LAND
SLIDE
PLAN

Book of Abstracts LandSlidePlan Project

University of Zagreb
FACULTY OF MINING, GEOLOGY AND PETROLEUM ENGINEERING

University of Rijeka
Faculty of Civil Engineering

HRZZ

University of Zagreb
FACULTY OF MINING, GEOLOGY AND PETROLEUM ENGINEERING

University of Rijeka
Faculty of Civil Engineering

Book of Abstracts
LandSlidePlan Project

LAND SLIDE PLAN

HRZZ

Project funded by Croatian Science Foundation

Book of Abstracts - LandSlidePlan Project

„Methodology development for landslide susceptibility assessment for land-use planning based on LiDAR technology“

This Book of Abstracts was created as a result of a scientific project entitled "Methodology development for landslide susceptibility assessment for land-use planning based on LiDAR technology" (HRZZ IP-2019-04-9900), funded by the Croatian Science Foundation.

The Book of Abstracts is also available on the project website www.landslideplan.eu.

INSTITUTION: University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering

PROJECT PARTNER: University of Rijeka, Faculty of Civil Engineering

PROJECT DURATION: Jan 1, 2020 - Dec 31, 2023

PROJECT LEADER
Snježana Mihalić Arbanas
University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering

EDITORS:

Martin Krkač
University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering

Sanja Bernat Gazibara
University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering

Hrvoje Lukačić
University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering

Petra Jagodnik
University of Rijeka, Faculty of Civil Engineering

Snježana Mihalić Arbanas
University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering

Published by: University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering
Cover design: MICHEL d.o.o.
Issued: December 2023, 30 copies
ISBN: 978-953-6923-49-6, 978-953-6923-50-2 (e-book)

Foreword

With the development of landslide science, which was unofficially established in the early 1990s, significant attention is paid to the research of the conditions and mechanisms of landslide occurrences, prediction of landslide initiations, reducing the risk of landslides, and the social aspects of landslide consequences. The number of landslides with fatal consequences in the world is increasing and is mainly caused by climate change, and more than half of them occur in areas exposed to extreme precipitation. To this trend of increasing the number of landslides and their consequences, landslide science has responded with a wide range of research in different directions, and the results of the research are followed by an almost exponential growth in the number of published papers, especially from 2010 until today.

One of the main directions in landslide research, especially in recent years, is towards modelling and simulations, assessment and management of landslide susceptibility, hazard, and risk, with the ultimate goal of reducing the consequences of landslides by appropriate spatial planning, landslide prevention and responsible space management. In this sense, the assessment of landslide susceptibility, which is the main topic in this Book, represents the first and most important link in the chain of landslide research. Landslide susceptibility is significantly researched in the world; in the last three years more than 3,500 scientific papers have been published in scientific journals on the subject, with exponential growth compared to the period until 2015. At the same time, the development of research methods is significant, in which the technological development, and lately artificial intelligence, certainly have a significant contribution. From the beginning, landslide susceptibility assessment methods were based on statistical models, while the trend of machine learning models and deep learning models is increasingly applied today. The Project Methodology Development for Landslide Susceptibility Assessment for Land-use Planning Based on LiDAR Technology (LandSlidePlan), funded by the Croatian Science Foundation (HRZZ) in the period 2020 to 2023, investigated mapping of small and shallow landslides and a methodology for assessing landslide susceptibility using LiDAR technology, which represents an innovative approach in scientific research on landslide susceptibility in Croatia, as well as in the world. Within the Project, numerous methods of landslide susceptibility approaches were analyzed in order to select the optimal ones for their application based on the appropriate preparation of input data for specific environments, conditions, and types of landslides. The results of the Project certainly represent significant scientific achievements that will be presented in international scientific journals in the coming years, but will also have a significant social impact on raising awareness and knowledge about methods and solutions for landslide risk prevention and the development of policies and regulations on the way and the use of landslide susceptibility maps in spatial planning and space management, which so far has not been present, recognized or regulated in the Republic of Croatia.

This Book of Abstracts contains 25 abstracts of papers presented at the Final Conference of the LandSlidePlan Project. The Book only gives an insight into the topics of scientific research that was conducted and presented to the scientific community and to the public. The most valuable results can be expected after the formal completion of the Project through publication in top scientific journals, which will show the true scientific value achieved by the scientific research team in the research of the landslide susceptibility assessment.

Professor Željko Arbanas

President of the International Consortium on Landslides

Contents

About the Project

Results of scientific research

Input data preparation: Landslide inventories and causal factor maps

Landslide susceptibility assessment: Modelling, evaluation, validation and zonation

Application of scientific research results

About the Project

LandSlidePlan - Scientific research project on landslide susceptibility assessment in large scale

Sanja Bernat Gazibara[(1)], Snježana Mihalić Arbanas[(1)], Marko Sinčić[(1)], Martin Krkač[(1)], Hrvoje Lukačić[(1)], Petra Jagodnik[(2)], Željko Arbanas[(2)]

HRZZ

1) University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Zagreb, Pierottijeva 6, Croatia
2) University of Rijeka, Faculty of Civil Engineering, Rijeka, Radmile Matječić 3, Croatia

Knowledge of the spatial distribution of geohazards in populated areas is a prerequisite for sustainable strategic planning and management. The scientific research project *Methodology development for landslide susceptibility assessment for land-use planning based on LiDAR technology* (*LandSlidePlan*, HRZZ IP-2019-04-9900), funded by the Croatian Science Foundation for the period 2020-2023, deals with new and under-investigated subjects in respect of inventory mapping of small and shallow landslides and presents innovative approaches to scientific research of landslide susceptibility assessment using LiDAR technology for collection of input data. The scientific research will be implemented in three typical Croatian environments, i.e., the City of Zagreb, Hrvatsko Zagorje and Istria, selected based on characteristic geological settings and urbanisation degree (Fig. 1).

The first goal of the project was to create the best optimal digital model of the bare-earth terrain (DTM) that shows realistic landslide footprints and differences between disturbed and undisturbed relief that may influence land use. The data used for the interpolation and analyses of optimal DTMs were acquired from airborne laser scanning (ALS), undertaken during the leaf-off period, in March 2020. The resulting LiDAR point clouds has an average point density of terrain class 15.6 pt/m^2. Interpolation of LiDAR DTM was carried out in six resolutions (0.15, 0.3, 0.5, 1, 2 and 5 m) using four commonly used interpolation methods (Inverse Distance Weighting, Natural Neighbor, Australian National University DEM and Kriging). Based on the point density, average point spacing, and quantitative geomorphological analysis, the bare-earth DTM with a 30 cm resolution using the kriging interpolation method was selected for visual landslide identification and mapping in all three pilot areas.

The second goal was to create the most reliable large-scale landslide susceptibility map with the best differentiation of landslide-prone and non-susceptible areas using scientific methods customised to specific engineering geological conditions. Landslide susceptibility analyses are planned by the application of different data-driven approaches such as bivariate, multivariate and machine learning methods. Landslide susceptibility analyses were performed on different mapping units and with the different types of landslide training data, such as landslide polygons and landslide points. The methodology for obtaining landslide susceptibility maps within the project is presented in Fig. 2.

The third goal was to create maps depicting information about landslides tailored according to the needs of the Croatian physical planning system (particularly land-use planning), encompassing local and regional level. Zonation of resulting susceptibility maps is crucial for land use spatial planning and management, which influences the possibilities of practical use of maps and the quality of information depicted by the map. The analysis compared and evaluated the reliability of the most commonly used classification methods, including equal intervals, natural breaks, quantiles, head/tail breaks and standard deviation. According to the clearly defined purpose of end-product maps, criteria and potential usage was determined by decision-makers, practitioners and experts from the domain of spatial and land use planning.

Keywords landslide susceptibility mapping, LiDAR, land use, LandSlidePlan

Published in: Bernat Gazibara S, Mihalić Arbanas S, Sinčić M, Krkač M, Lukačić H, Jagodnik P, Arbanas Ž (2022) LandSlidePlan - Scientific research project on landslide susceptibility assessment in large scale. In Peranić J, Vivoda Prodan M, Bernat Gazibara S, Krkač M, Mihalić Arbanas S, Arbanas Ž (eds) Proceedings of the 5th ReSyLAB “Landslide Modelling & Applications”. University of Rijeka Faculty of Civil Engineering, University of Zagreb Faculty of Mining, Geology and Petroleum Engineering, Rijeka, Zagreb, pp 99–106.

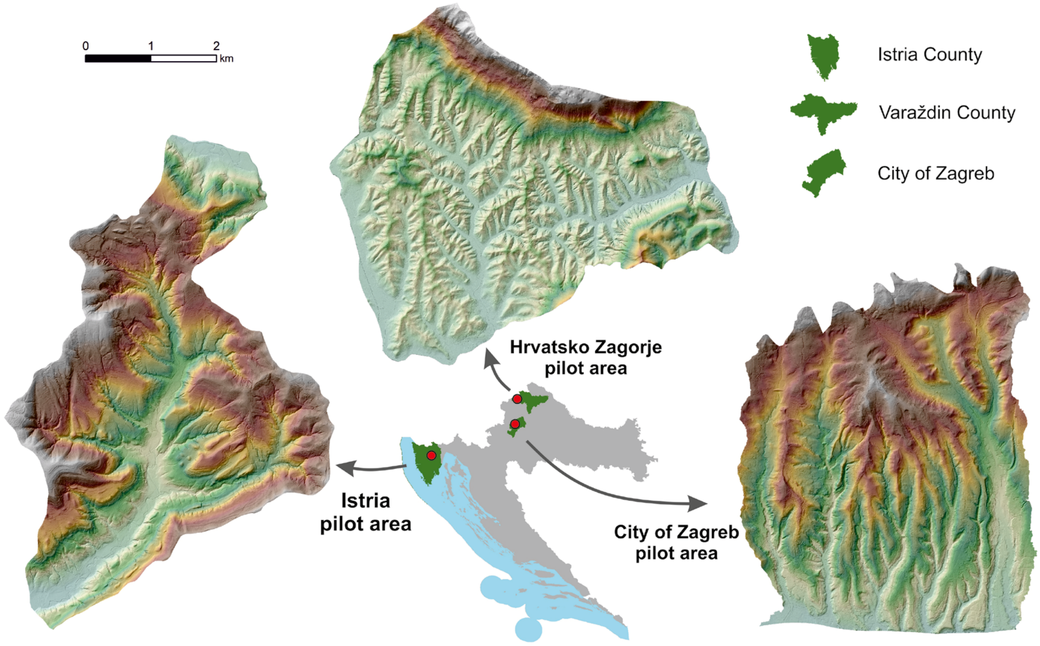


Figure 1 Locations of pilot areas in the scientific research project LandSlidePlan.

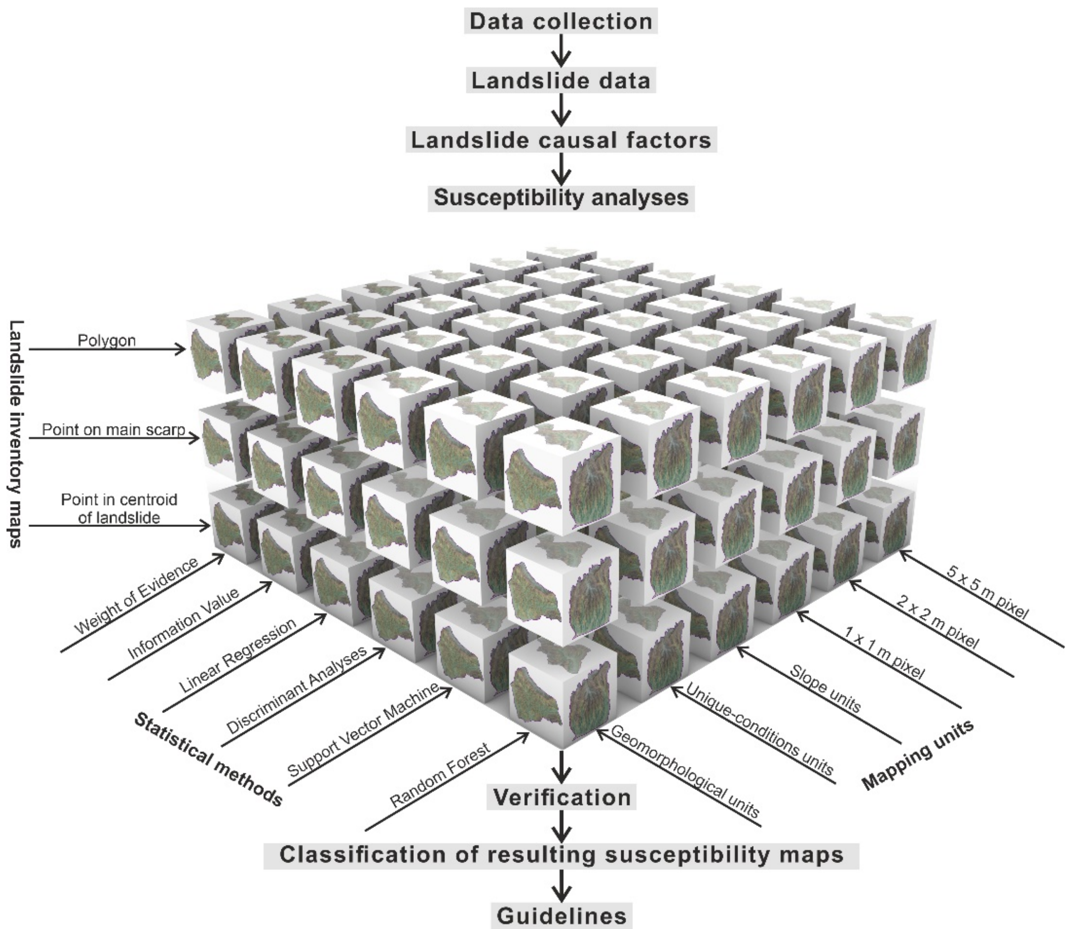


Figure 2 Flow chart of the methodology for landslide susceptibility assessment in the scientific research project LandSlidePlan.

