Rock Frost Weathering and Rockfall Activity Assessment in Slovenia

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Abstract Rockfalls as mass movements occur more frequently in areas with high energy potential of the terrain (steep slopes, rock faces), which is enhanced by the weathering of the rocks on site. For physical weathering, hydrometeorological factors are important (air humidity & temperatures, wind direction & intensity, precipitation types & amounts). The weathering rate depends on the rock type and the discontinuities present.

In order to study rock frost weathering and potential rockfall activity in Slovenia, an analysis of land surface temperatures and air temperatures was performed. For the former, the ERA5-Land reanalysis data provided by Copernicus were used, and for the latter the measurement data from the precipitation monitoring network of Slovenia (Slovenian Environment Agency-ARSO) were used. The grid for LST was 9x9 km, and the number of meteorological stations in Slovenia used was more than 150 (period 2016-2020). We used hourly data to better assess frost weathering potential. Station-based air temperatures were compared to land surface temperatures and their diurnal, monthly, and seasonal differences were discussed. Using reanalysis ERA5-Land data, analysis of the annual number of daily freeze-thaw cycles was conducted and a freeze-thaw map of Slovenia was prepared. Additionally, multiple simple rockfall susceptibility models were tested. Several impact factors were used as input data such as slope, lithology, aspect, mean annual precipitation, 5-minute rainfall with the 100-year return period, seismic-hazard map and freeze-thaw map were selected. It was confirmed that slope and lithology are the two factors that have the most significant effect on the model performance. Consideration of the newly develop freeze-thaw map of Slovenia did not significantly improve the performance of the simple rockfall susceptibility model. The same can be said for the consideration of the seismic-hazard map. This especially applies to the rockfalls that occur in coastal flysch cliffs. In this area (Mediterranean coastal area) the number of freeze-thaw cycles are the smallest, the seismic-hazard map is characterized by lower acceleration values, and total precipitation amount is not very high, though rockfalls are abundant.

Keywords rockfalls, hazard assessment, frost weathering, Slovenia

Introduction

In Slovenia, rockfalls, landslides, torrential erosion in headwaters, and riverbank erosion are one of the most hazardous phenomena (Mikoš et al., 2004). In Slovenia, there are a variety of landslide forms (Jemec Auflič et al., 2017). Rockfalls and rock slides are common in northern and north-western Slovenia, in steep gorges or canyons and in overthrust areas where carbonate rocks overthrust the softer rocks (mostly flysch) (Mikoš et al., 2013). For a long, rockfall susceptibility was relatively poorly investigated in Slovenia (Komac, 2017a). After the devastation in Log pod Mangartom in 2000, caused by a debris flow, the development of landslide research in Slovenia was obvious (Komac, 2017a; Mikoš, 2020).

Rockfalls were more often studied at a local scale rather than regional or national scale: developing a deterministic model for rockfall hazard assessment (Zorn and Komac, 2004), rockfall computer simulations (Petje et al., 2005b), dynamics of rockfall motion on slopes (Petje et al., 2006), rockfalls as a hazard for traffic infrastructure (Turković et al, 2005; Petje et al., 2005a) or rockfalls causing rockwall retreat on badlands (Zorn and Mikoš, 2008).

At larger scales, the first modern susceptibility map of Slovenia was produced in 1995/6 by the Geological Survey of Slovenia (Ribičič, 2002) on the basis of the Engineering-Geological Map of Slovenia in scale 1:400,000 from 1994, introducing a 4-classes susceptibility map, originally called Stability Map of Slovenia – Rockfalls (GeoZS, 2021) in a gridded 242 x 242 m raster form (Fig. 1).

In 2011, a new Rockfall Susceptibility map of Slovenia in scale 1:250,000 was prepared by the Geological Survey of Slovenia (Čarman et al., 2011). The map was produced in the GIS environment based on slope, lithology and distance to tectonics features (Fig. 2). The most important factors considered were: lithology (lithological map of Slovenia in scale 1:250,000), slope angle and distance to tectonic-structural elements (Komac, 2017b). Susceptibility was divided into 6 classes from high susceptibility to no susceptibility (Fig. 2).

The main problem in any work on rockfall susceptibility in Slovenia is a lack of a consistent cadastre and a lack of abundant historical data to validate a statistical model. The first validated rockfall susceptibility map was prepared at the municipal scale of 1:25,000 for Bovec Municipality in NW Slovenia (Čarman et al. 2015)

(Fig. 3). The map was developed, based on the probabilistic model of slope mass movement susceptibility proposed for Bovec municipality by Komac (2005). This study has a research question: can the analysis of rock frost weathering improve/change the assessment of rockfall susceptibility in Slovenia?

