# Rainfall-induced landslides and debris flows under the influence of climate change: review of recent Slovenian studies

**Nejc Bezak[(1)], Matjaž Mikoš[(1)], Mateja Jemec Auflič[(2)]**

1) University of Ljubljana, Faculty of Civil and Geodetic Engineering, UNESCO Chair on Water-related Disaster Risk Reduction, Ljubljana, Jamova cesta 2, Slovenia, +386 4768 685 (nejc.bezak@fgg.uni-lj.si)

2) Geological Survey of Slovenia, Ljubljana, Slovenia

**Abstract** Climate changes are expected to increase the frequency and magnitude of the most intense precipitation events. In addition, the elements of the hydrological cycle and the seasonal characteristics of climatological and hydrological processes are expected to change in the future. Therefore, these changes will also affect the frequency, magnitude, and impact of landslides, debris flows, rockfalls, and similar natural hazards. This paper reviews recent studies conducted by Slovenian researchers, focusing on Slovenia and other European countries. Special emphasis is placed on the characteristics of precipitation events responsible for triggering mass movements and on an overview of the effects of climate change.

**Keywords** Rainfall characteristics, landslides, debris flows, rock falls, climate change, Slovenia.

## Introduction

It is clear that global warming and the associated effects of climate change affect the stability of slopes and have consequences for landslides, rock falls, debris flows, and similar phenomena (Gariano and Guzzetti 2016). However, it is not clear to what extent climate change will affect the frequency and magnitude of mass movements in different parts of the world (Gariano and Guzzetti 2016). It can be seen that mass movements activity is or will increase in many parts of the world including parts of Asia, Africa, North and South America (Gariano and Guzzetti 2016). Among all continents, Europe is the most diverse in its response to climate change in terms of mass movement activity (Gariano and Guzzetti 2016). Hence, additional attention should be paid to this part of the world to better identify climate change's changing patterns and impacts. Therefore, this paper provides an overview of recent studies conducted by Slovenian researchers focusing on precipitation characteristics related to the triggering of landslides, debris flows and rock falls.

## Larger-scale studies

### Rainfall event characteristics above the empirical global rainfall thresholds at the continental scale

Bezak and Mikoš (2021) investigated characteristics of rainfall events positioned above the empirical global rainfall thresholds for landslides triggering. The focus of the study was to analyse the magnitude and frequency of rainfall events. Changes for the areas classified as at least moderately susceptible to landslides (according to the ELSUS v2 map; $1.8 \times 10^6$ km²) were evaluated for the 1961-2018 period where precipitation reanalysis data was used as input (Bezak and Mikoš 2021). It was found that around 15% more rainfall events were detected above the selected thresholds for 1991-2018 period compared to the 1961-1990 period (Bezak and Mikoš 2021). Additionally, several regions across Europe were detected where these changes were positive and statistically significant with the selected significance level of 5% (Bezak and Mikoš 2021). Such examples are Italy or the Carpathian Mountains, where landslides frequently occur (Fig. 1). There were also regions where the detected changes were negative (and statistically significant) such as the Alps or Pyrenees (Fig. 1). Moreover, no significant change could be detected for around 50% of the area. Hence, it can be seen that climate change already has an effect, in some parts of Europe, on the rainfall characteristics that could trigger landslides or debris flows.

### Human exposure to landslides

Recent study also investigated human exposure to landslides. Modugno et al. (2022) used a GIS-based and multi-scale approach to indicate when and where a country is affected by a high probability of landslide occurrence (Modugno et al. 2022). It was shown that most of the people living in landslide hazard areas are located in Asia in countries such as Nepal, India, Philippines, etc. Exposure in Europe is generally smaller than some other parts of the world. However, countries like Italy, Switzerland, and Slovenia have quite high exposure. A recent study showed that 48 million people are exposed to landslides in Europe (Mateos et al. 2020). While the number of fatalities in Europe is relatively small (i.e. 39 in the 2015-2017 period by 3,907 landslides (Mateos et al. 2020) or 1,370 deaths in 1995-2014 (Haque et al. 2016)), the number of fatalities is much higher in other parts of the world, exceeding 1,000 in the 2007-2018 period in countries such as Brazil, India, Philippines, China, etc (Modugno et al. 2022). Therefore, a novel methodological approach, such as the one proposed by Modugno et al. (2022), will need to be developed in the future to predict landslides better, debris flows, and rock falls.