Results of scientific research

Input data preparation: Landslide inventories and causal factor maps

Qualitative and quantitative assessments of input LiDAR data for landslide inventory mapping

Marko Sinčić[(1)], Sanja Bernat Gazibara[(1)], Hrvoje Lukačić[(1)], Martin Krkač[(1)], Snježana Mihalić Arbanas[(1)]

1) University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Zagreb, Pierottijeva 6, Croatia

An innovative technique for detailed landslide inventory mapping is airborne laser scanning and LiDAR-derived DTMs in high resolution. LiDAR data used in this study was obtained in the framework of the "Methodology development for landslide susceptibility assessment for land use planning based on LiDAR technology (LandSlidePlan IP-2019-04-9900)" project fully supported by the Croatian Science Foundation. To select the optimal digital terrain model (DTM) for landslide delineation, quantitative (Table 1) and qualitative (Fig. 1) assessments were done individually for three landslides. The quantitative assessment included a comparison of minimum, maximum, mean, and standard deviation values of DTMs derived by using four interpolation methods (Kriging, IDW, Natural Neighbor, and ANUDEM) in six raster resolutions (0.15, 0.3, 0.5, 1, 2, and 5 m) (Table 1). Furthermore, by comparing point cloud LiDAR data and interpolated DTMs elevation values, the mean-absolute-error difference (MAE) and root-mean-square-error (RMSE) were calculated (Table 1). Hillshade, roughness, and curvature morphometric maps were derived for 24 DTMs per landslide, resulting in the qualitative assessment of 216 different morphometric maps (Fig. 1). The quantitative assessment showed minimum and negligible differences between DTMs for landslide areas; therefore, the qualitative assessment prioritised determining the optimal DTM for deriving morphometric maps needed for landslide delineation. Based on visual interpretability of landslide parts (i.e. crown, ridges, and toe) and the terrain quality (i.e. expressed details, irregularities, and blurriness) on the derived morphometric maps, the LiDAR DTM derived using the Kriging method in 0.3 m resolution was selected for landslide inventory mapping in further studies.

Keywords LiDAR point cloud, digital terrain model, Kriging, IDW, Natural Neighbor, ANUDEM

Published in: Sinčić M, Bernat Gazibara S, Lukačić H, Krkač M, Mihalić Arbanas S (2022) Qualitative and quantitative assessments of input LiDAR data for landslide inventory mapping. In Peranić J, Vivoda Prodan M, Bernat Gazibara S, Krkač M, Mihalić Arbanas S, Arbanas Ž (eds) Book of Abstracts of the 5th ReSyLAB "Landslide Modelling & Applications". University of Rijeka Faculty of Civil Engineering, University of Zagreb Faculty of Mining, Geology and Petroleum Engineering, Rijeka, Zagreb, pp 22-22.

Table 1 Quantitative assessment of three study landslides considering four interpolation methods and six resolutions.

Method & resolution		Landslide one						Landslide two						Landslide three					
		min	max	Mean	st. dev.	MAE	RMSE	min	max	Mean	st. dev.	MAE	RMSE	min	max	Mean	st. dev.	MAE	RMSE
IDW	0.15	257.94	280.45	267.90	5.80	8.14	288.90	275.14	293.22	284.67	4.65	28.20	538.38	257.29	295.57	274.13	11.29	4.76	220.85
	0.30	257.94	280.45	267.90	5.80	16.30	408.70	275.14	293.13	284.67	4.65	39.49	636.97	257.31	295.56	274.13	11.29	20.22	455.68
	0.50	257.98	280.36	267.90	5.80	48.88	708.24	275.23	293.09	284.67	4.65	62.07	798.63	257.27	295.53	274.12	11.29	24.98	506.24
	1	258.03	280.22	267.90	5.80	100.44	1015.08	275.23	293.00	284.67	4.65	135.40	1179.63	257.27	295.47	274.12	11.29	51.15	724.33
	2	258.08	280.16	267.90	5.80	190.02	1396.11	275.31	293.00	284.67	4.66	293.33	1736.39	257.34	295.37	274.13	11.30	117.72	1099.07
	5	258.51	278.82	267.86	5.76	521.15	2312.31	275.51	292.39	284.55	4.73	761.51	2797.82	257.71	295.10	274.07	11.32	305.55	1770.73
Natural Neighbor	0.15	257.92	280.43	267.90	5.80	8.15	288.90	275.14	293.15	284.67	4.66	28.20	538.38	257.30	295.58	274.13	11.29	4.76	220.85
	0.30	257.94	280.42	267.90	5.80	16.30	408.70	275.14	293.13	284.67	4.66	45.13	680.93	257.33	295.56	274.13	11.29	21.42	468.91
	0.50	257.97	280.36	267.90	5.80	51.59	727.60	275.17	293.09	284.67	4.65	78.98	900.94	257.28	295.57	274.13	11.29	24.99	506.24
	1	258.03	280.21	267.90	5.80	100.44	1015.08	275.22	293.00	284.68	4.65	152.29	1251.00	257.28	295.55	274.13	11.29	52.33	732.66
	2	258.05	280.19	267.91	5.80	190.02	1396.11	275.22	293.00	284.69	4.65	304.60	1769.43	257.34	295.41	274.13	11.29	114.15	1082.21
	5	258.49	278.83	267.98	5.72	504.77	2275.40	275.63	292.41	284.74	4.66	761.43	2797.55	257.70	295.10	274.12	11.30	311.48	1787.79
ANUDEM	0.15	258.00	280.29	267.90	5.80	8.16	288.90	275.19	293.14	284.67	4.66	11.30	340.42	257.37	295.55	274.13	11.29	4.77	220.85
	0.30	258.00	280.29	267.90	5.80	16.31	408.70	275.20	293.11	284.67	4.66	39.49	636.97	257.37	295.54	274.13	11.30	20.23	455.68
	0.50	258.02	280.22	267.90	5.80	48.89	708.24	275.23	293.07	284.67	4.66	62.07	798.63	257.46	295.52	274.12	11.29	24.99	506.24
	1	258.10	280.10	267.90	5.79	100.46	1015.08	275.30	292.97	284.67	4.65	135.41	1179.63	257.58	295.45	274.12	11.29	51.16	724.33
	2	258.26	279.89	267.90	5.77	190.05	1396.11	275.41	292.82	284.67	4.64	293.37	1736.39	257.68	295.26	274.12	11.28	117.77	1099.07
	5	258.80	278.65	267.80	5.67	521.21	2312.31	276.12	292.33	284.64	4.60	761.55	2797.82	257.68	294.85	273.98	11.36	305.67	1770.73
Kriging	0.15	257.92	280.44	267.90	5.80	8.15	288.90	275.14	293.22	284.67	4.66	28.20	538.38	257.28	295.58	274.13	11.30	4.76	220.85
	0.30	257.94	280.44	267.90	5.80	16.30	408.70	275.14	293.13	284.67	4.66	39.49	636.97	257.30	295.57	274.13	11.30	20.22	455.68
	0.50	257.97	280.37	267.90	5.80	48.88	708.24	275.19	293.09	284.68	4.66	62.07	798.63	257.28	295.55	274.13	11.30	24.98	506.24
	1	258.03	280.25	267.90	5.80	100.45	1015.08	275.22	293.00	284.67	4.66	135.40	1179.63	257.28	295.54	274.13	11.30	51.14	724.33
	2	258.04	280.20	267.90	5.80	190.02	1396.11	275.23	293.00	284.67	4.67	293.33	1736.39	257.33	295.68	274.13	11.30	117.72	1099.07
	5	258.49	278.83	267.86	5.76	521.15	2312.31	275.51	292.40	284.56	4.74	761.51	2797.82	257.66	295.10	274.07	11.32	305.55	1770.73

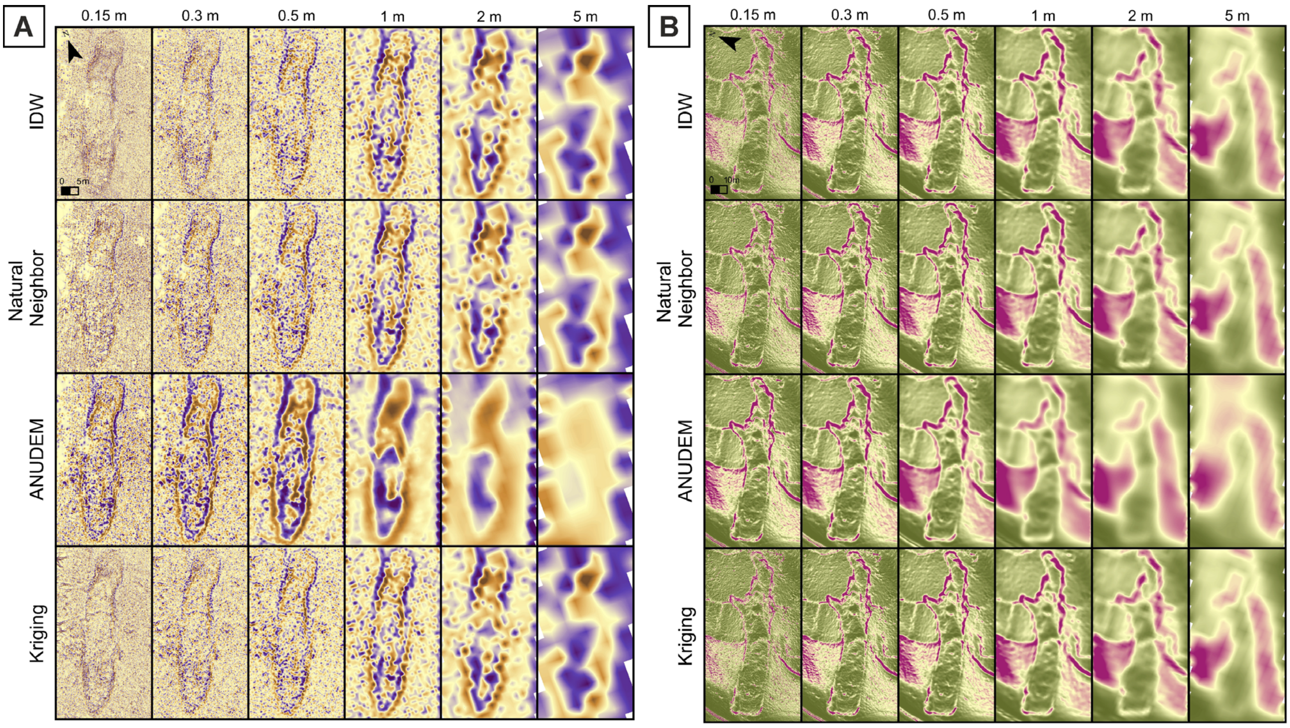


Figure 1 Morphometric maps derived from Digital Terrain Models considering four interpolation methods and six resolutions: (A) Curvature maps, (B) Roughness maps.

Landslide inventory mapping based on LiDAR data: A case study from Hrvatsko Zagorje (Croatia)

Martin Krkač[1], Sanja Bernat Gazibara[1], Marko Sinčić[1], Hrvoje Lukačić[1], Snježana Mihalić Arbanas[1]

1) University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Zagreb, Pierottijeva 6, Croatia

The paper presents a result of landslide inventory mapping at the Bednja Municipality and Lepoglava City study area, located in Hrvatsko Zagorje region, NW Croatia. The landslides were interpreted and manually mapped from the high-resolution digital elevation model (DEM) and its derivatives (Fig. 1). The DEM was interpolated from the point cloud obtained by airborne laser scanning undertaken in spring 2020, which corresponds to the winter leaf-off period in Croatia. The scanning covered approximately 20 km^2 of a hilly area, with bedrock geology of predominantly Miocene sediments composed of sandstones, marls and limestones. The total number of points in the LiDAR point cloud was approximately 6.2×10^8. Of all data points, 52.2% were classified as ground (bare earth) points. The average spacing of the ground points was 0.28 m, from which the bare-earth DEM with a 0.3 m resolution was created. After the field checking, the total number of interpreted landslides was 912, making the average density of 45.1 ls/km^2. The average size of mapped landslides is 448 m^2. The largest mapped landslide is 13,778 m^2, and the smallest mapped landslide is 3.3 m^2. The frequency–size distribution of all mapped landslides in the pilot area showed two scaling regimes: a positive power-law scaling for small landslides and a negative power-law scaling for medium and large landslides. Based on the rollover at approximately 200 m^2, 48% of the mapped landslides are small (<200 m^2) and 52% are medium and large (>200 m^2) in size. The small size of the landslides is probably the result of geological conditions (mainly Miocene marls covered with residual soils) and geomorphological conditions, where the differences between the valley bottoms and the top of the hills are rarely higher than 100 meters. The prevailing dominant types of landslides are shallow soil slides.

The land use, obtained from the official spatial plans of the Municipality of Bednja (2019) and the City of Lepoglava (2017), shows that most of the studied area (52%) is covered by forests, 40% of the area is agricultural land and approx. 8% is an urban and partly constructed area. The analysis showed that the highest density of landslides (63.5 ls/km^2) is in the forest areas, while the lowest density of landslides is in the urban areas (14.7 ls/km^2). The density of landsides in agricultural areas and pastures is 26.7 ls/km^2. Furthermore, analysis shows that 60.5% of landslides are located within 50 m of the roads and approximately 34% within 100 m of buildings, transportation facilities and residential houses. The spatial distribution of the elements at risk and the landside inventory are presented in Fig. 2. One of the possible explanations for such a spatial distribution of landslides is that LiDAR-based landslide inventories can often be incomplete on settlements and arable lands due to frequent anthropogenic influences. Another probable reason is that the higher landslide density in forests is associated with prevailing steep slopes and forest gullies (the average slope angle of the forest class in the study area is 25°). Because of various possible applications, the presented landslide inventory map is intended for numerous users from spatial and urban planning, construction, and civil protection. In addition, the inventory map also provides valuable and necessary data for preparing a landslide susceptibility map on a detailed scale for local application, another essential tool for spatial development and land-use planning.