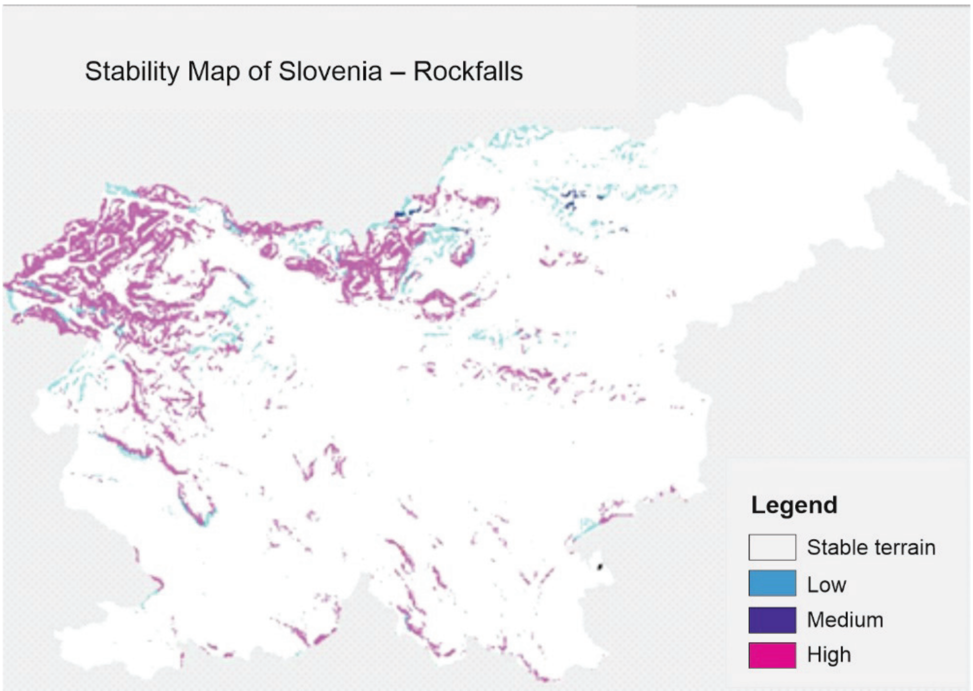

Figure 1 Stability Map of Slovenia – Rockfalls in the scale 1:400,000 from 1995/6.

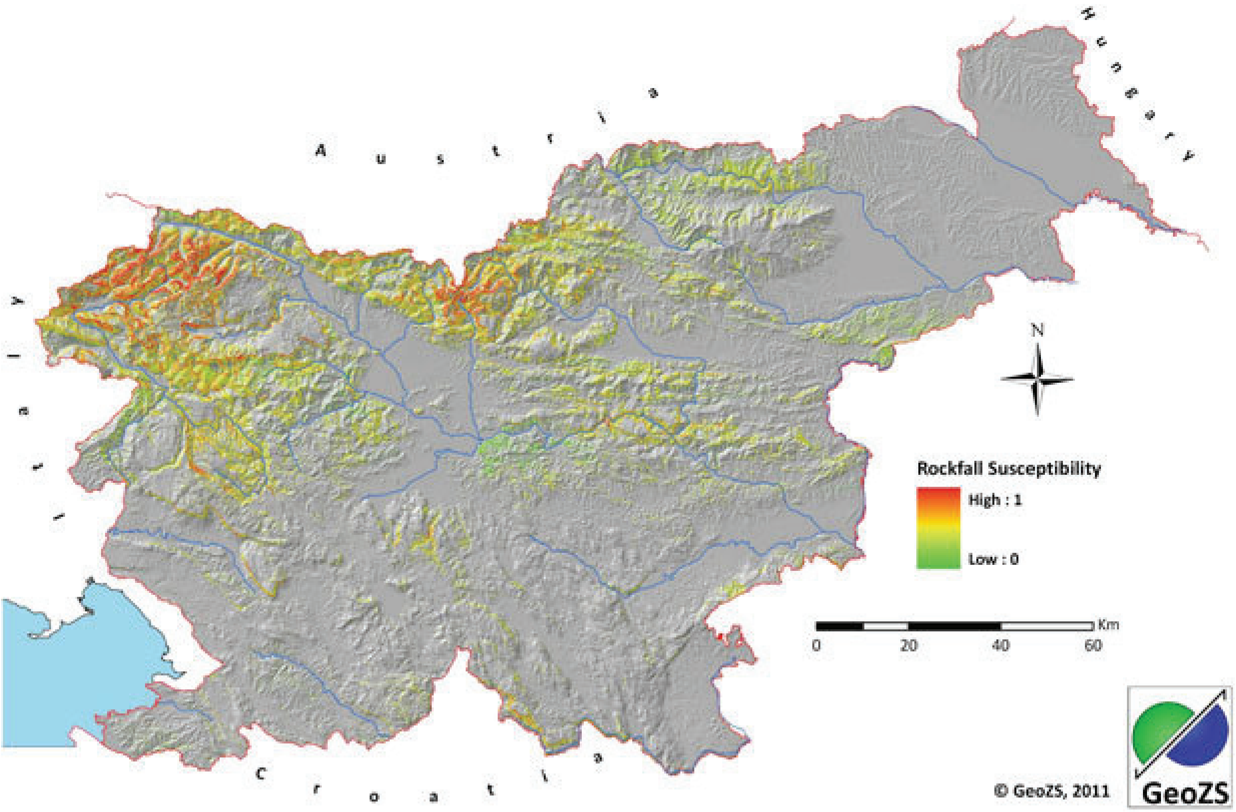

Figure 2 Rockfall Susceptibility Map of Slovenia at scale 1:250,000 (Čarman et al., 2011)