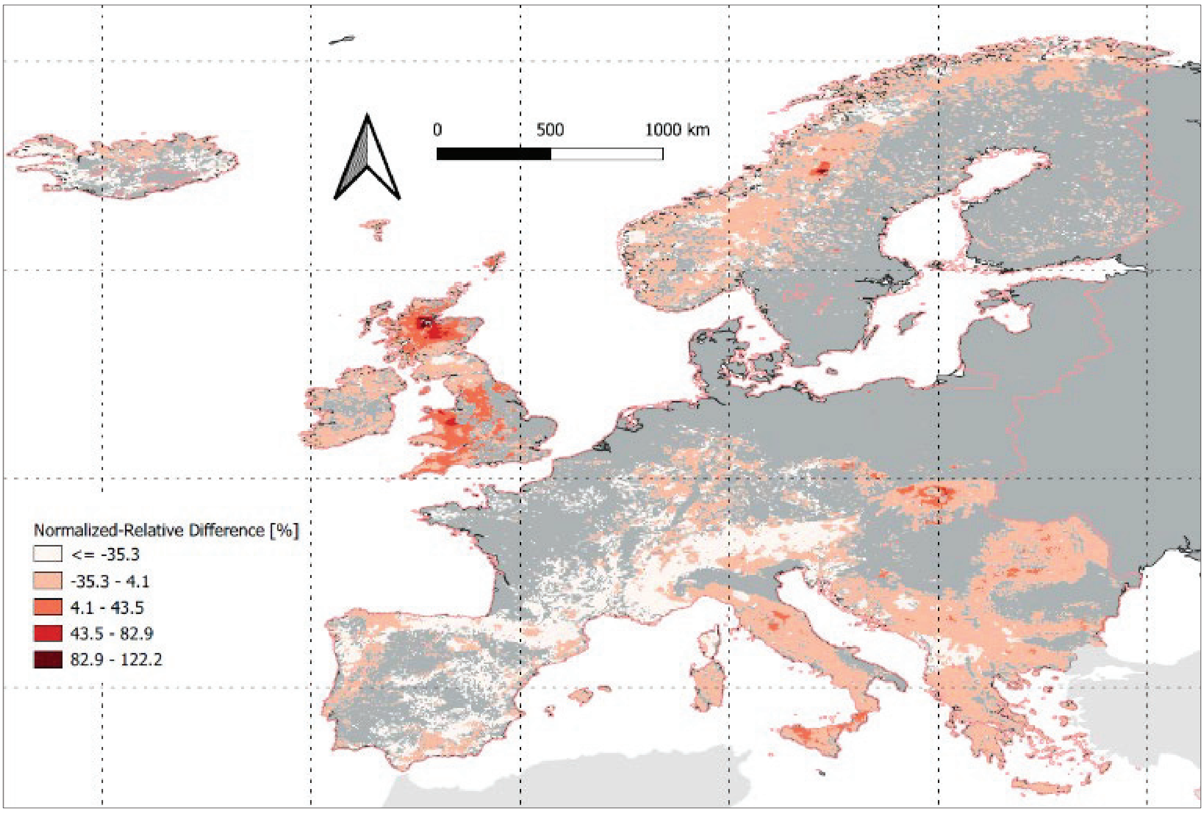


Figure 1 Relative difference between recent and historic periods (1991-2018 and 1961-1990) based on the consideration of the normalized threshold. Pink line shows the area at least moderately susceptible to landslides. Adopted after (Bezak and Mikoš 2021).