Keywords landslide inventory, LiDAR, high-resolution DEM, land use

Published in: Krkač M, Bernat Gazibara S, Sinčić M, Lukačić H, Mihalić Arbanas S (2022) Landslide Inventory Mapping Based on LiDAR Data: A Case Study from Hrvatsko Zagorje (Croatia). In Peranić J, Vivoda Prodan M, Bernat Gazibara S, Krkač M, Mihalić Arbanas S, Arbanas Ž (eds) Proceedings of the 5th ReSyLAB "Landslide Modelling & Applications". University of Rijeka Faculty of Civil Engineering, University of Zagreb Faculty of Mining, Geology and Petroleum Engineering, Rijeka, Zagreb, pp 81–86.

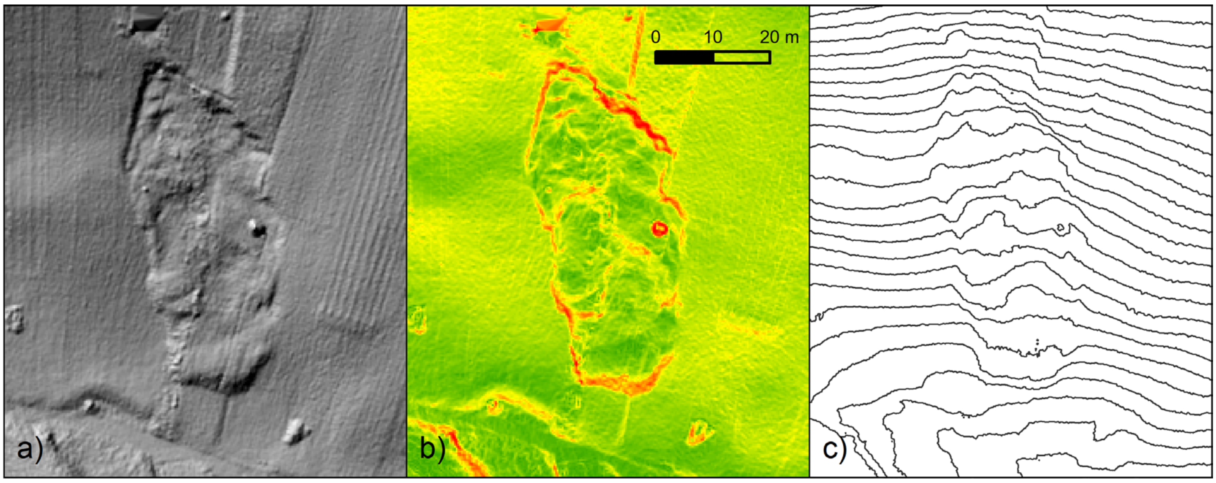


Figure 1 Landslide identified on the three different topographic derivative DTM maps: (a) hillshade map; (b) slope map; and (c) contour map (0.5 m spacing).

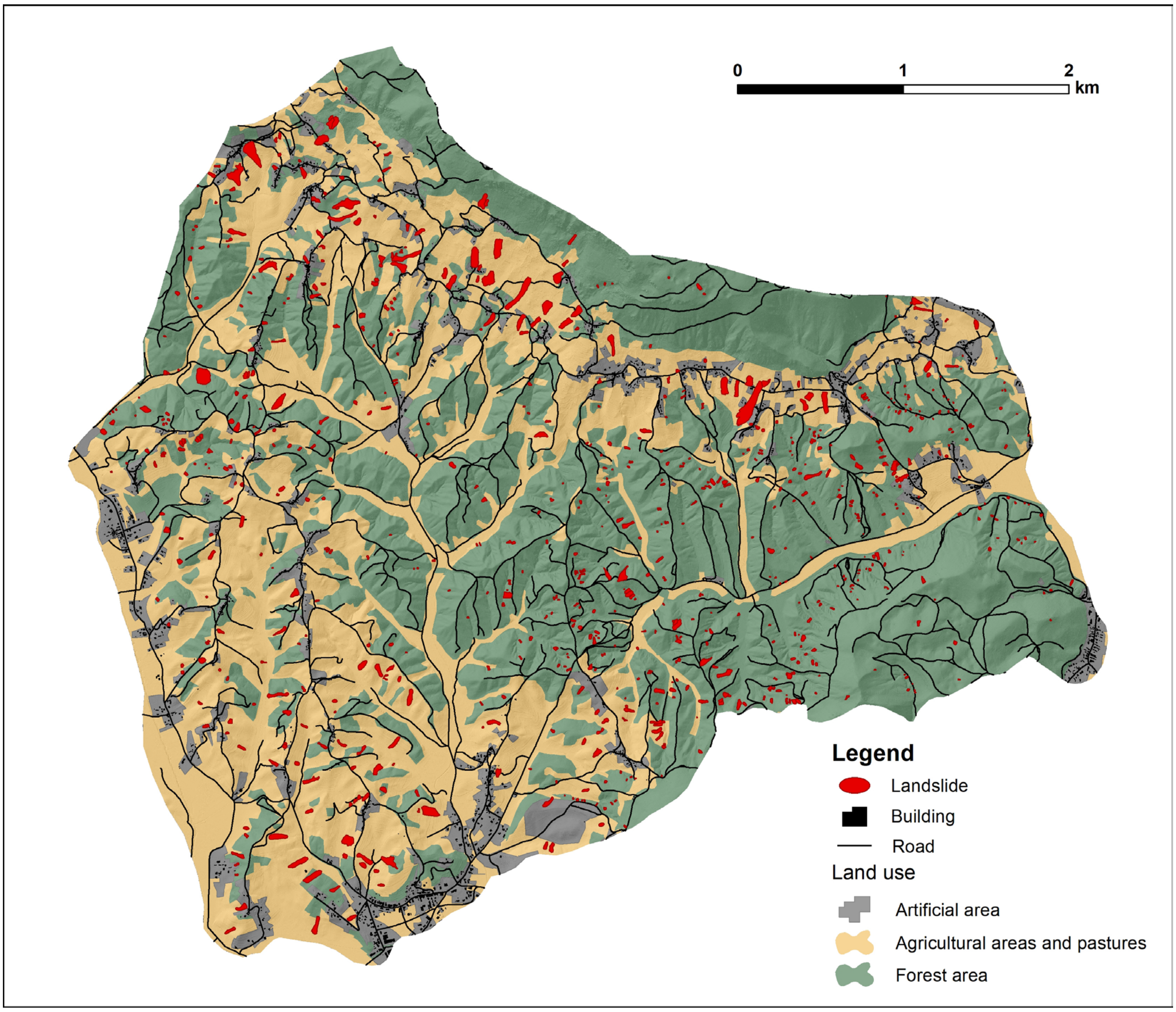


Figure 2 Spatial distribution of the anthropogenic landslide causal factors in the study area and landside inventory mapped on the LiDAR DEM.

Geomorphological characteristics of landslides in Hrvatsko Zagorje (NW Croatia)

Martin Krkač(1), Sanja Bernat Gazibara(1), Marko Sinčić(1), Hrvoje Lukačić(1), Snježana Mihalić Arbanas(1)

1) University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Zagreb, Pierottijeva 6, Croatia

A landslide inventory presents a detailed register of the distribution and characteristics of past landslides in a specific area. Landslide inventory maps and other maps such as landslide susceptibility, hazard and risk maps are essential in landslide risk management, supporting authorities, practitioners and decision-makers in developing more appropriate and sustainable land planning and risk mitigation strategies. In recent years, Light Detection and Ranging (LiDAR) data have been commonly used to map landslide morphology and estimate landslide activity. LiDAR is a consolidated remote sensing technique used to obtain digital representations of the topographic surface for areas ranging from a few hectares to thousands of square kilometers. From elevation point clouds obtained by laser scanning, a detailed digital elevation model (DEM) and different DEM derivatives, such as slope, hillshade or contour maps, can be produced. This study presents and analyses a historical landslide inventory map of the Hrvatsko Zagorje area (NW Croatia), interpreted from LiDAR high-resolution DEM (HRDEM) derivates, regarding geomorphological characteristics. The study area comprises 20.22 km^2 of the hilly terrain (88% of the area has slope angles >5°), mostly covered by forests (52%). The area is composed of Triassic carbonate rocks, Miocene clastic sedimentary rocks and soils and Quaternary alluvial soils. LiDAR data for the study area was acquired in the project „Methodology development for landslide susceptibility assessment for land-use planning based on LiDAR technology (LandSlidePlan), "financed by the Croatian Science Foundation.

The topographic derivative datasets used to interpret the landslide morphology were hillshade maps, slope maps and contour lines. Landslide identification on the LiDAR HRDEM derivatives (0.3 m resolution) was manual and GIS-assisted, based on recognizing landslide features (e.g., concave main scarps, hummocky landslide bodies, and convex landslide toes). The mapping was performed at a large scale (1:100–1:500) to ensure the correct delineation of the landslide boundaries. Totally 912 landslides were mapped. The total area of mapped landslides is 0.408 km^2 or 2.02% of the study area, and the mean landslide density is 45.1 slope failures per square kilometer. The average landslide area is 448 m^2 (median = 173 m^2). The small size of the landslides is probably the result of geological conditions (mainly Miocene marls covered with residual soils) and geomorphological conditions, where the differences between the valley bottoms and the top of the hills are rarely higher than 100 meters. Geomorphological characteristics of mapped landslides were compared with characteristics of the stable terrain using different DEM derivatives. According to the analyses, slope, roughness, and curvature values are distributed differently in landslides and stable terrain. Fig. 1 presents the difference of the slope map LiDAR derivatives in different resolutions, and Fig. 2 illustrates the difference of slope distributions within the terrain and in various types of landslides. Knowledge of the difference between the geomorphological characteristics of landslides and stable terrain provides valuable information for the automated mapping of landslides and potently unstable slopes.

Keywords landslide inventory, LiDAR, topographic derivative datasets, landslide morphology

Published in: Krkač M, Bernat Gazibara S, Sinčić M, Lukačić H, Mihalić Arbanas S (2022) Geomorphological characteristics of landslides in Hrvatsko Zagorje (NW Croatia). 10th International Conference on Geomorphology, Coimbra, Portugal. ICG2022-410. https://doi.org/10.5194/icg2022-410, 2022

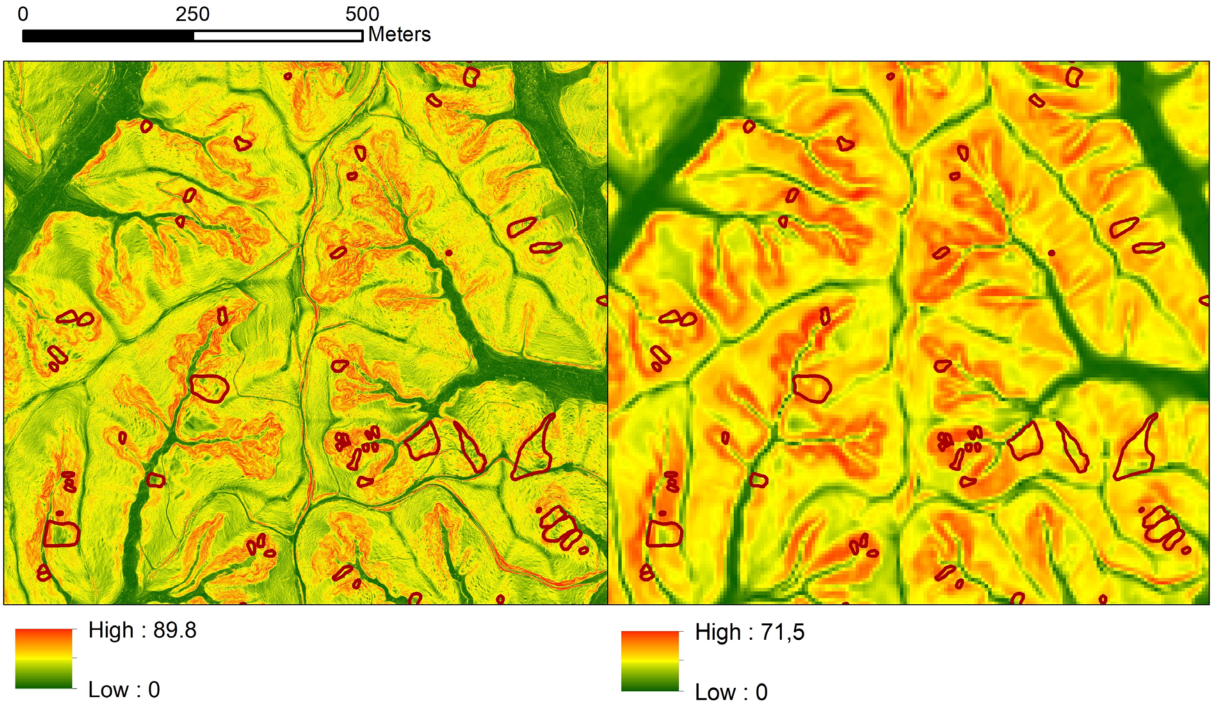


Figure 1 Difference between slope map LiDAR derivatives of 0.3 m (left) and 5 m (right) resolution.

