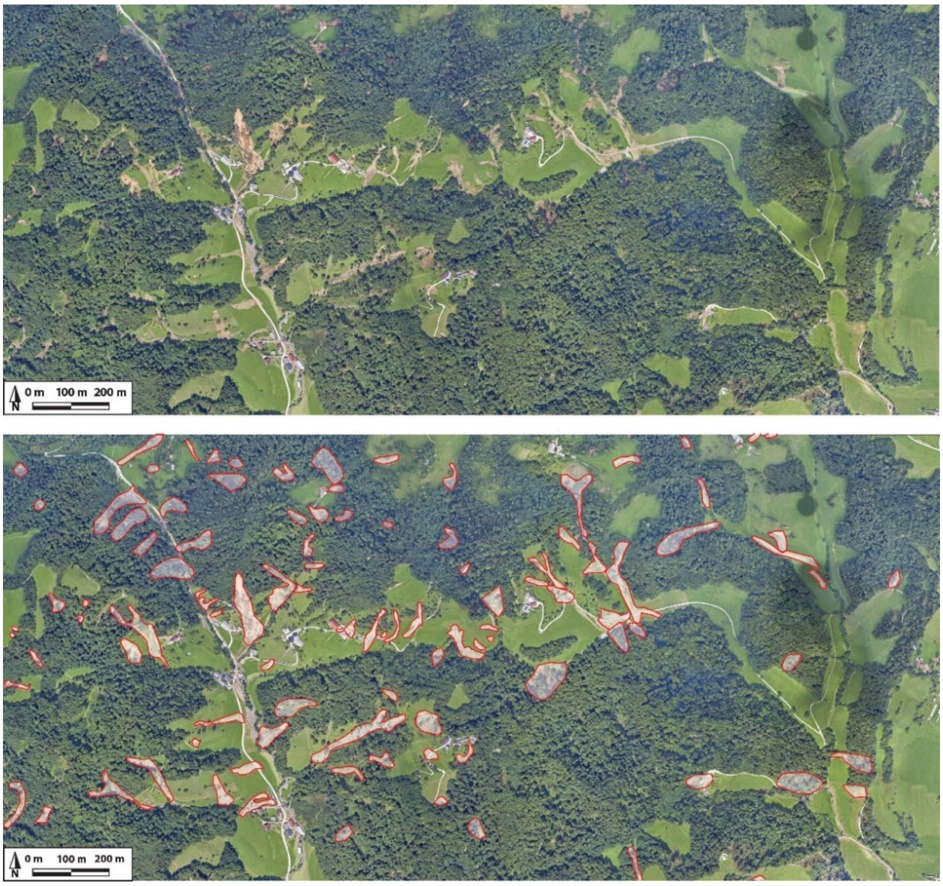

Figure 5 Comparison of a section from a digital orthophoto image of the area of Lanišče in the municipality of Kamnik, where the area consists of Oligocene clastic rocks. Over 50 landslides can be counted on an area of about 1 km² (polygons outlined in red), most of which have turned into mud or debris flows. As a result, their area of influence and thus the damage was much greater.

Figure 6 Examples of slope mass movements. A) Landslide that has mobilised into a debris flow, consisting of sand, gravel and several boulders with a size of several m². B) At the bottom of the valley, the debris flow has partially covered the stream bed. C) An example of a landslide that has mobilised into a mudslide of sand, silt and clay. D) An example of a water-saturated slide with roots and trees that led to the complete destruction of a house. The landslide occurred on a limestone base, which is unusual for landslides to occur.

In most cases, the weathered soils are covered by clastic sediments of varying thickness. In Koroška region there is also weathering of metamorphic and magmatic rocks. Less frequent were cases of wedge-shaped rockfalls, where material slid along deep structural discontinuities in the slope. In some exceptional cases, landslides occurred on very unusual geologic units where they would not otherwise be expected, such as steep limestone and dolomite slopes. In these cases it was a shallow landslide with roots and trees, indicating that there was an exceptional amount of water liquefying the soil (Fig. 6 C).

Landslides vary greatly in size, ranging from shallow deposits of a few meters (up to 1000 m^2) to large-scale landslides that mobilized tens of thousands of m^3 of material. In addition to the classic landslides, rockfalls, mudflows and debris flows, various hyper-concentrated flows (a mixture of water, rock, soil and sediments of different grain sizes) were also important processes during the rainfall event. These formed along torrential ravines with a carbonate background and high energy potential. In these cases, the water in the hinterland eroded large quantities of carbonate aggregates and carried them into the valleys in the form of grain streams or debris floods along the river beds. In such cases, over 100,000 m^3 of material could be transported in places. The material was mostly deposited on alluvial fans or in river valleys, where it blocked the path of larger watercourses. But various other types of slope movements also brought material directly into the watercourses, causing the water to gain a lot of erosive power and destroy buildings and infrastructure downstream.

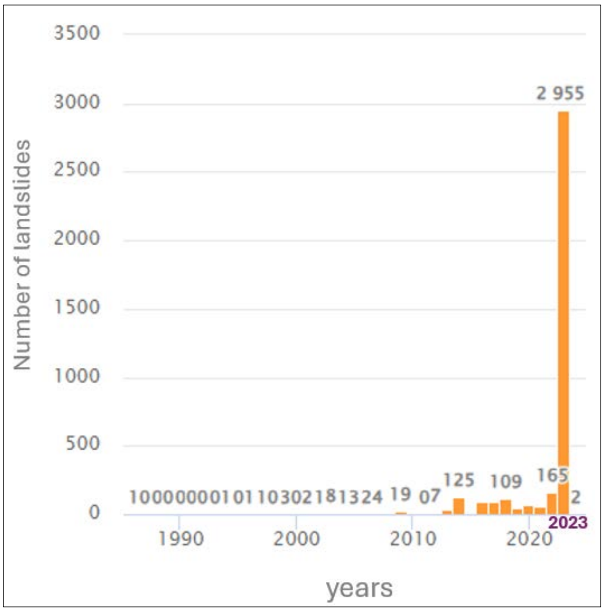

Figure 7 Recorded landslides in the e-Plaz application for landslide collection after rainfall event in August 2023.

These landslides have reduced the stability of the banks and as a result, many areas are prone to the reactivation of existing or the formation of new ones. All these areas must be carefully monitored until remediation is complete, especially during periods of heavy rainfall. The lateral mass movements also had a significant impact on watercourses by introducing a greater amount of sediment into the riverbeds, streams and torrents. Larger quantities of material remained in the riverbeds after collection, which present a risk for triggering bedload and hyper-concentrated flows during heavy rainfall. At the end of February 2024 the landslide database contained 2955 landslide events reported in municipalities after flood event in August 2023. Even this inventory does not reflect the full number of landslides, as municipalities are still entering landslides into the database.

Conclusions

The heavy rainfall in August 2023 triggered a large number of different slope mass movements, with a large proportion of the slopes and landslides becoming mudflows and mudslides. The formation of debris flows and mudflows increased the extent of the affected areas as well as the damage to buildings and infrastructure. At the same time, the movements took place on an unusual geological base (limestones and dolomites) where they would not otherwise be expected. The lateral mass movements brought large amounts of material into the river, stream and torrent beds, increasing the erosive force of the water and destroying buildings and infrastructure downstream. The material remained in the riverbeds in many places. In the event of further heavy rainfall, the locations of slope movements and riverbeds with large amounts of sediment must be carefully monitored, as there is a risk of new events being triggered. A systematic inventory of the locations and extent of landslides was not carried out after the accident, so data on the resulting phenomena is still being collected, mainly via the e-Plaz system.

Acknowledgement

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