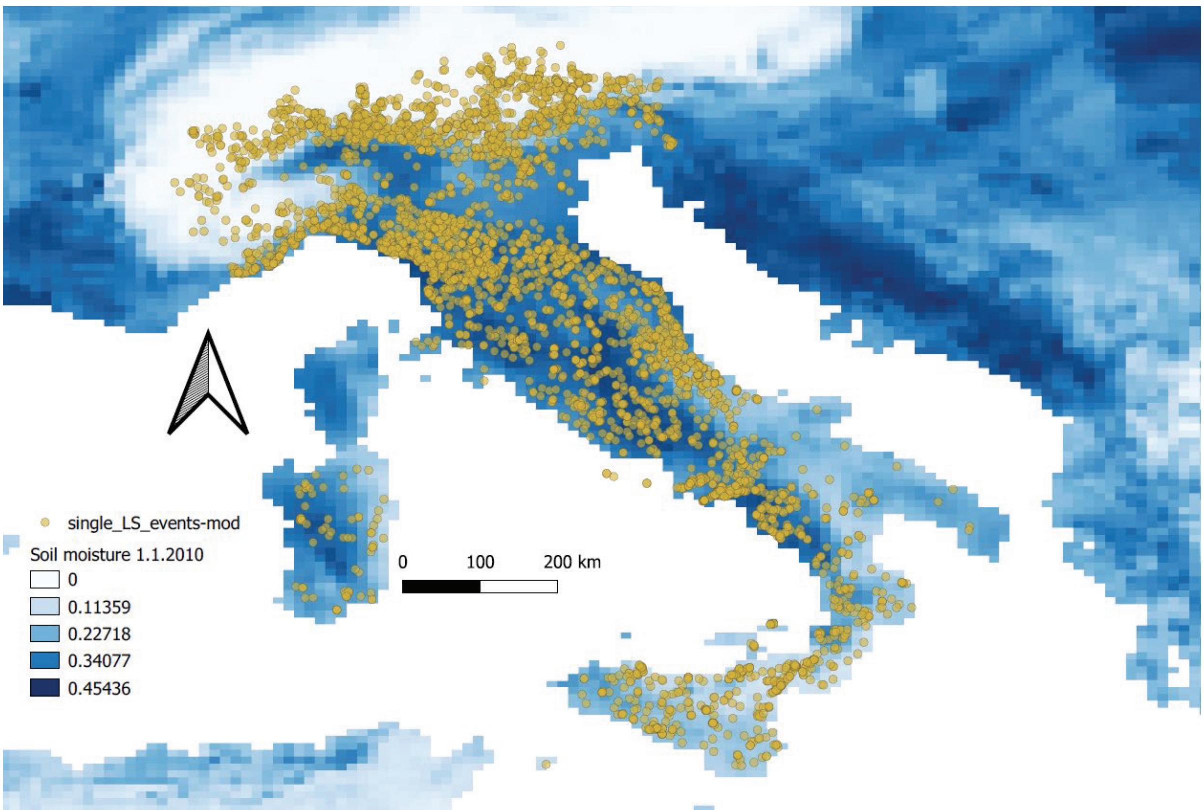


Figure 2 Soil moisture reanalysis data ($m^3/m^3$) on a specific date (i.e. 1.1.2010) and all the landslides included in the FraneItalia database. Adopted after Bezak et al. (2021).

#### Improving landslides predictions

Recently, Bezak et al. (2021) tested the added value of the reanalysis soil moisture data (i.e. Copernicus Uncertainties in Ensembles of Regional Reanalyses (UERRA)) in predicting historical landslides events in Italy (Fig. 2). It was found that precipitation is much better predictor of landslides occurrence compared to soil moisture data. Moreover, using only soil moisture data (without precipitation) a small fraction of landslides could be predicted. However, other more detailed satellite-based soil moisture data should be tested to additionally evaluate the added value of the soil moisture data.

### Slovenian case studies

Besides global and continental studies, Slovenian researchers have also focused on the smaller-scale studies including national ones with focus on Slovenia.

#### Rainfall events characteristics

Bezak and Mikoš (2019) investigated trends and temporal changes in intensity-duration-frequency (IDF) and extreme rainfall events that can also trigger landslides and other mass movements (Bezak et al. 2016). Using high-frequency data for 10 rainfall stations with 44 years of data (i.e. 1975-2018) it was found that no clear pattern could be detected in precipitation trends. Minimal changes in the seasonal characteristics of 5- and 30-minutes rainfall events (tend to occur a few days earlier, Fig. 3) and of 360- and 720-minutes events (tend to occur a few days later) were detected. Moreover, Bezak et al. (2016) also investigated the possibility to use copula functions for the definition of the IDF curves and compared these curves with empirical global rainfall thresholds that are used for the shallow-landslides triggering.

Jordanova et al. (2020) reconstructed the cumulated event rainfall and the duration of the rainfall conditions responsible for landslide occurrences for the period of 2007 and 2018 in order to obtain reliable thresholds that could be implemented in a landslide early warning system.