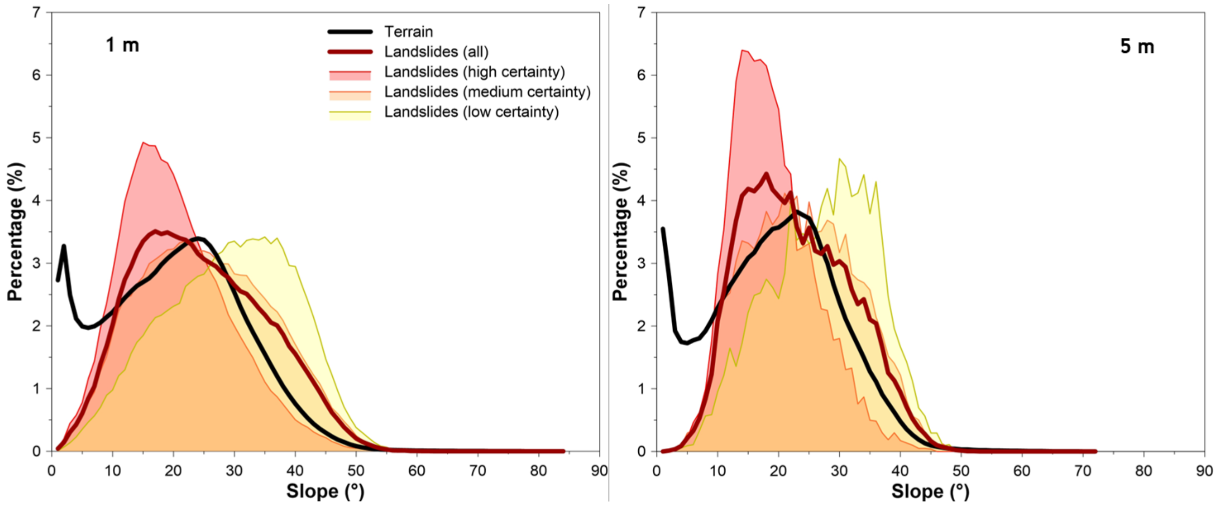


Figure 2 The difference of slope distributions within the terrain and different types of landslides for two slope maps of different resolutions.

Landslide and soil erosion inventory mapping based on high-resolution remote sensing data: A case study from Istria (Croatia)

Sanja Bernat Gazibara[1], Petra Jagodnik[2], Hrvoje Lukačić[1], Marko Sinčić[1], Martin Krkač[1], Gabrijela Šarić[1], Željko Arbanas[2], Snježana Mihalić Arbanas[1]

1) University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Zagreb, Pierottijeva 6, Croatia
2) University of Rijeka, Faculty of Civil Engineering, Rijeka, Radmile Matječić 3, Croatia

Inventory mapping of slope processes presents essential input parameters for multiple spatial analyses such as landslide or erosion susceptibility, hazard, and risk assessment, especially in the case of large-scale hazard zoning. However, the traditional landslide and erosional inventory mapping methods include field mapping and interpretation of aerial photos and satellite images, which produces a limited amount of data in case of an inaccessible and overgrown area. Therefore, the LiDAR data is the only appropriate remote sensing tool for landslide and soil erosion mapping in a forest or densely vegetated areas.

The central part of the Istrian Peninsula (Croatia) is the area of the Eocene flysch basin, i.e. "Gray Istria", which is prone to weathering and active geomorphological processes. The high erodibility of the Istrian marls led to the formation of steep barren slopes and badlands exceptionally susceptible to slope movements. There was a lack of detailed inventory maps because systematic mapping was not performed for any part of Istria until the scientific research project LandSlidePlan (HRZZ IP-2019-04-9900), funded by the Croatian Science Foundation. This research presents the application of high-resolution remote sensing data, i.e., Light Detection and Ranging (LiDAR) data and orthophoto images, for landform mapping at a large scale (1:500). Visual interpretation of remote sensing data (Fig. 1) was done for the pilot area (20 km^2) near City of Buzet to produce detailed inventory maps for implementation in the spatial planning system. For the purpose of landslide and soil erosion inventory mapping morphometric derivative maps were derived from a 30 cm resolution digital terrain model (DTM). A total of four types of morphometric derivatives were used; (i) hillshade map, (ii) slope map, (iii) roughness map, and (iv) stream power index map (SPI).

After preliminary visual interpretation of LiDAR DTM and field verifications, it was concluded that four types of landforms could be mapped, i.e. badlands, gully and combined erosion, unstable slopes and landslides. The proposed methodology for accurately identifying and detailed inventory mapping of badlands, gully and combined erosion, unstable slopes and landslides on a large scale presented in this paper can be used as guidance in future studies in areas with similar geological settings and degree of urbanisation. By analysing inventory completeness and size of mapped landforms, we can estimate the quality of LiDAR-derived inventory maps. Therefore, the LiDAR-base landslide and erosion inventory maps prepared using the proposed mapping procedure are usually considered sustainably complete for future applications, such as landslide and erosion susceptibility assessment or estimating temporal changes in gully erosion. Derived inventory maps can be used to manage landslide and soil erosion hazards in populated areas by restricting development in badland areas or enforcing codes for excavation and construction in areas endangered by registered landslides or gully and combined erosion processes (Fig. 2).

Keywords landslides, soil erosion, inventory mapping, LiDAR

Published in: Bernat Gazibara S, Jagodnik P, Lukačić H, Sinčić M, Krkač M, Šarić G, Arbanas Ž, Mihalić Arbanas S (2023) Landslide and soil erosion inventory mapping based on high-resolution remote sensing data: A case study from Istria (Croatia). In Alcántara-Ayala I, Arbanas Ž, Cuomo S, Huntley D, Konagai K, Mihalić Arbanas S (eds) Progress in Landslide Research and Technology, Volume 2 Issue 1. Springer, Cham, pp 363-375. https://doi.org/10.1007/978-3-031-39012-8_18

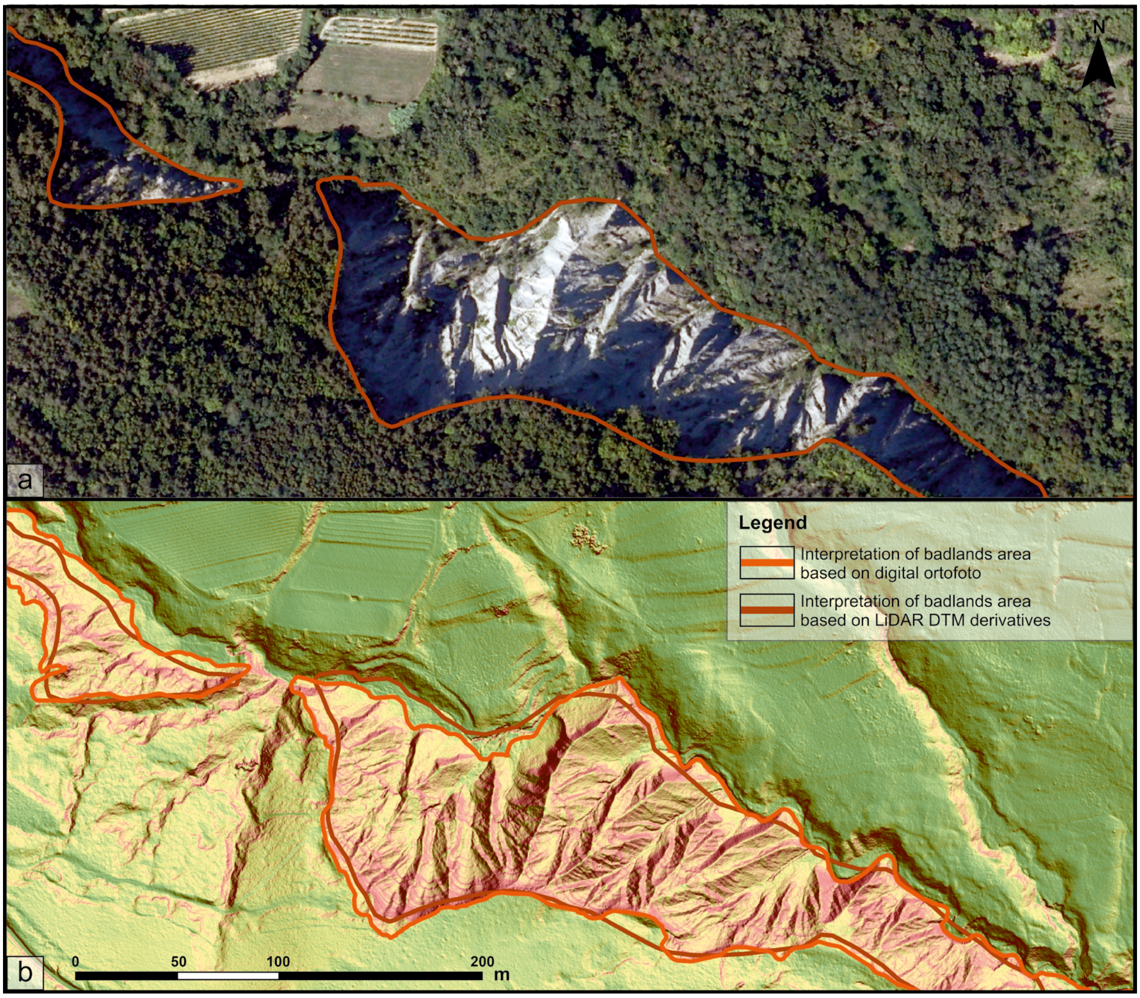


Figure 1 Badland inventory mapping: (a) interpretation based on digital orthophoto map; (b) interpretation based on LiDAR DTM derivatives.

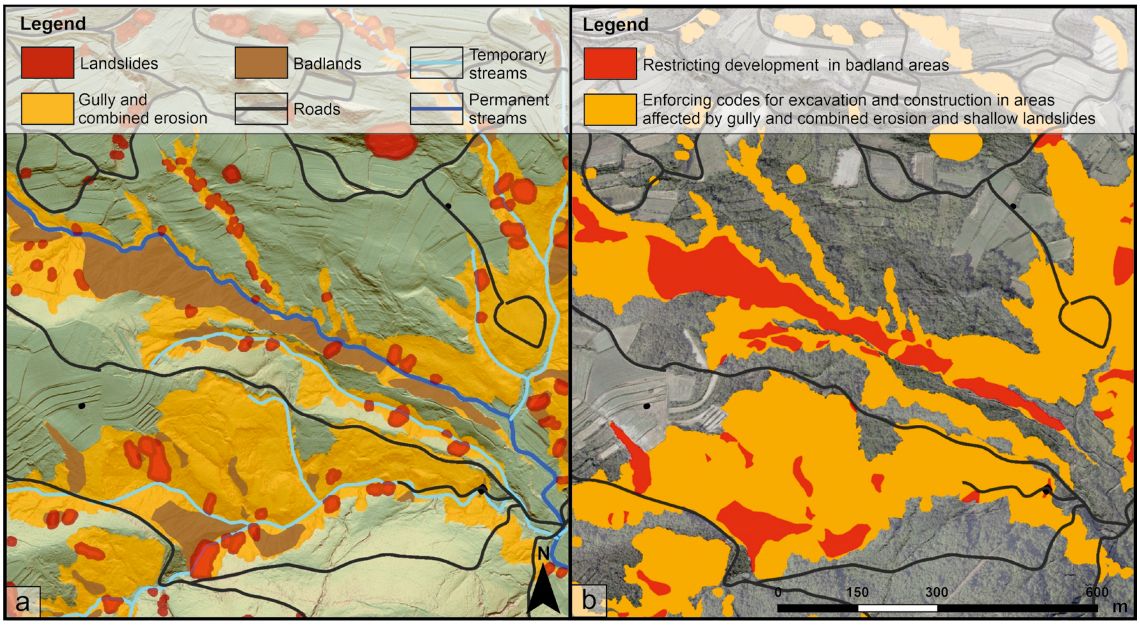


Figure 2 Application of landslide and soil erosion inventory maps in the spatial planning system: (a) close-up extent of final inventory map; (b) derived map with defined spatial plan measures.

Influence of expert knowledge on completeness and accuracy of landslide inventory maps – Example from Istria, Croatia

Hrvoje Lukačić[1], Sanja Bernat Gazibara[1], Marko Sinčić[1], Martin Krkač[1], Željko Arbanas[2], Petra Jagodnik[2], Vedran Damjanović[1], Snježana Mihalić Arbanas[1]

1) University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Zagreb, Pierottijeva 6, Croatia
2) University of Rijeka, Faculty of Civil Engineering, Rijeka, Radmile Matječić 3, Croatia

This paper presents the application of Light Detection and Ranging (LiDAR) data for landslide identification and mapping in the pilot area at the Istria Penninsula (Croatia) and the analyses of the influence of expert knowledge on the quality of landslide inventory. Visual interpretation of landslides was carried out on high-resolution airborne laser scanning (ALS) LiDAR dataset. Remote sensing methods, such as airborne LiDAR, are used for highly accurate and precise visual landslide interpretation, resulting in substantially complete and representative inventory maps. However, to use high-resolution LiDAR Point Cloud for such purposes, it is mandatory to automatically filter vegetation and all other above-earth surface objects, resulting in a bare-earth DEM. LiDAR data for the study area were acquired in the framework of the project "Methodology development for landslide susceptibility assessment for land-use planning based on LiDAR technology (LandSlidePlan IP-2019-04-9900) funded by the Croatian Science Foundation". Scanning was taken in March 2020.

Based on the characteristics of the acquired LiDAR Point Cloud, a bare-earth digital elevation model (DEM) with 30 cm resolution was created. Different topographic derivative datasets such as slope, hillshade, contour lines, and roughness maps were created to interpret the LiDAR data. Eight experts with different levels of expert knowledge on LiDAR interpretation were given one week to carry out visual identification and mapping of potential landslides in the test area (0.3 km^2) at a large scale (1:200) to provide detailed landslide mapping. Seven experts independently mapped the landslides in the test area, while Expert 8 represents the joint mapping procedure of Experts 5 and Expert 6 mentored by an Expert with high LiDAR mapping experience in a similar geomorphological environment. Both experience in landslide identification on the topographic derivative maps and research knowledge of the study area were expressed as 'high', 'medium', 'low', and 'no experience' for each Expert (Table 1). Landslides identified by experts at the LiDAR dataset were checked during the field survey in January 2022. Boundaries of the checked landslides were eventually modified in the field based on landslide morphology, so the resulting landslide inventory consisted of correctly identified and mapped landslides (Fig. 1).