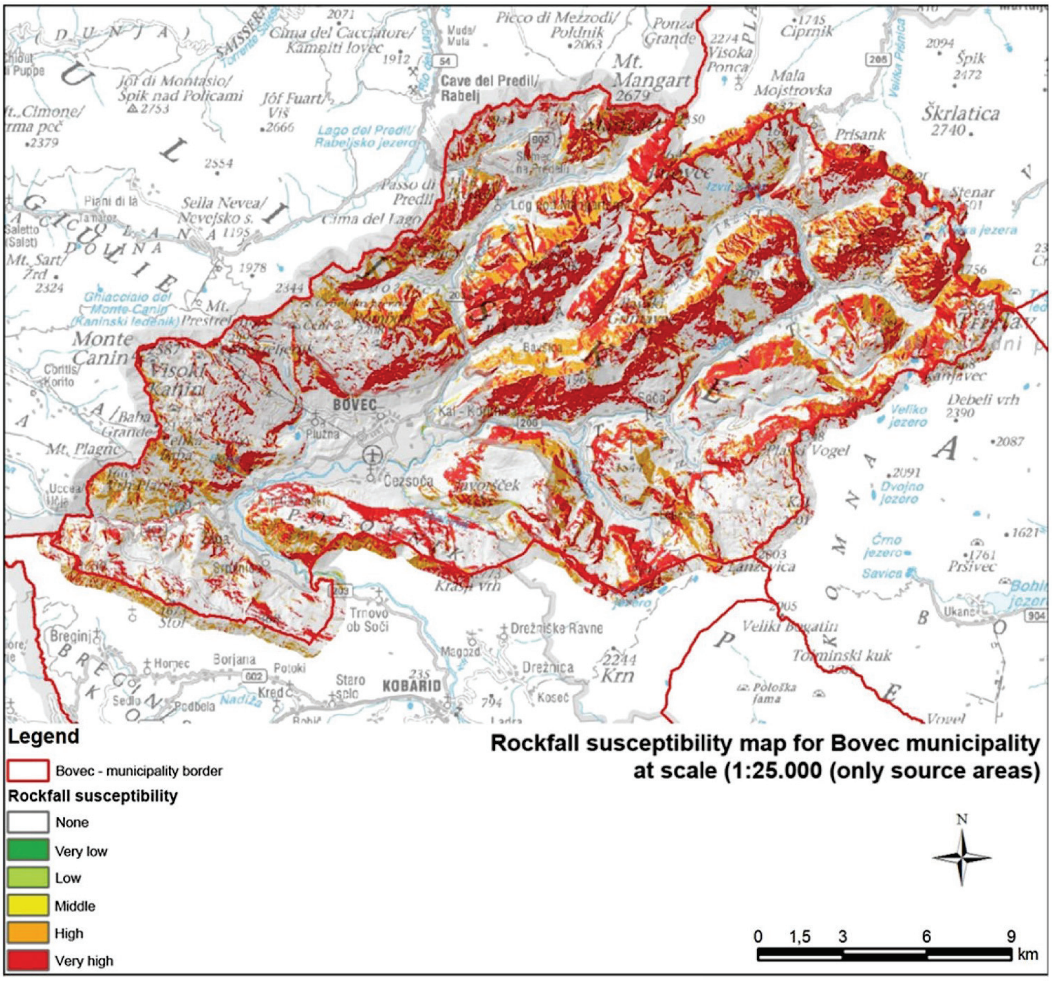

Figure 3 Rockfall Susceptibility Map of Bovec Municipality at scale 1:250,000 (Čarman et al., 2015).

Materials and Methods

Frost weathering

Frost weathering of rocks is defined as a collective term for several mechanical weathering processes induced by stresses created by the freezing of water in rocks discontinuities.