#### Climate change studies

Several recent studies have investigated a direct climate change impact on conditions related to landslides triggering. Jemec Auflič et al. (2021) studied climate change impact on landslides in the mid of the 21st century in Slovenia. They used the Representative Concentration Pathway climate scenario (RCP4.5) and MASPREM (landslide prediction system) system for modelling. They found that extreme rainfall events are likely to occur more frequently in the future (2041-2070; Fig. 4), which may lead to a higher frequency of landslides in some areas in Slovenia.

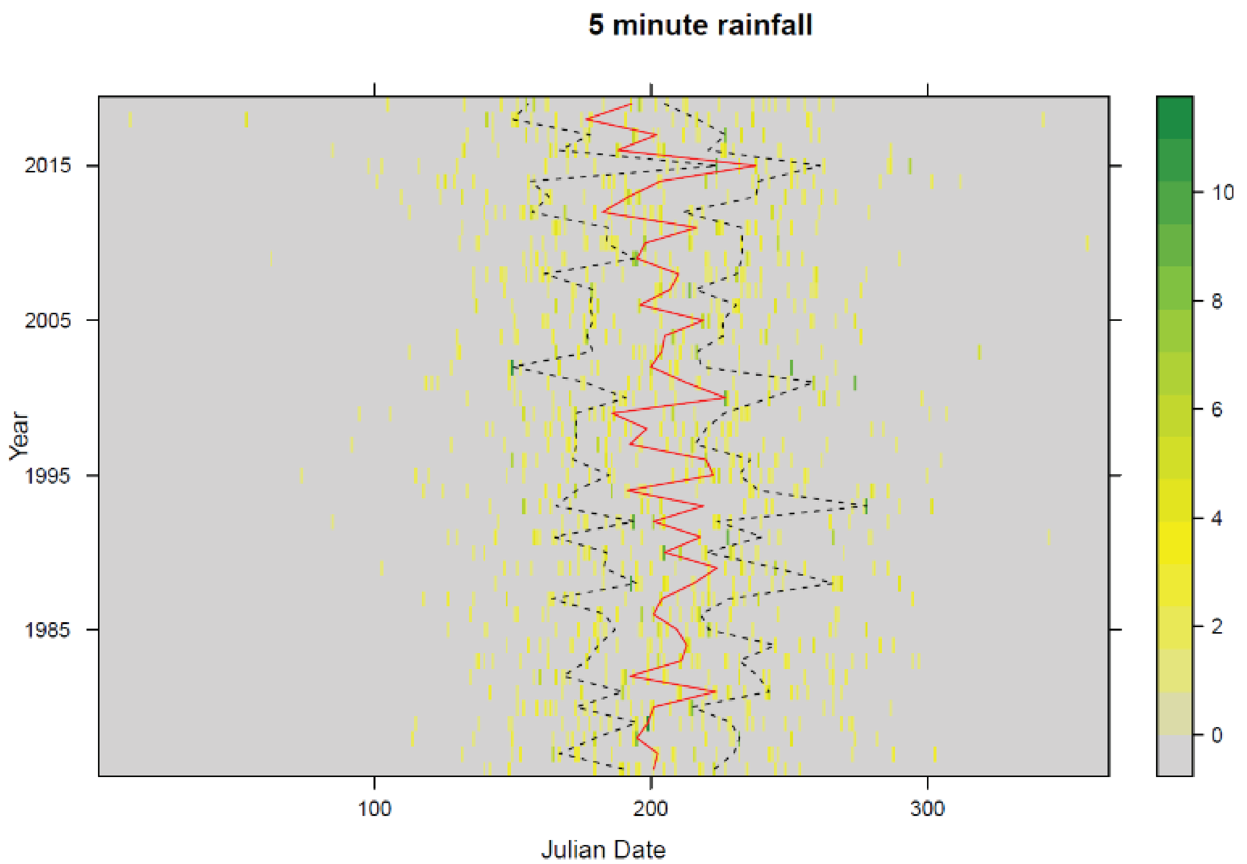


Figure 3 Temporal clustering of the annual maximum rainfall events with the duration of 5 minutes. Red line indicates the median Julian data and the dotted black lines indicate 25% and 75% Julian date. Adopted after Bezak and Mikoš (2019).