Statistical analyses were performed based on the collected data to determine differences in the mapping accuracy and the number of recognized landslides by the experts. The initial landslide inventory map produced by seven experts consists of 178 landslides making up the total landslide area of 0.037 km^2. In addition, the field verification was conducted on 93 landslides or 51.2 % of the total number of landslides in the inventory. Based on the total number of verified landslides, 37.6 % were confirmed, 10.8% of landslides were confirmed with modification of landslide boundaries, 33,3 % of landslides were abolished since a landslide location was inside multi-hazard areas, and 18.3 % of landslides remained unconfirmed.

The analysis of landslides mapped by seven experts showed that the experience and knowledge about a research area play a crucial role in landslide recognition in complex geological conditions such as flysch formation in the City of Buzet wider area. Furthermore, the obtained results for Expert 8, which represents the joint mapping procedure of three Experts, show that the same pilot area needs to be mapped multiple times to accomplish a high-accuracy landslide inventory map.

Keywords landslides, inventory mapping, remote sensing, LiDAR

Published in: Lukačić H, Bernat Gazibara S, Sinčić M, Krkač M, Arbanas Ž, Jagodnik P, Damjanović V, Mihalić Arbanas S (2022) Influence of expert knowledge on completeness and accuracy of landslide inventory maps – Example from Istria, Croatia. In Peranić J, Vivoda Prodan M, Bernat Gazibara S, Krkač M, Mihalić Arbanas S, Arbanas Ž (eds) Proceedings of the 5th ReSyLAB "Landslide Modelling & Applications". University of Rijeka Faculty of Civil Engineering, University of Zagreb Faculty of Mining, Geology and Petroleum Engineering, Rijeka, Zagreb, pp 87–92.

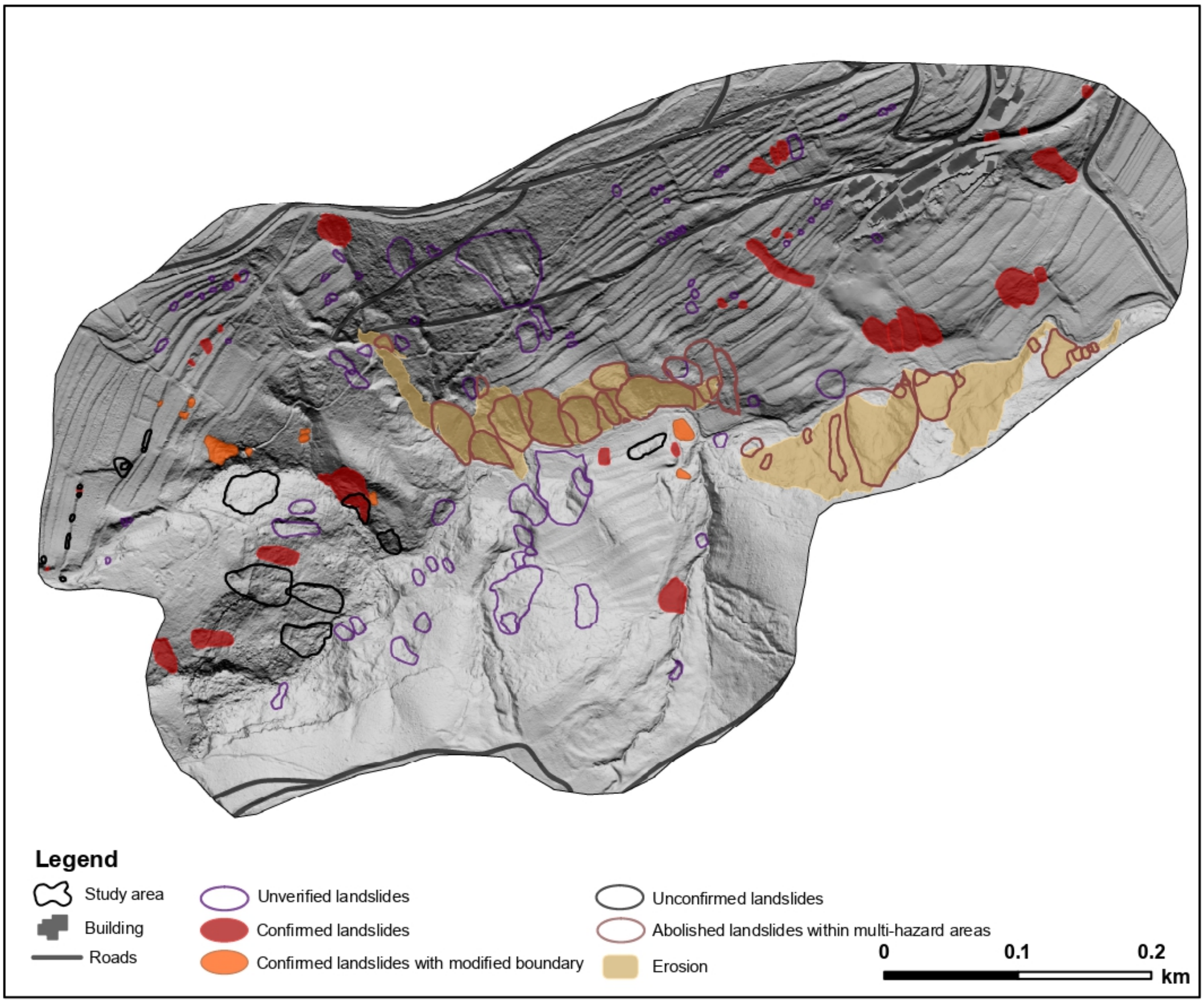


Figure 1 Landslide inventory map produced by the experts with indicated confirmed landslides and erosion.

Table 1 Landslide mapping results based on expert knowledge on LiDAR mapping and research knowledge of the study area.

Expert no.	LiDAR mapping experience	Researcher knowledge on study area	Number of mapped landslides	Number of verified landslides	Correctly mapped landslide area (m2)	Percentage of correctly mapped landslide area (%)
Expert 1	Low	High	16	13	1822.79	25.47
Expert 2	Medium	Medium	76	38	2962.98	41.40
Expert 3	High	Medium	44	29	2858.13	39.94
Expert 4	High	Medium	21	18	2079.00	29.05
Expert 5	Low	Low	49	36	3518.37	49.16
Expert 6	Low	Low	26	20	2348.19	32.81
Expert 7	No experience	Low	7	7	1457.46	20.37
Expert 8	Medium	High	109	49	5012.19	70.04

Landslides, gully erosion and badlands as associated geological hazards in flysch environment – Analysis of geomorphological inventories and LiDAR DTM at a large scale

Petra Jagodnik[1], Sanja Bernat Gazibara[2], Marko Sinčić[2], Hrvoje Lukačić[2], Gabrijela Šarić[2], Martin Krkač[2], Željko Arbanas[1], Snježana Mihalić Arbanas[2]

1) University of Rijeka, Faculty of Civil Engineering, Rijeka, Radmile Matječić 3, Croatia
2) University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Zagreb, Pierottijeva 6, Croatia

Central part of Istrian Peninsula (Croatia) is composed of Eocene flysch sediments, with predominantly marls and sandstones in alternation. The study area (19.96 km^2) comprises the part of the City of Buzet, where weathering processes and high erodibility of mechanically weak bedrock led to the formation of erosional features and numerous landslides. Despite to their significant impact on the environment and elements at risk, detailed mapping, and study of the relationship between the soil erosion and sliding processes have never been performed before. Acquisition of the high-resolution remote sensing data that effectively enable such research is performed in the frame of the scientific research project "Methodology development for landslide susceptibility assessment for land-use planning based on LiDAR technology" (LandSlidePlan, HRZZ IP-2019-04-9900), funded by the Croatian Science Foundation. The 0.3 m airborne LiDAR (Light Detection and Ranging) digital terrain model (DTM) was used to identify and map landslides, gullies, and badlands at a large scale.

The purposes of this research are: (i) to create the first detailed geomorphological inventories of landslides, gullies, and badlands in flysch deposits of Central Istria by using high-resolution airborne LiDAR data; (ii) to determine typical geomorphological settings of landslides; and (iii) to qualitatively determine the spatial relationship between the landslide and soil erosion phenomena, i.e., gullies, and badlands at the selected representative portions of the study area.

Airborne laser scanning was performed in March 2020, with an average point density of 16 pt/m^2. Topographic datasets were derived from the 0.3 m bare-earth LiDAR DTM and visually interpreted: (i) hillshade map; (ii) slope map; (iii) contour map; (iv) topographic roughness map; and (v) stream power index map. Visual identification and mapping of landslides, gullies, and badlands were performed at a large scale (> 1:500). Badlands were first identified on orthophoto images at 0.5 m resolution, and subsequently mapped on LiDAR datasets. In this study, three detailed geomorphological inventory maps are created (Fig. 1): (i) the landslide inventory map, comprising 1 164 landslides; (ii) the gully inventory map, comprising 337 gullies; and (iii) the badland inventory map, comprising > 200 badlands. Predominant landslide types are slides, and slide-flows. Landslides are mostly shallow, and very small to small. They generally occur in three typical environments (Fig. 2): (i) within complex gullies (approx. 65 % of landslides), (ii) along agricultural terraces, (iii) and on artificial slopes along the roads. On the other hand, landslide phenomena within badlands are sporadical.

In this study, first geomorphological landslide and soil erosion inventory maps in flysch environment of Central Istria are produced at a large scale by using high-resolution LiDAR datasets. Strong relationship between gully erosion and sliding processes determine the geomorphological settings, types, and geometry of most of the landslides. It is considered that the inventories can significantly contribute to the sustainable land management in the study area, and also for estimating temporal changes in gully erosion. Moreover, in the future research, the results will be used to test the relevance of gullies and badlands as landslide conditioning factors in landslide susceptibility modelling at a large scale.

Keywords LiDAR-based geomorphological inventory, landslides, erosion, associated geological hazards, central Istria

Published in: Jagodnik P, Bernat Gazibara S, Sinčić M, Lukačić H, Šarić G, Krkač M, Arbanas Ž, Mihalić Arbanas S (2023) Landslides, gully erosion and badlands as associated geological hazards in flysch environment – analysis of geomorphological inventories and LiDAR DTM at a large scale. In Tofani V, Casagli N (eds) Abstract book of the 6th World Landslide Forum „Landslide science for sustainable development". OIC S.r.l., Firenze, pp 110-110.

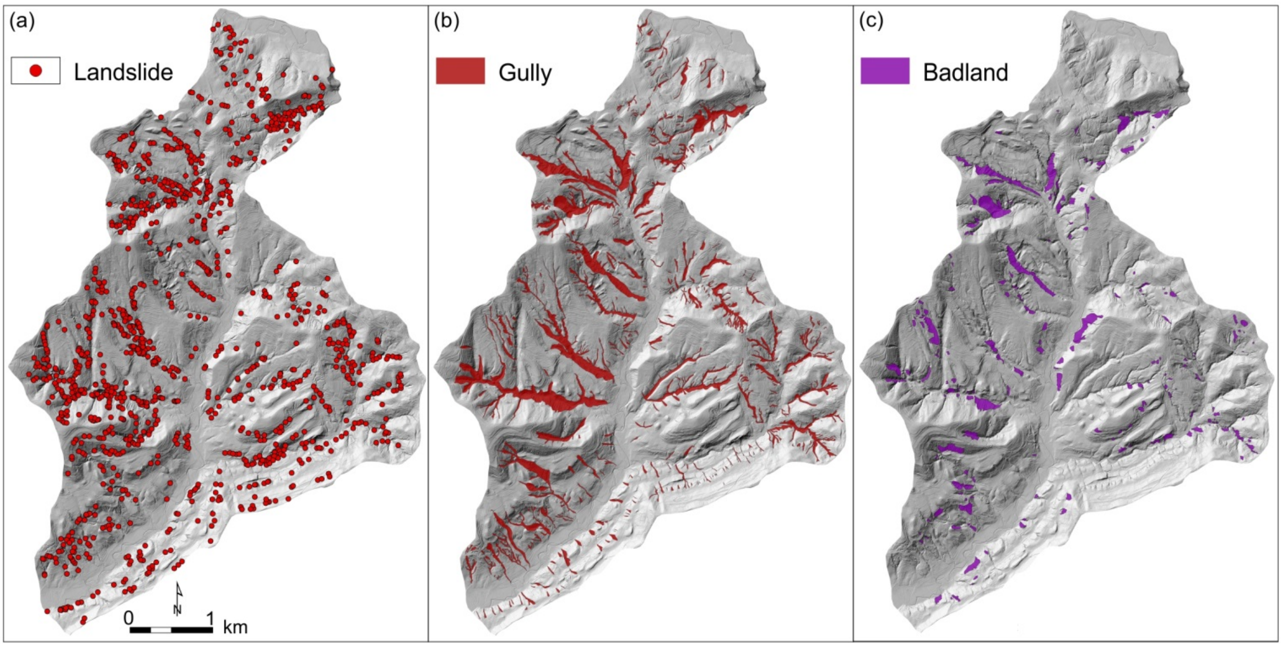


Figure 1 First detailed geomorphological inventories produced for a pilot area in flysch environment in central Istria in Croatia, i.e., city of Buzet, using the innovative airborne LiDAR technology: (a) landslide inventory map; (b) gully inventory map; and (c) badland inventory map. The inventories are prepared based on the expert-knowledge by the visual interpretation of LiDAR DTM topographic derivatives at a large scale.