Rockfall causal factors

Rockfalls can be triggered by earthquakes, strong storms or thunderstorms, by strong winds and heavy rainfall, not to mention human activities, such as slope undercutting or blasting. The study was focused on the question "Where it can happen?" and not to the question "When it can happen? Since the result in the form of a regional/national rockfall susceptibility map was envisaged, the following rockfall causal factors were considered:

- Lithology – the Lithological map of Slovenia in scale 1:250,00 was used in its digital form (shape files for each lithological unit on the map). All in all, 28 engineering-geology units were classified into 6 classes with regard to the susceptibility of lithology to weathering and crack initiations due to frost and thermal weathering and susceptibility to seismic activity.
- New Seismic Hazard (SH) map of Slovenia (ARSO, 2021) showing peak ground accelerations (PGA), determined for the 475-year return period (Fig. 4).
- These accelerations are valid for bedrock or other geological formations with at least an elastic wave velocity of 800 m/s and less than 5 m of weak soil cover. For the new seismic hazard map, for the first time is Slovenia, active faults and fault sources were considered that might be of importance also for rockfall susceptibility modelling.
- Slope gradient as an indicator for available terrain energy available to release rockfalls.
- Slope aspect as an indicator of thermal stress due to solar insulation.
- Mean annual precipitation (P), and 5-minute precipitation with the 100-year return period (P_{100}) (from the Crossrisk project, https://www.crossrisk.eu/en/) as an indicator for weathering rates, rock moisture, and snow cover.
- Freeze-thaw cycles as an indicator for crack initiations in rocks – cycles were estimated using dial fluctuations of air temperatures and land surface temperatures.

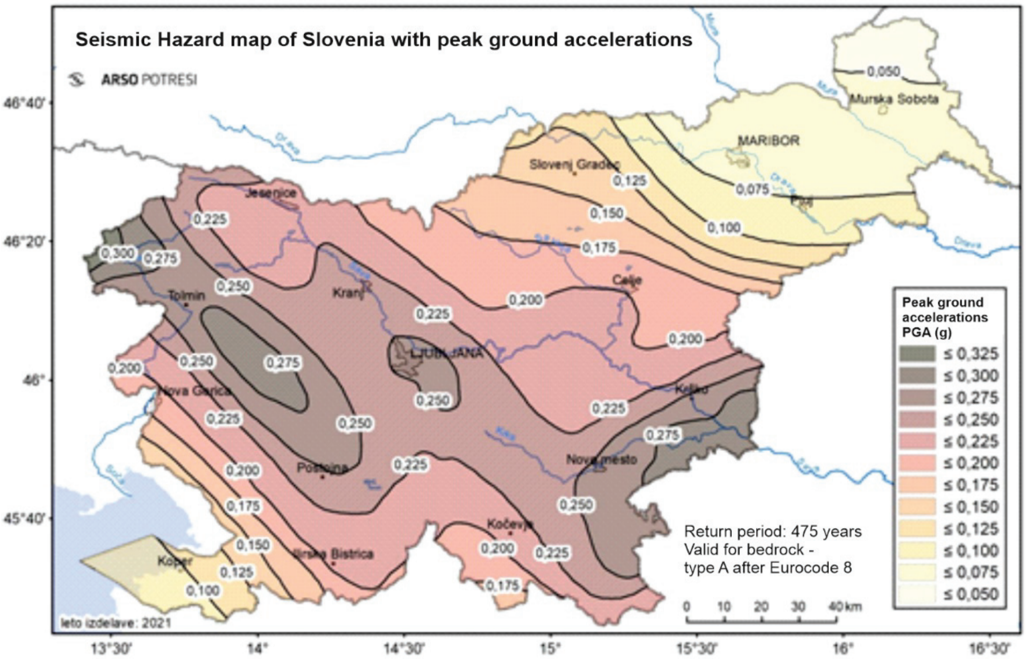

Figure 4 Seismic Hazard map of Slovenia with peak ground accelerations (PGA in g), return period 475 years and valid for bedrock – type A after Eurocode 8 (ARSO, 2021).

Reanalysis data and meteorological data

The relevant reanalysis data was used, i.e. the ERA5-Land reanalysis hourly data for the period 2016-2020 provided by the Copernicus (2021). We applied the following data: "2 m temperature", "Soil temperature level 1", and "Snow depth". "2m temperature" represents the air temperature at 2m above the surface of land, sea or in-land waters (Copernicus, 2021). It is obtained by the interpolation of the Earth's surface and lowest model level (Copernicus, 2021).

The "Soil temperature level 1" represents temperature of the soil level (0-7 cm) that comes from the ECMWF Integrated Forecasting System (Copernicus, 2021). While the "Snow depth" variable represents the grib-box mean of the snow thickness on the ground while excluding snow on the canopy (Copernicus, 2921). An example of the reanalysis data is shown in Fig. 5.

Additionally, the 2-m air temperature at hourly scale was obtained for the same periods 2016-2020 from over 150 meteorological stations from the state monitoring system operated by ARSO (Slovenian Environmental Agency, 2021). Fig. 6 shows the location of stations that had air temperature data available in the 2016-2020 period.

GIS environment and tools

Investigations related to the extraction of the reanalysis data were carried out using program R (2021) and available packages such as *raster*, *rgdal*, *sp*, and *gstat*. R software was also used for pre-processing the hourly station-based data and for the interpolation. Analyses related to susceptibility models were performed in the SAGA GIS environment that is a free open access software for geoscientific analyses (SAGA, 2021) – we used version 8.