Bezak et al. (2021b) also investigated impact of climate change on the water balance elements of the Koroška Bela area (Jemec Auflič et al. 2017; Sodnik et al. 2017; Janža et al. 2018; Bezak et al. 2021c). The results indicated that total and effective rainfall could increase in future. Due to the air temperature increase we could also expect an increase in the evapotranspiration. However, these changes does not linearly translate in the water balance elements of the Koroška Bela area (Bezak et al. 2021b). More specifically, projected changes in the total runoff, percolation, etc. are within the range of 5% compared to the baseline period (Bezak et al. 2021b). Additionally, mGROWA water balance model was also used to evaluate possible changes in the water balance elements (Bertalanič et al. 2018) for the Koroška Bela area. An example of such modelling results is shown in Fig. 5 for the groundwater recharge variable. Moreover, changes in the IDF curves were also evaluated (Fig. 6) and also no significant changes between future and baseline periods could be detected (Fig. 6). In general the climate change evaluation in Slovenia was conducted by the Slovenian Environment Agency (ARSO) (Bertalanič et al. 2018) but they did not focus specifically on mass movements such as landslides or debris flows.

### Modelling improvements

Several improvements have also been made with respect to landslides-related modelling. The landslide prediction system for modelling the probability of landslides through time in Slovenia (MASPREM, Fig. 7) has been in operation since 2013 (Jemec Auflič et al. 2016). Since then, the system has been updated at the national level with new rainfall thresholds. At the municipal level, the system now makes predictions for 25 municipalities in the scale of 1:25,000 and at the local level for one landslide-prone area (Koroška Bela). A very important part of the system is also the data collection, which is done through the application e-Plaz (https://www.e-plaz.si/). Also hydrological models have been suggested to be applied for the prediction of the shallow landslides at the catchment level in Slovenia (Bezak et al. 2019a). Moreover, recently several modelling applications have been conducted using the RAMMS debris flow module at various locations across the country (Bezak et al. 2019b, 2020, 2021c; Mikoš and Bezak 2021). Example of such simulations are shown in Fig. 8.

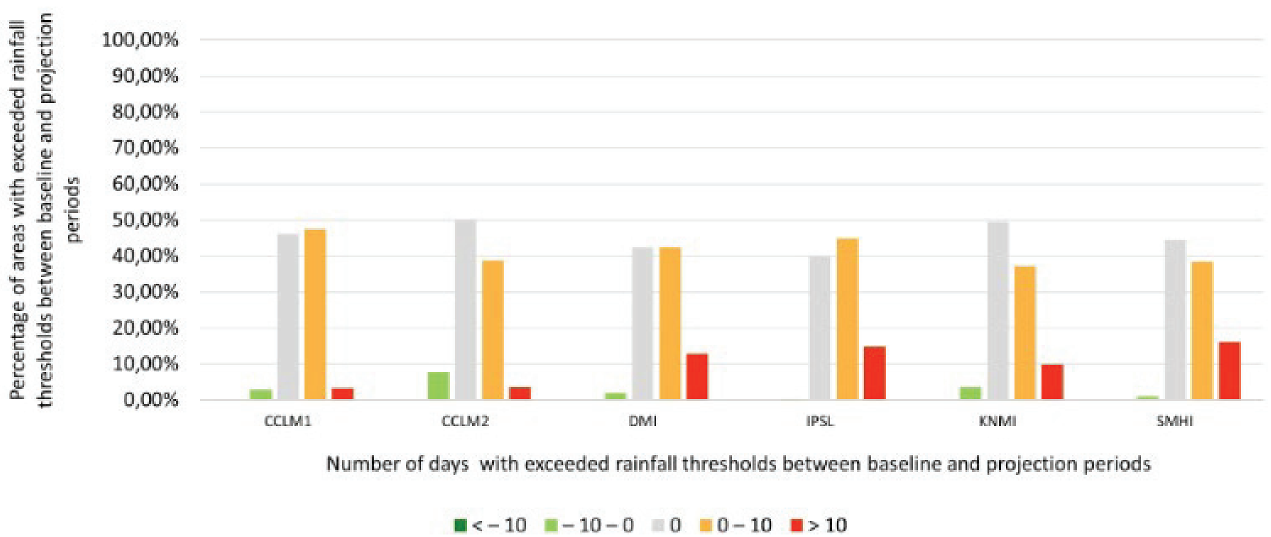


Figure 4 Percentage of areas for which rainfall thresholds between baseline and future periods was exceeded. Six RCP4.5 model runs are shown (i.e. one per column). Adopted after Jemec Auflič et al. (2021).