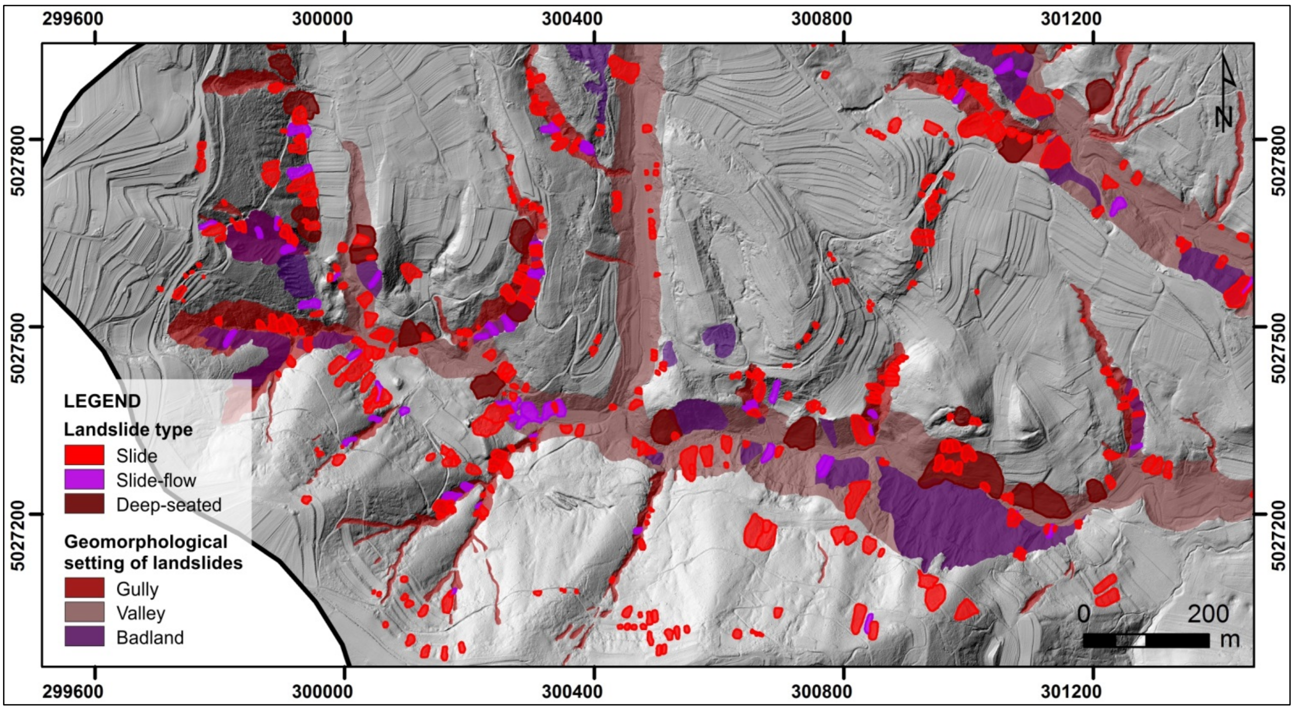


Figure 2 Detail from the geomorphological landslide inventory map in the flysch environment of the City of Buzet, showing the landslide types and their spatial distribution within characteristic geomorphological settings of landslides in the pilot area.

Geomorphological settings and types of landslides in the City of Buzet identified using LiDAR digital terrain model

Petra Jagodnik[(1)], Sanja Bernat Gazibara[(2)], Marko Sinčić[(2)], Hrvoje Lukačić[(2)], Željko Arbanas[(1)], Snježana Mihalić Arbanas[(2)]

1) University of Rijeka, Faculty of Civil Engineering, Rijeka, Radmile Matječić 3, Croatia
2) University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Zagreb, Pierottijeva 6, Croatia

This study presents the results of landslide detection and mapping at a large scale, performed in the area of the city of Buzet in central Istria. The research was conducted within the frame of scientific research project *"Methodology development for landslide susceptibility assessment for land-use planning based on LiDAR technology"* (LandSlidePlan, HRZZ IP-2019-04-9900). The study area (20 km^2) consists of Eocene flysch sediments, composed of a rhythmical alternation of marl and carbonate sediments in the lower part of the complex, and thinly bedded carbonate-siliciclastic turbidite sediments in the upper part.

For the first time, the detailed geomorphological landslide inventory map is created for the area in the flysch environment in central Istria, using innovative remote sensing technology that proved to be effective in mapping landslides. Identification and mapping of landslides was carried out based on the visual interpretation of topographic datasets derived from the bare-earth LiDAR (Light Detection and Ranging) Digital Terrain Model (DTM) at a 0.3 m spatial resolution. Airborne laser scanning was performed in March 2020, with an average point density of 16 points per m^2.

In the study area, more than 1,160 landslides are identified, with high geographical accuracy and thematic certainty due to the clear visibility of landslide features on LiDAR DTM derivatives. However, it was quite a challenge to identify and map individual landslides in areas of gully erosion and badlands, which represent the typical geomorphological phenomena in the flysch environment of central Istria. Landslide density is 58 landslides per km^2. Most of the landslides are debris slides, and debris slide-debris flows, which are the main types of landslides in flysch deposits. Landslides are predominantly small and shallow. Their sizes are in the range between only 4 m^2 to 8 ha.

Generally, there are three typical geomorphological settings of landslides in the study area (Fig. 1): (*i*) complex gullies; (*ii*) agricultural fields; and (*iii*) artificial slopes along the roads. Gullies are the predominant environment for the occurrence of landslides, with approximately 65% of identified landslides being situated in gullies. Such specific geomorphological setting of landslide phenomena confirmed that there is a significant interplay between mass movements and fluvial processes in the investigated area. Therefore, in the future research, the results of this study will be used for testing the relevance of gully and badland phenomena as conditioning factors in landslide susceptibility modelling at a large scale.

Keywords visual interpretation of LiDAR DTM, landslide inventory map, geomorphological settings of landslides, landslides in gullies, Buzet

Published in: Jagodnik P, Bernat Gazibara S, Sinčić M, Lukačić H, Arbanas Ž, Mihalić Arbanas S (2023) Geomorphological settings and types of landslides in the City of Buzet identified using LiDAR digital terrain model. In Fio Firi K (ed) Book of Abstracts of the 7th Croatian Geological Congress with international participation. Croatian Geological Survey, Zagreb, pp 79-79.

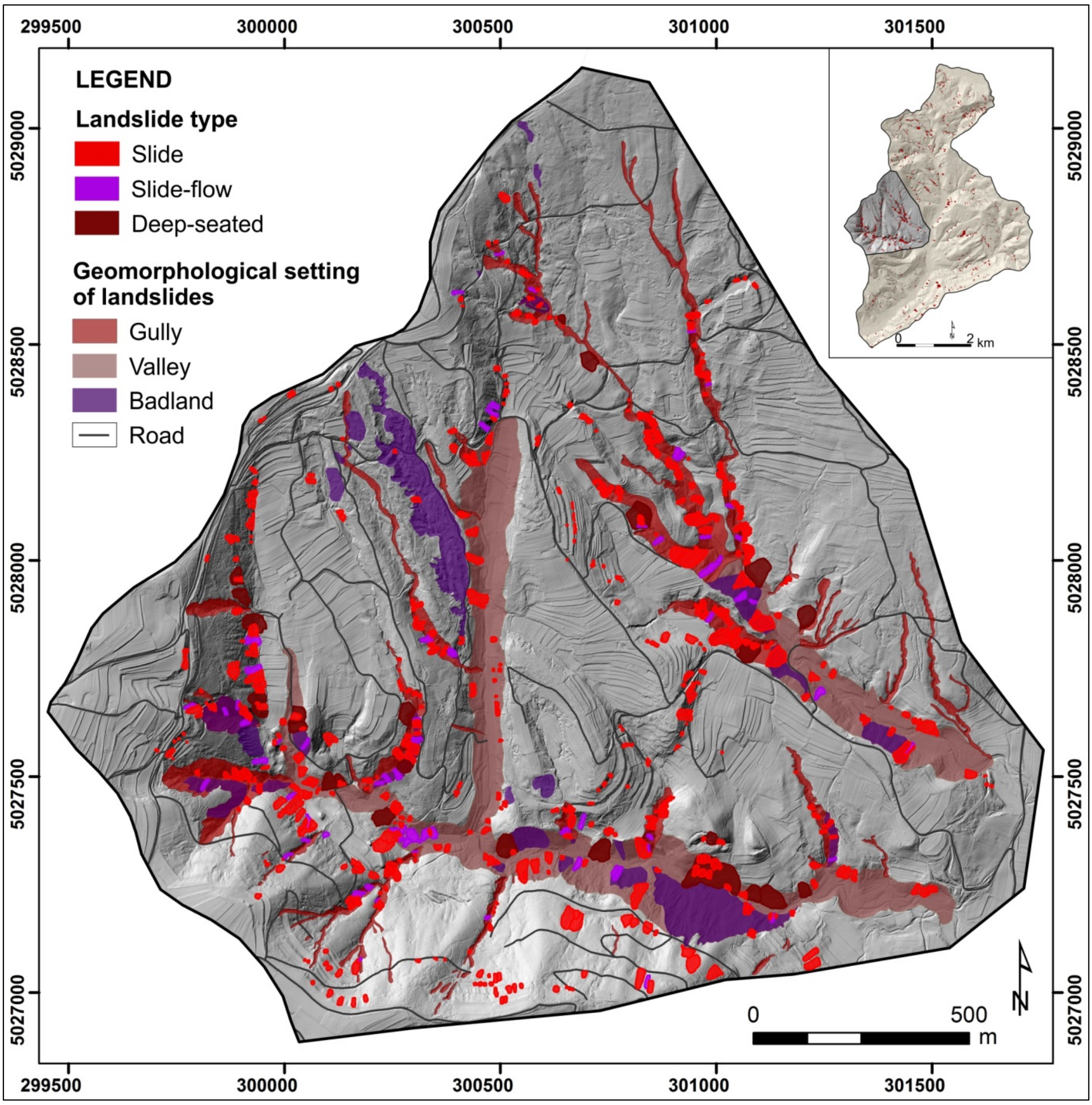


Figure 1 Landslide types and typical geomorphological settings of landslides identified in the city of Buzet in central Istria, presented on the hillshade map for the representative mapping segment (area 3 km²) in the western part of the study area.

Interpretation challenges when detecting landslides in flysch environment: Examples from visual analysis of LiDAR DTM in the City of Buzet

Petra Jagodnik[1], Sanja Bernat Gazibara[2], Federica Fiorucci[3], Michele Santangelo[3]

1) University of Rijeka, Faculty of Civil Engineering, Rijeka, Radmile Matječić 3, Croatia
2) University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Zagreb, Pierottijeva 6, Croatia
3) Research Institute for Geo-Hydrological Protection, Perugia, Via Madonna Alta 126, Italy

Landslide inventory maps document the extent of landslides in a territory, providing information about the spatial distribution, types, pattern, recurrence and statistics of landslides. In recent studies, inventory maps are commonly prepared by visual interpretation of innovative remote sensing imagery, e.g., LiDAR (Light Detection and Ranging) topographic datasets, by detecting the geomorphic expression of landslide features. Given that landslide inventories are essential input parameters for a variety of subsequent analyses in landslide research, the accuracy of the final inventory map is an important issue. While the geographic accuracy mainly depends on the type and resolution of the interpreted imagery, thematic accuracy may strongly depend on the interpreter's skills at identification and classification of slope failures. However, distinguishing landslides from other specific topographic forms in areas characterized by complex geological settings and multi-hazard processes may become challenging even for highly experienced interpreters. In such environments, errors in landslide mapping can result either from geomorphologic convergence between landslides and other morphological processes, or if landslide features have been strongly modified or even removed by other processes. In this study, we present several case studies of the visual interpretation of 0.3 m LiDAR DTM in the City of Buzet in Croatia, showing difficulties of unambiguous landslide detection. The research was conducted within the frame of scientific research project "Methodology development for landslide susceptibility assessment for land-use planning based on LiDAR technology" (LandSlidePlan, HRZZ IP-2019-04-9900). The study area (19.96 km^2) is flysch terrain in central Istria, composed of a rhythmical alternation of marls, thinly bedded carbonate-siliciclastic turbidite sediments, and carbonates. Weathering processes and high erodibility of bedrock led to the formation of numerous landslides and various erosional features. First, we present specific morphological features formed along hillslopes and sidewalls of low-order valleys, and discuss whether they actually represent landslides (Fig. 1). Furthermore, we show the appearance of Badlands and gully head on LiDAR DTM derivatives and explain the possible morphological convergence between these phenomena and landslides. For example, they both may create similar arcuate scarp and sharp flanks, and share little apparent difference along the toes. Finally, we present examples of numerous concave scarps formed along the edges of gully channels and discuss the differences between forms representing zones of landslide depletion and erosional features.