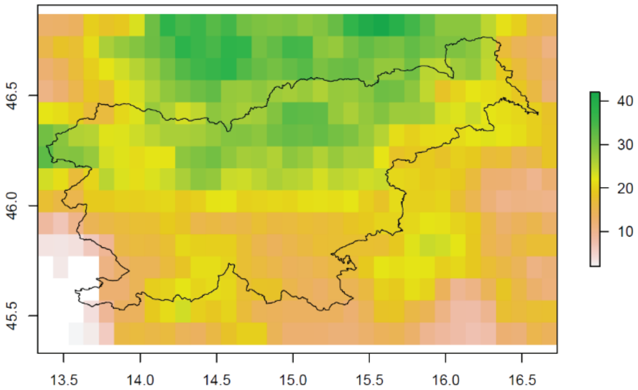

Figure 5 Era5-Land reanalysis data for the area of Slovenia, the legend shows average number of days when soil temperature at level 1 is below and above 0°).

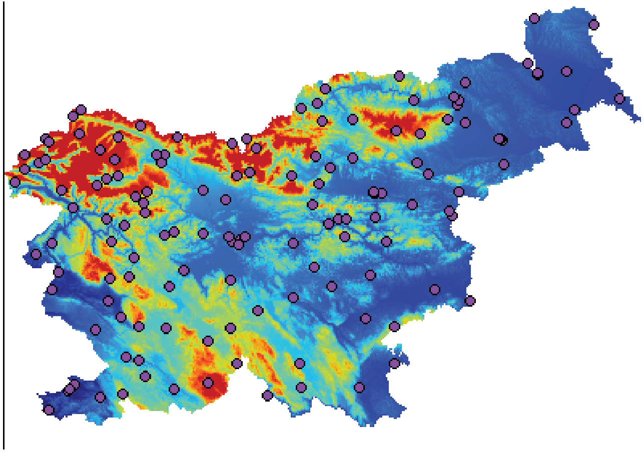

Figure 6 Location of meteorological and climatological stations with the hourly 2m air temperature data availability in the period 2016-2020. Digital elevation model is shown as background.

Rockfall cadastre data

A rockfall cadastre was compiled based on data from various sources (GH50 project, Civil Administration database, and personal collections). A total of 164 rockfalls from GH50 project were used in this study.

Results and Discussion

Reanalysis data and station-based data investigations

For the investigations related to the freeze-thaw cycles we used both reanalysed and station-based data. Fig. 7 shows the average number of days when the air temperature is below and above 0°. It can be seen that these maps are to some extent different as the one shown in Fig. 5.

Thus, the further comparison was made between air temperature and soil temperature data (Fig. 8). It was found that differences to some extent depend on the station location since for high altitude stations differences were more explicit than for low-altitude stations (Fig. 8).

This was further confirmed by conducting a similar analysis for all the locations shown in Fig. 6. The results are presented in Fig. 9. It can be seen that the difference in the number of freeze-thaw cycles depends on the station altitude. The main reason for these differences is the snow cover depth that varies from station to station. Moreover, we additionally compared air temperature data obtained from ERA5-Land and station-based data (ARSO). It was again found that agreement between two datasets depended on the station location (Fig. 11) and was estimated as acceptable.

Freeze-thaw map of Slovenia based on the soil temperature

Based on the conducted investigations, we decided to use the soil temperature data from the ERA5-Land to estimate the average annual number of freeze-thaw cycles for entire Slovenia. This variable was assumed to be the most relevant for the description of the actual number of freeze-thaw cycles. Based on the location of stations (Fig. 6) we extracted the ERA5-Land data and performed interpolation using the ordinary kriging. The final map is shown in Fig. 11. This map was used in the further steps of this study.

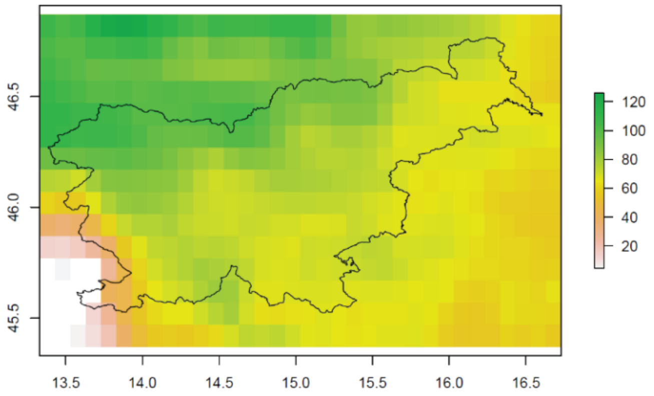

Figure 7: Average number of days when air temperature data is below and above 0°.