## Conclusions

This contribution provides a short overview of recent studies conducted by Slovenian researchers related to the triggering and prediction of landslides and debris flows under the impact of climate change. As can be seen quite some number of studies have been conducted in this field. Some of the studies also investigated global and large regional scales while others were conducted at national scale. However, further research is needed and will be conducted in Slovenia. For example, in the scope of the on-going basic research project "Deciphering the sensitivity of rock faces to climatic changes and freeze-thaw cycles in permafrost-free regions (J1-3024)" climate change impact on the rock fall triggering will be investigated. Further work is also needed to continuously fill landslide inventory with new landslide cases to be able to validate susceptibility and triggering models and better predict potential climate change impact.

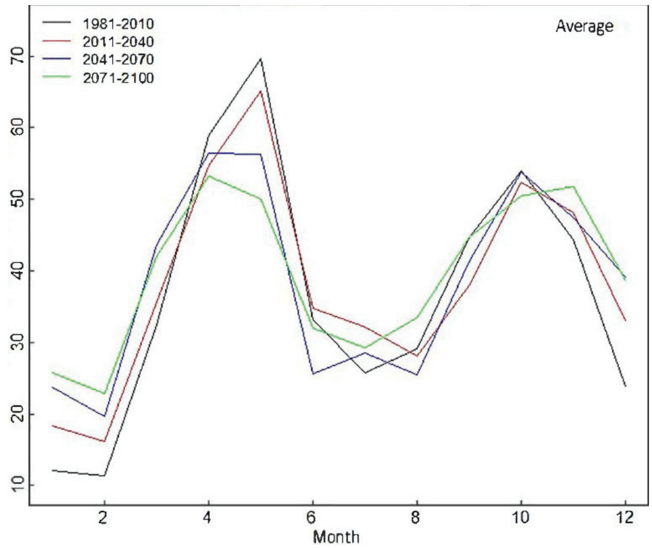


Figure 5 Monthly (x-axis) variations in the monthly groundwater recharge (y-axis; in mm) for a baseline (1981-2010) and three future periods for the Koroška Bela area based on the simulations using the mGROWA water balance model. Average values for the six GCM/RCMs are shown.

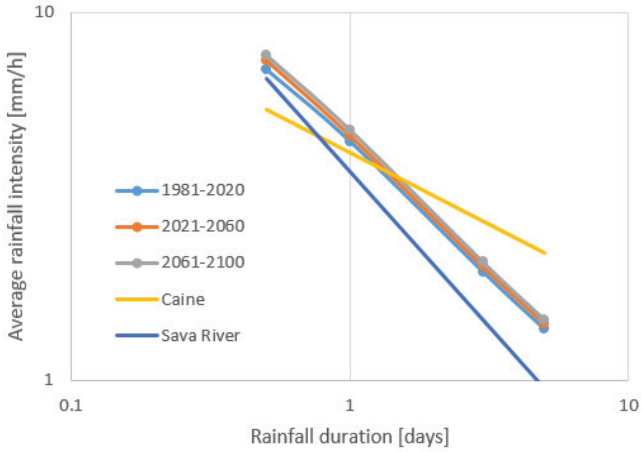


Figure 6 Comparison of the empirical rainfall thresholds (one for Sava River basin and one Global threshold) and IDF curves for the 2-year return period for the Koroška Bela area. Adopted after Bezak et al. (2021b).