Keywords landslide inventory, mapping accuracy, geomorphological convergence, LiDAR, City of Buzet

To be published in: Jagodnik P, Bernat Gazibara S, Fiorucci F, Santangelo M (2024) Interpretation challenges when detecting landslides in flysch environment: examples from visual analysis of LiDAR DTM in the City of Buzet. In Abolmasov et al. (eds) Abstract proceedings of the 6th ReSyLAB. University of Belgrade Faculty of Mining and Geology, Belgrade, In publ

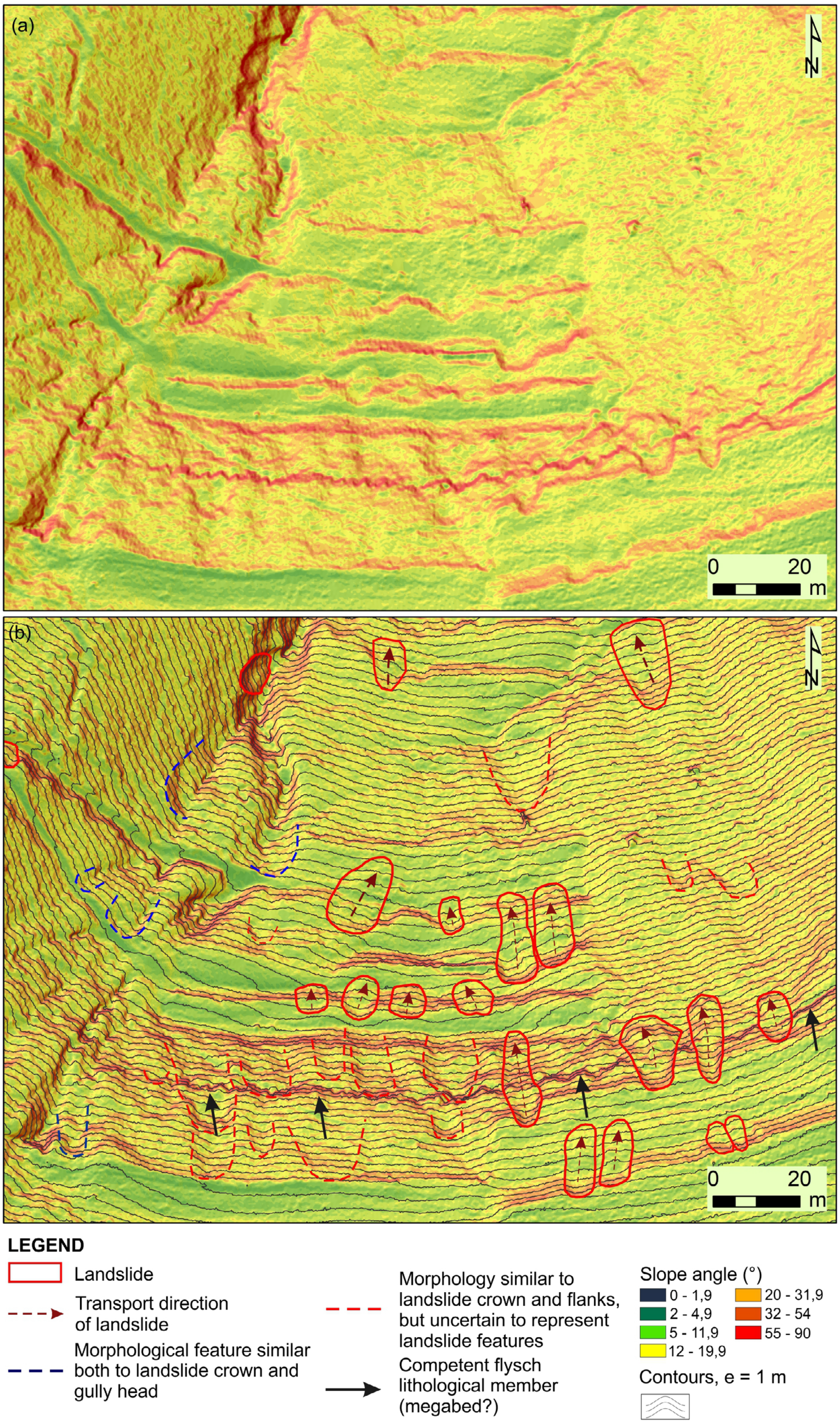


Figure 1 Examples of (a) typical morphological appearance of flysch slopes and (b) landslides detected in the study area of the City of Buzet, with certain morphological features visible along the slopes similar to landslide crowns.

Engineering geological mapping using airborne LiDAR datasets – An example from the Vinodol Valley, Croatia

Petra Jagodnik[(1)], Sanja Bernat Gazibara[(2)], Željko Arbanas[(1)], Snježana Mihalić Arbanas[(2)]

1) University of Rijeka, Faculty of Civil Engineering, Rijeka, Radmile Matječić 3, Croatia
2) University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Zagreb, Pierottijeva 6, Croatia

This study presents the potential of airborne LiDAR Digital Terrain Model (DTM) for engineering geological mapping in geologically complex and forested area, at a large scale. For the pilot area (16.75 km^2) located in the Vinodol Valley in Croatia, the multipurpose, comprehensive engineering geological map is created. It is the first engineering geological map in the Republic of Croatia that was produced using the innovative LiDAR technology. The method for its preparation is the visual interpretation of LiDAR DTM at 1-m spatial resolution. Eight topographic datasets were derived from the DTM and were visually interpreted to identify and map lithologies and geomorphological processes. During the preliminary visual analysis, testing of the possibilities for unambiguous identification and mapping of lithologies and geomorphological processes directly from LiDAR datasets was performed. Then, the findings from the preliminary step were used for the detailed lithological and geomorphological mapping according to established criteria. There are 12 engineering geological units identified in the pilot area, representing the engineering formations. The results indicated that the units composed of sedimentary bodies that are clearly visible on DTM derivatives can be mapped with very high geographic accuracy. However, the thematic accuracy of mapping directly from LiDAR DTM can be reduced due to the morphological convergence of individual sedimentary bodies of different lithologies. Hence, the LiDAR-based lithological mapping was accompanied by field reconnaissance mapping, laboratory soil testing, and archival data analysis.

A total of 31 gullies were delineated in the pilot area. The elongated and branched shape of a gully channel can be easily recognized already on the hillshade map (Fig. 1a). Nevertheless, the slope map is the most effective derivative for delineation of the gully channels, while the best reflection of the linear shape of the gully thalwegs is on stream power index map. In this study, more than 500 landslides were manually delineated and classified into 10 landslide types. For most of identified landslides, e.g. debris slides and debris slide-debris flows, the whole landslide boundary representing the entire landslide body can be identified and delineated on LiDAR maps. In contrast, for some landslide types, e.g. rock irregular slides, mostly the zones of depletion can be delineated on LiDAR maps. For most of the landslides, the crown and main scarp are easily recognized on the slope map and contour map (Fig. 1b), while the main scarp is also easily recognized on the topographic roughness map (Fig. 1c) and profile curvature map (Fig. 1d). A landslide foot is most clearly expressed on topographic roughness map and profile curvature map (Fig. 1c and d). The planform curvature map (Fig. 1e) and stream power index map (Fig. 1f) have enabled a clear recognition of the landslide toes, as well as the landslide tips, in particular when the landslide boundaries coincide with the gully thalweg. The approach of engineering geological mapping described in this study can be easily applied in other study areas with similar geological conditions. The engineering geological map produced for the pilot area can be applied for various planning and engineering purposes, as well as the base for geological hazard and risk assessment.

Keywords Engineering geological mapping, LiDAR DTM, visual interpretation, engineering formation, geomorphological processes, Vinodol Valley

Published in: Jagodnik P, Bernat Gazibara S, Arbanas Ž, Mihalić Arbanas S (2020) Engineering geological mapping using airborne LiDAR datasets – an example from the Vinodol Valley, Croatia. Journal of Maps 16(2): 855-866. https://doi.org/10.1080/17445647.2020.1831980

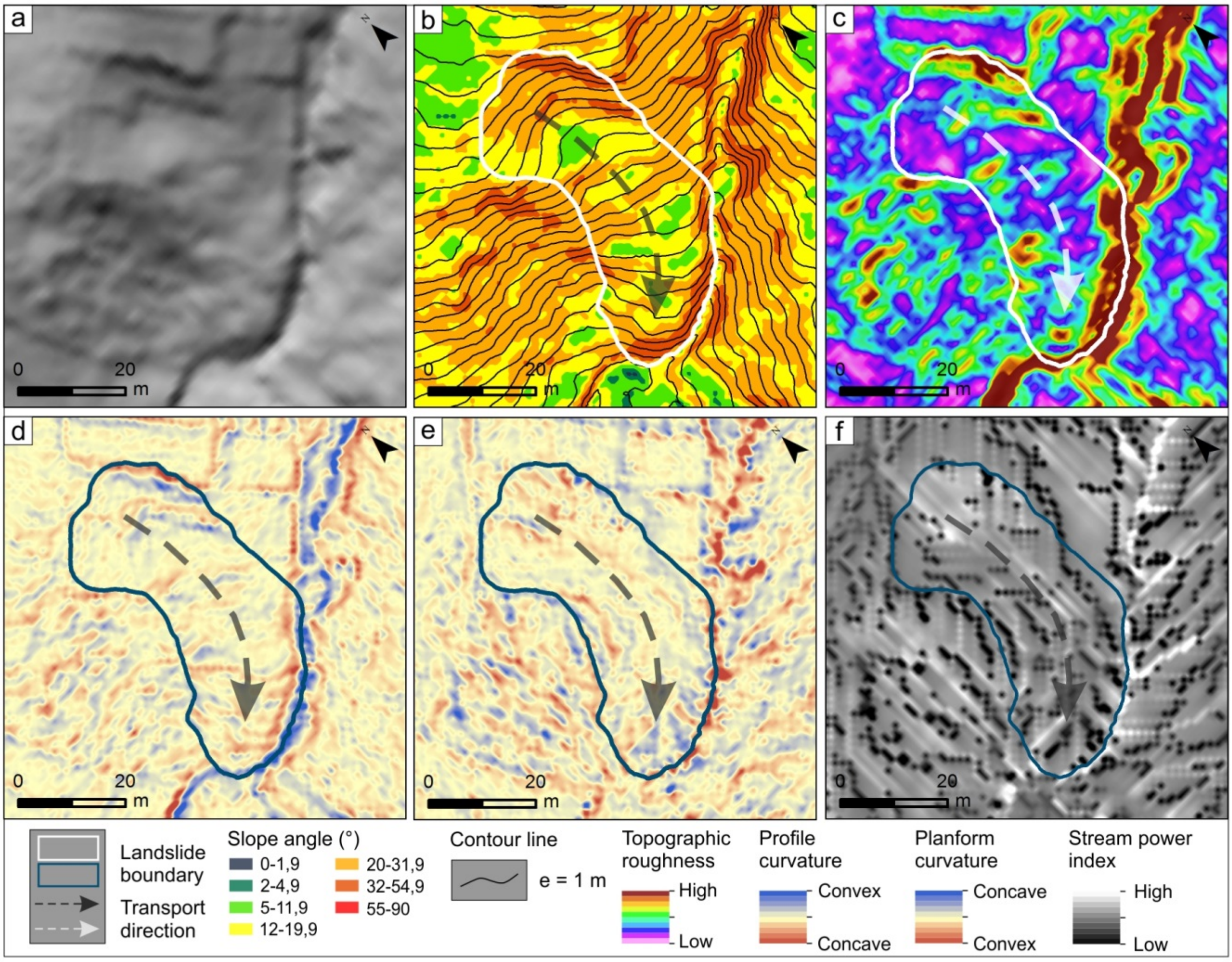


Figure 1 A representative example of the landslide topography identified in the pilot area on HR LiDAR derivatives: (a) the hillhade map; (b) the contour line map over the slope map; (c) the topographic roughness map; (d) the profile curvature map; (e) the planform curvature map; and (f) the stream power index map.

The use of high-resolution remote sensing data in preparation of input data for large-scale landslide hazard assessments

Marko Sinčić[1], Sanja Bernat Gazibara[1], Martin Krkač[1], Hrvoje Lukačić[1], Snježana Mihalić Arbanas[1]

HRZZ

1) University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Zagreb, Pierottijeva 6, Croatia

Preparing input data and cartographic thematic layers is an essential and demanding step in landslide hazard assessment, where the input data often depends on availability and resources. The objective of the study is to show that landslide conditioning factors derived from different source data give significantly different relative influences on the weight factors derived with statistical models for landslide susceptibility modelling and risk analysis. The analysis of the input data for large-scale landslide hazard assessment was performed on a study area (20.2 km^2) in Hrvatsko Zagorje (Croatia, Europe), an area highly susceptible to sliding with limited available geoinformation data.

The initial phase of the study was analyses of free available data for deriving landslide conditioning factors and an inventory map as a preparatory phase for landslide hazard assessments for the study area on a large scale. Those freely available input data included digital terrain models (DTMs) with resolutions of 10 and 25 meters, topographic maps at scales of 1:5.000 and 1:25.000, satellite orthophoto images with resolutions of 10, 20 and 60 meters, aerial orthophoto at scale 1:5.000, geological map at scale 1:100.000, and land use data from Corine Land Cover at a scale 1:100.000, official land-use planning maps at a scale 1:25.000 and Open Street Map. Various conditioning factor maps were produced from the available input data and compared with conditioning factor maps derived from high-resolution Light Detection and Ranging (LiDAR) data, which served as an indicator of the quality necessary for conducting large-scale landslide hazard assessments. The example of the comparison between conditioning factor classes and landslide area distribution in the geomorphological factor maps derived form different DTMs is presented in Fig. 1. The LiDAR data, from which a high resolution (1, 2 and 5 m) conditioning factor maps were derived, had an average density of bare earth points of 0.28 meters. Prior to deriving all the landslide conditioning factors, the analysis of how the interpolation method and resolution affect the quality of the LiDAR DTMs was performed. LiDAR DTMs were tested in three raster resolutions (1, 2 and 5 m) and in five interpolation methods, i.e., Inverse Distance Weighted, Natural Neighbor, ANUDEM, Kriging, and Local Polynomial interpolation methods.

The visual interpretation of LiDAR DTM morphometric derivatives resulted in a detailed and complete landslide inventory map, which consists of 912 identified and mapped landslides, ranging in size from 3.3 to 13,779 m^2. This inventory was used for quantitative analysis of 16 input data layers from 11 different sources to analyse landslide presence in factor classes and thus comparing landslide conditioning factors from available small-scale data with high-resolution LiDAR data and orthophoto images, pointing out the negative influence of small-scale source data. Therefore, it can be concluded that small-scale landslide factor maps derived from publicly available sources should not be used for large-scale analyses because they will result in incorrect assumptions about conditioning factors, compared with LiDAR DTM derivative factor maps. Furthermore, high-resolution LiDAR DTM and orthophoto images are optimal input data because they enable derivation of the most commonly used landslide conditioning factors for susceptibility modelling and detailed datasets about elements at risk (i.e., buildings and traffic infrastructure data layers).