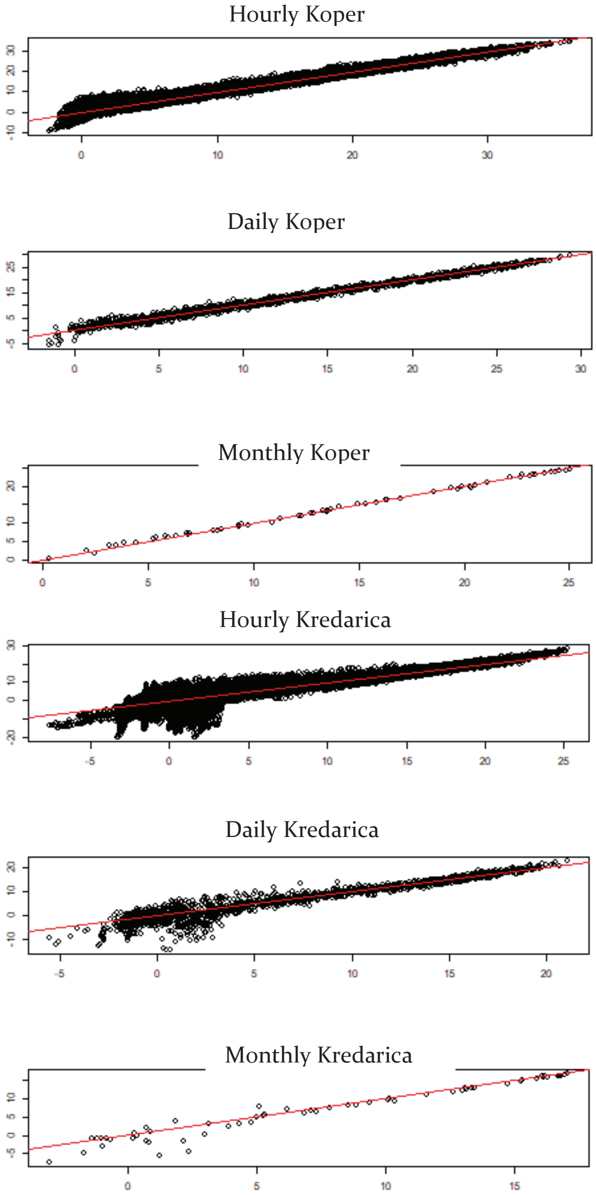

Figure 8: Comparison between 2 m air temperature (y-axis) and soil temperature level 1 (x-axis) at hourly, daily and monthly time step for Kredarica (high-altitude Alpine station) and Koper (low-altitude Mediterranean station) stations.

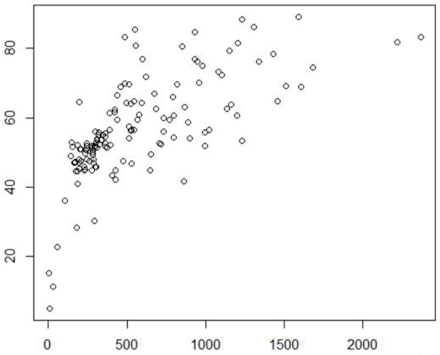

Figure 9: Relationship between station altitude (x-axis) and number of cycles calculated using air temperature and soil temperature data (y-axis). The grid locations for all stations shown in Fig. 6 are shown (one point-one station).