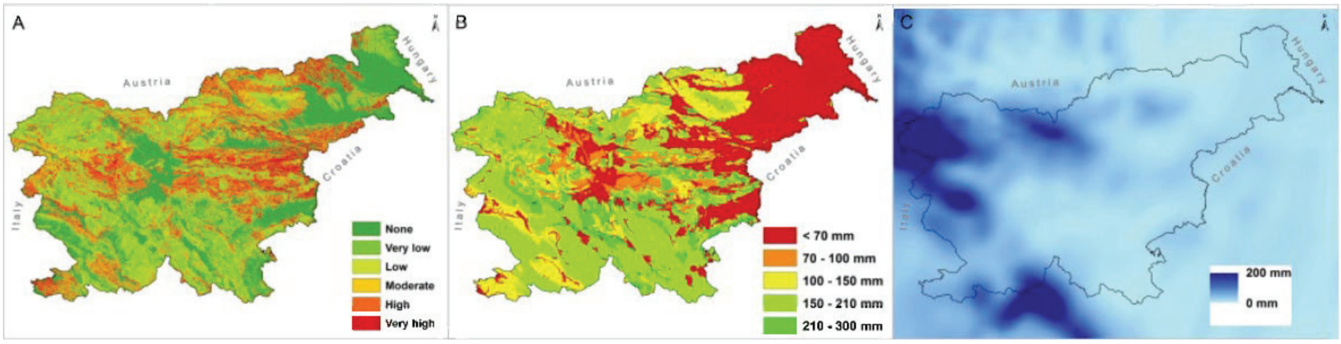


Figure 7 Three major elements of the MASPREM system: landslide susceptibility model, triggering rainfall thresholds and precipitation forecasting model. Adopted after Jemec Auflič et al. (2016).

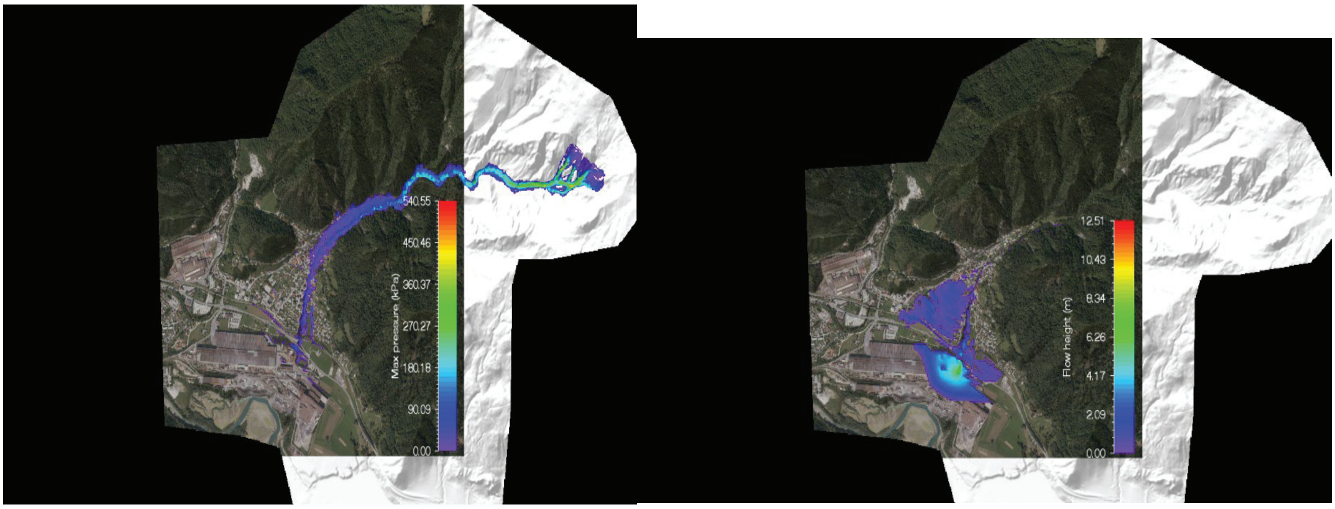


Figure 8 Example of RAMMS debris flow modelling results for the Koroška Bela area using hydrograph as input (peak of around 3,000 $m^3/s$ and magnitude of around 340,000 $m^3$). Flow height at the end of simulation and maximum pressure are shown for the RAMMS model parameters $\mu = 0.075$ and $\xi = 200\ m/s^2$.

## Acknowledgments

The authors would like to thank Slovenian Research Agency (ARRS) for financial support through core financing P2-0180 and P1-0011, and two research projects J1-2477 and J1-3024, respectively.

## References

Bertalanič R, Mojca D, Andrej D et al. (2018) Estimation of climate change impact in Slovenia until 2100, 1st edn. Slovenian Environment Agency, Ljubljana. (in Slovenian)

Bezak N, Jemec Auflič M, Mikoš M (2019a) Application of hydrological modelling for temporal prediction of rainfall-induced shallow landslides. Landslides. 16: 1273–1283. https://doi.org/10.1007/s10346-019-01169-9

Bezak N, Jemec Auflič M, Mikoš M (2021a) Reanalysis of Soil Moisture Used for Rainfall Thresholds for Rainfall-Induced Landslides: The Italian Case Study. Water. 13(14): 1977. https://doi.org/10.3390/w13141977

Bezak N, Jež J, Sodnik J et al. (2020) An extreme May 2018 debris flood case study in northern Slovenia: analysis, modelling, and mitigation. Landslides. 17: 2373-2383. https://doi.org/10.1007/s10346-019-01325-1

Bezak N, Mikoš M (2021) Changes in the rainfall event characteristics above the empirical global rainfall thresholds for landslide initiation at the pan-European level. Landslides. 18: 1859-1873. https://doi.org/10.1007/s10346-020-01579-0

Bezak N, Mikoš M (2019) Investigation of trends, temporal changes in Intensity-Duration-Frequency (IDF) curves and extreme rainfall events clustering at regional scale using 5 min rainfall data. Water (Switzerland). 11(10): 2167. https://doi.org/10.3390/w11102167

Bezak N, Peternel T, Medved A, Mikoš M (2021b) Climate Change Impact Evaluation on the Water Balance of the Koroška Bela Area, NW Slovenia. In: Vilimek V, Wang F, Storm A et al. (eds) Understanding and Reducing Landslide Disaster Risk. Springer

Bezak N, Sodnik J, Maček M et al. (2021c) Investigation of potential debris flows above the Koroška Bela settlement, NW Slovenia, from hydro-technical and conceptual design perspectives. Landslides. 18: 3891–3906. https://doi.org/10.1007/s10346-021-01774-7

Bezak N, Sodnik J, Mikoš M (2019b) Impact of a random sequence of Debris flows on torrential fan formation. Geosci. 9(2): 64. https://doi.org/10.3390/geosciences9020064

Bezak N, Šraj M, Mikoš M (2016) Copula-based IDF curves and empirical rainfall thresholds for flash floods and rainfall-induced landslides. J Hydrol. 541(Part A): 272-284 https://doi.org/10.1016/j.jhydrol.2016.02.058

Gariano SL, Guzzetti F (2016) Landslides in a changing climate. Earth-Science Rev 162: 227–252. https://doi.org/10.1016/j.earscirev.2016.08.011

Haque U, Blum P, da Silva PF, et al. (2016) Fatal landslides in Europe. Landslides. 13: 1545–1554. https://doi.org/10.1007/s10346-016-0689-3

Janža M, Serianz L, Šram D, Klasinc M (2018) Hydrogeological investigation of landslides Urbas and Čikla above the settlement of Koroška Bela (NW Slovenia). Geologija 61:191–203. (in Slovenian) https://doi.org/10.5474/geologija.2018.013

Jemec Auflič M, Bokal G, Kumelj Š et al. (2021) Impact of climate change on landslides in Slovenia in the mid-21st century. Geologija. 64: 159–171. https://doi.org/10.5474/geologija.2021.009

Jemec Auflič M, Jež J, Popit T et al (2017) The variety of landslide forms in Slovenia and its immediate NW surroundings. Landslides. 14: 1537–1546. https://doi.org/10.1007/s10346-017-0848-1

Jemec Auflič M, Šinigoj J, Krivic M et al. (2016) Landslide prediction System for rainfall induced landslides in Slovenia (Masprem). Geologija. 59: 259–271. https://doi.org/10.5474/geologija.2016.016

Jordanova G, Gariano SL, Melillo M, et al. (2020) Determination of empirical rainfall thresholds for shallow landslides in Slovenia using an automatic tool. Water (Switzerland). 12(5): 1449. https://doi.org/10.3390/w12051449

Mateos RM, López-Vinielles J, Poyiadji E et al. (2020) Integration of landslide hazard into urban planning across Europe. Landsc Urban Plan 196: 103740. https://doi.org/https://doi.org/10.1016/j.landurbplan.2019.103740

Mikoš M, Bezak N (2021) Debris Flow Modelling Using RAMMS Model in the Alpine Environment With Focus on the Model Parameters and Main Characteristics. Front Earth Sci. 8: 605061. https://doi.org/10.3389/feart.2020.605061

Modugno S, Johnson SCM, Borrelli P et al. (2022) Analysis of human exposure to landslides with a GIS multiscale approach. Nat Hazards. https://doi.org/10.1007/s11069-021-05186-7

Sodnik J, Kumelj Š, Peternel T et al. (2017) Identification of Landslides as Debris Flow Sources Using a Multi-model Approach Based on a Field Survey---Koroška Bela, Slovenia. In: Mikos M, Tiwari B, Yin Y, Sassa K (eds) Advancing Culture of Living with Landslides. Springer International Publishing, Cham, pp 1119–1126.