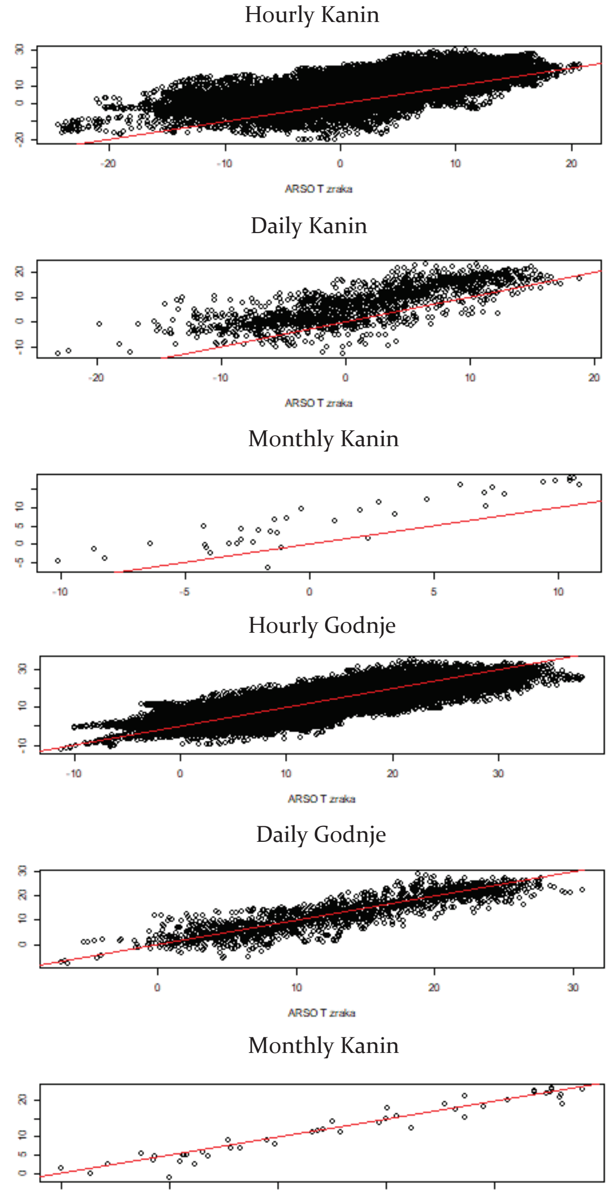

Figure 10: Comparison between 2 m air temperature from the ERA5-Land (y-axis) and station-based air temperature (x-axis) at hourly, daily and monthly time step for Kanin (high-altitude Alpine station) and Godnje (low-altitude Mediterranean station) stations.

Rockfall Susceptibility Models

Multiple simple models were tested to evaluate if the developed freeze-thaw map can improve the performance of simple rockfall susceptibility models (Tab. 1). In addition, simple evaluation of model performance was performed (Tab. 1). Some examples of the tested models are shown in Fig. 12, Fig. 13, Fig. 14 and Fig. 15.

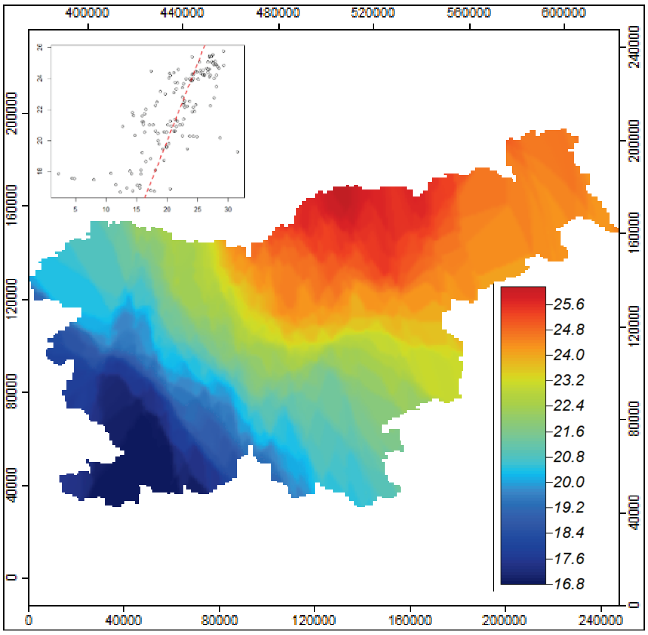

Figure 11: Freeze-thaw map of Slovenia (average annual daily free-thaw cycles) based on the ERA5-Land soil temperature data and results of the leave-one-out cross validation (scatter plot) for ordinary kriging (elevation was used for the interpolation).

Table 1. List of tested rockfall susceptibility models (legend: S-Slope; LI-Lithology; FT-Freeze-Thaw, A-Aspect, P-Total annual precipitation; P100-5-minute rainfall with 100-year return period; SH-Seismic-Hazard). For all models, mean values are given for the entire Slovenia (MVS) and for the cells with rockfalls (MVR).

ID	Model	MVS	MVR (Min-Max values)
1	0.2*S+0.2*LI+0.2*P+0.2*FT+0.2*A	0.46	0.55 (0.15-0.87)
2	0.3*S+0.3*LI+0.1*P+0.2*FT+0.1*A	0.47	0.59 (0.12-0.90)
3	0.3*S$^{1/2}$+0.3*LI+0.1*P+0.2*FT+0.1*A	0.51	0.63 (0.19-0-89)
4	0.3*S$^{1/2}$+0.3*LI$^{1/2}$+0.1*P+0.2*FT+0.1*A	0.55	0.67 (0.19-0-91)
5	0.5*S$^{1/2}$+0.5*LI$^{1/2}$	0.51	0.68 (0.18-0.94)
6	0.7*S$^{1/2}$+0.3*LI$^{1/2}$	0.45	0.63 (0.24-0-93)
7	0.7*S$^{1/2}$+0.3*LI	0.42	0.60 (0.24-0.92)
8	0.3*S$^{1/2}$+0.3*LI$^{1/2}$+0.1*P$_{100}$+0.2*FT+0.1*A	0.56	0.68 (0.22-0-88)
9	0.3*S$^{1/2}$+0.3*LI$^{1/2}$+0.1*P$_{100}$+0.1*FT+0.1*A+0.1*SH	0.50	0.64 (0.22-0.91)

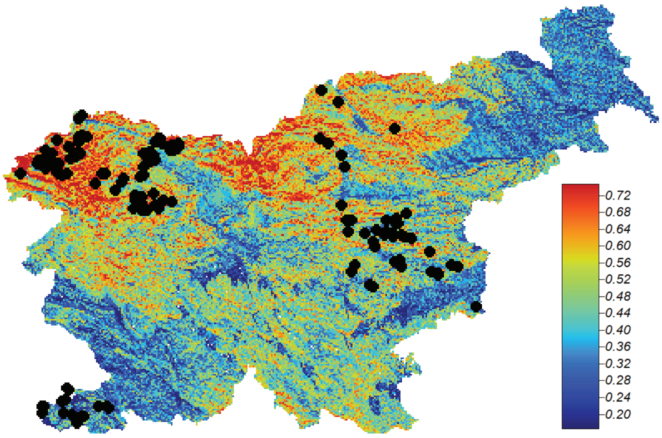

Figure 12: Tested rockfall susceptibility model number 1 with the location of 164 rockfalls used in this study.

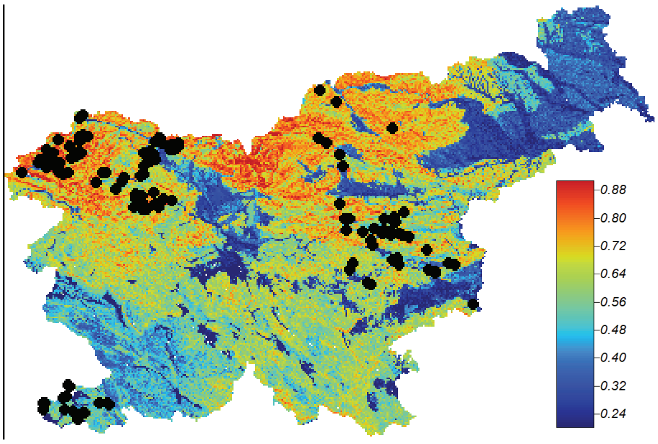

Figure 13: Tested rockfall susceptibility model number 4 with the location of 164 rockfalls used in this study.

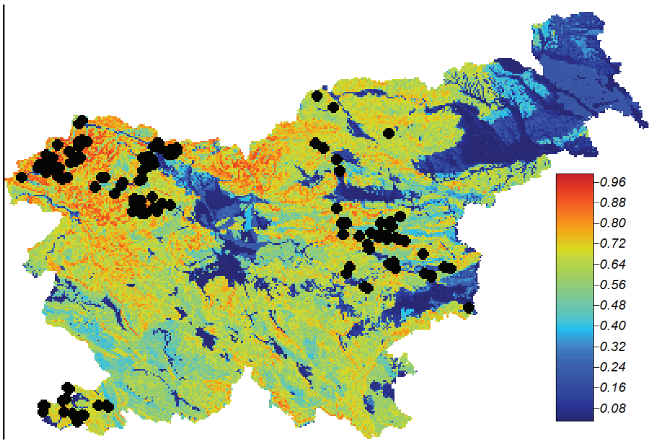

Figure 14: Tested rockfall susceptibility model number 5 with the location of 164 rockfalls used in this study.

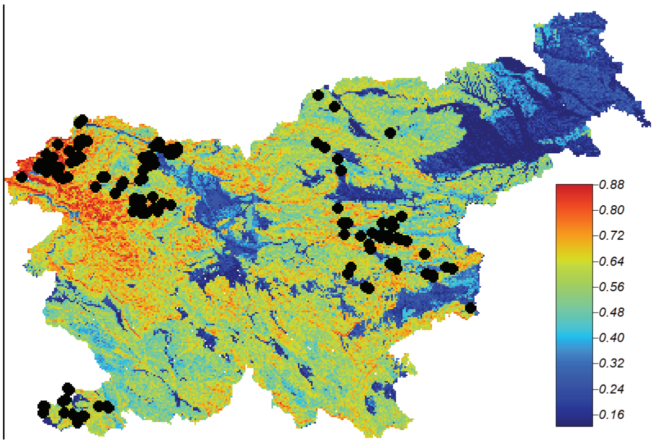

Figure 15: Tested rockfall susceptibility model number 9 with the location of 164 rockfalls used in this study.

Conclusions

Based on the presented results it can be concluded that the consideration of the newly developed freeze-thaw map of Slovenia does not significantly improve the performance of the simple rockfall susceptibility model. The same can be said for the consideration of the seismic-hazard map.

Based on the results, slope and lithology are considered as the main preconditioning factors that impact the performance of such simple rockfall susceptibility models. This especially applies for the rockfalls that occur in coastal flysch cliffs. In this area (Mediterranean coastal area) the number of freeze-thaw cycles is the smallest, the seismic-hazard map is characterized by lower peak ground acceleration (PGA) values and the total precipitation amount is not very high. A variable that could be used in this part of the Slovenia is the P_{100}. Moreover, additional investigations are needed to improve the performance of the larger-scale regional rockfall susceptibility model.

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