Keywords landslide, large-scale landslide hazard assessment, LiDAR, high-resolution orthophoto, landslide inventory, landslide conditioning factors, elements at risk

Published in: Sinčić M, Bernat Gazibara S, Krkač M, Lukačić H, Mihalić Arbanas S (2022) The Use of High-Resolution Remote Sensing Data in Preparation of Input Data for Large-Scale Landslide Hazard Assessments. Land 11(8): 1360. https://doi.org/10.3390/land11081360

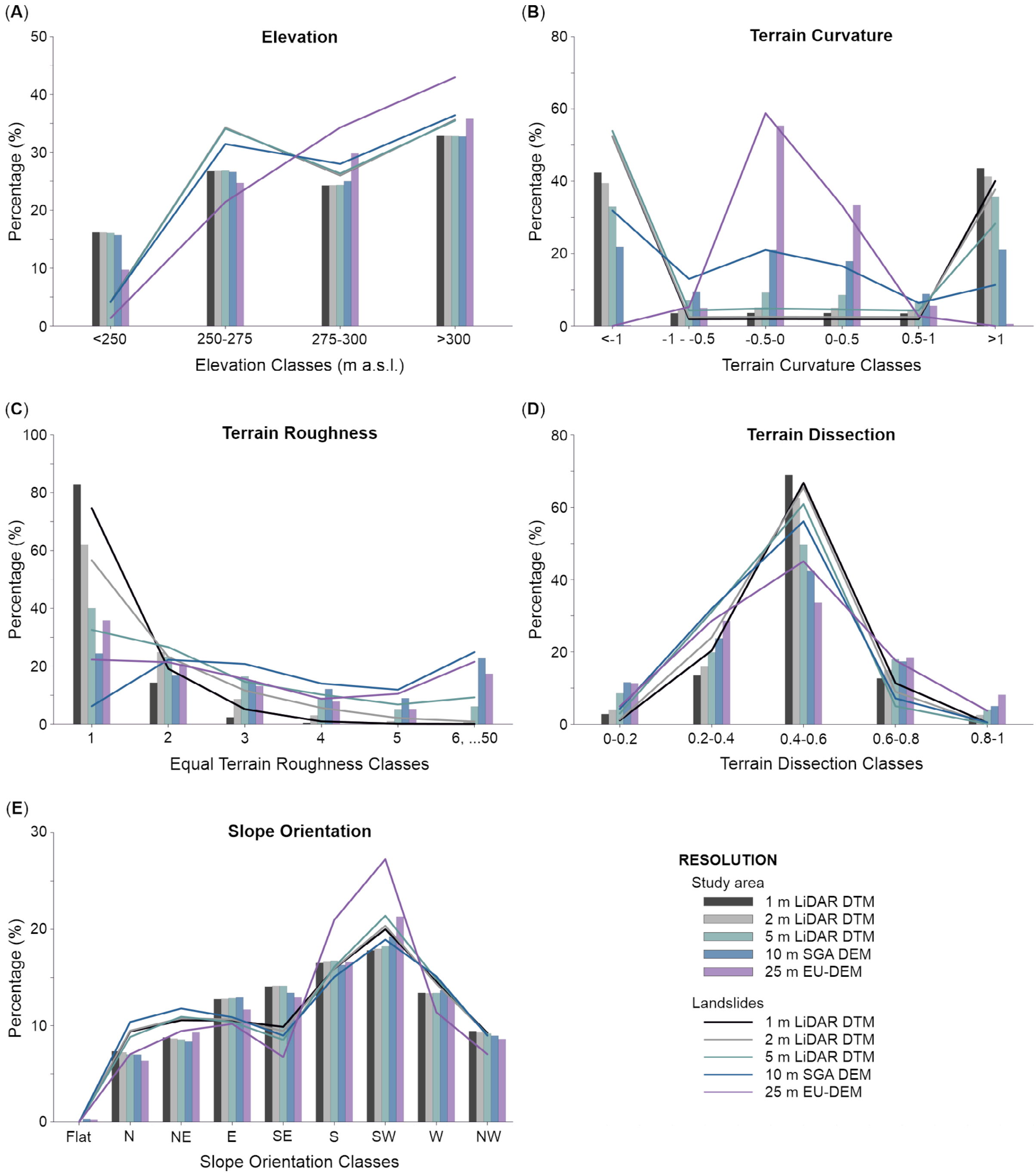


Figure 1 Comparison of conditioning factor classes and landslide area distribution in the geomorphological factor maps derived from 1, 2, and 5 m LiDAR DTMs, 10 m SGA (State Geodetic Administration) DEM and 25 m EU-DEM.

Impact of input data on the quality of the landslide susceptibility large-scale maps: A case study from NW Croatia

Martin Krkač[(1)], Sanja Bernat Gazibara[(1)], Marko Sinčić[(1)], Hrvoje Lukačić[(1)], Gabrijela Šarić[(1)], Snježana Mihalić Arbanas[(1)]

1) University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Zagreb, Pierottijeva 6, Croatia

One of the prerequisites for risk reduction measures and mitigation of landslide consequences is the creation of prognostic maps, such as landslide susceptibility maps. Reliable susceptibility maps on a large scale require quality input data, i.e., detailed and complete landslide inventories and appropriate resolution and spatial accuracy of geo-environmental and triggering factors. This study analyses the impact of input data on the quality of the landslide susceptibility large-scale maps. The study area of 20.22 km² was located in the Hrvatsko Zagorje region, NW Croatia. For comparison, two input data sets were used to produce two causal factor map sets and, thus, two landslide susceptibility maps. The first input data set (Scenario 1) included publicly available data, i.e. EU Digital Elevation Model in 25 m resolution, Basic Geological Map on a scale of 1:100 000, and Corine Land Cover and Open Street Map. The second input data set (Scenario 2) included high-resolution remote sensing data obtained within the LandSlidePlan (HRZZ IP-2019-04-9900) project, i.e. high-resolution LiDAR digital terrain models (DTM) and orthophoto map at a scale 1:5000. The same nine types of landslide causal factor maps (elevation, slope, aspect, distance from the drainage network, topographic wetness, lithology, distance from the geological contact and land use) were derived from the two input data sets.

The detailed LiDAR-based landslide inventory and bivariate statistical method, i.e., the Information Value method, were used for susceptibility modelling. Susceptibility analysis and information values showed that the same factor classes in both scenarios influenced the occurrence of landslides. Only factor classes in topographic wetness and proximity to geological contact maps in the two scenarios have the opposite effect on landslide susceptibility. The most significant factor classes for the landslide occurrence in Scenario 1 were slope class 20-25° and aspect class NE, while the most significant factor classes in Scenario 2 were slope classes 35-45°. Furthermore, the most significant factor class in Scenario 2 has two to three times higher information value than the most significant factor class in Scenario 1. High information values in Scenario 2 resulted in different ranges of total susceptibility values for the two landslide susceptibility maps. The resulting large-scale landslide susceptibility maps for two scenarios were compared with ROC curves. The success and predictive rates for Scenario 1 are approximately 10 % lower than the AUC values for Scenario 2. Moreover, unclassified landslide susceptibility maps for both scenarios looked relatively similar (Fig. 1). However, after the classification of landslide susceptibility into three classes (Fig. 1), based on the quantile method, it was possible to observe on the Scenario 1 map that the low susceptibility class is spread from the flat valleys to the hilly slopes. On the contrary, on the Scenario 2 map, the low susceptibility class was confined only to flat areas.

In the end, it can be concluded that different input data resolutions and scales can provide similar information regarding large-scale landslide susceptibility assessment, although high-resolution input data provide more spatially accurate information. Also, large-scale landslide susceptibility modelling based on small-scale input data would show significantly different results if we did not use a complete LiDAR-based landslide inventory in the analysis. Furthermore, it follows that landslide weight factors obtained from small pilot areas (10-30 km²) with high-resolution remote sensing data sets can be applied for regional landslide susceptibility assessment in wider research areas (> 100 km²) with similar geomorphological and geological conditions.

Keywords landslide susceptibility, LiDAR landslide inventory, input data, causal factor maps, resolution, spatial accuracy

Published in: Krkač M, Bernat Gazibara S, Sinčić M, Lukačić H, Šarić G, Mihalić Arbanas S (2022) Impact of input data on the quality of the landslide susceptibility large-scale maps: A case study from NW Croatia. In Alcántara-Ayala I, Arbanas Ž, Cuomo S, Huntley D, Konagai K, Mihalić Arbanas S (eds) Progress in Landslide Research and Technology, Volume 2 Issue 1. Springer, Cham, pp 135-146. https://doi.org/10.1007/978-3-031-39012-8_4

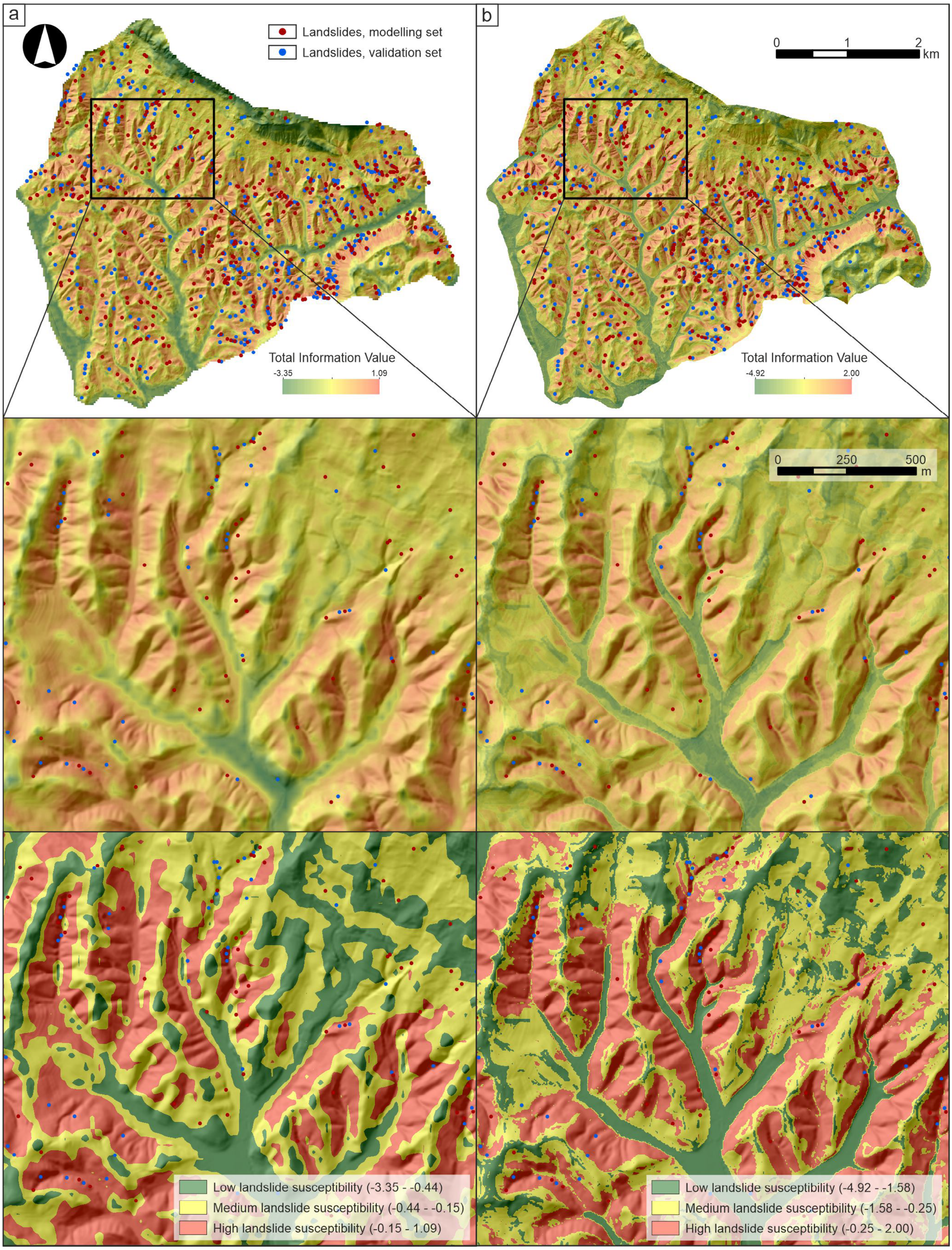


Figure 1 Comparison of landslide susceptibility map classes derived from different types of input data: a) Scenario 1; b) Scenario 2.

Influence of landslide conditioning factor selection on landslide susceptibility modelling in large scale

Marko Sinčić(1), Sanja Bernat Gazibara(1), Gabrijela Šarić(1), Martin Krkač(1), Snježana Mihalić Arbanas(1)

1) University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Zagreb, Pierottijeva 6, Croatia

In Hrvatsko Zagorje region, NW Croatia, a significant amount of landslides threaten the elements at risk. To address the issue, LiDAR data from airborne laser scanning was obtained in the frame of the scientific research project "Methodology development for landslide susceptibility assessment for land-use planning based on LiDAR technology" (LandSlidePlan, HRZZ IP-2019-04-9900), funded by the Croatian Science Foundation. The LiDAR digital terrain model was used to create a complete landslide inventory and derive most of the landslide conditioning factors (LCFs). The purpose of this study is to test LCFs individual relevance and influence on large scale landslide susceptibility models (LSMs), including the number of used LCFs and their combination. Finally, by testing and optimizing the scenarios we aim to provide new insight into landslide occurrences in the study area, as well as optimize the LSMs. In the pixel-based analyses, 15 LCFs were used in the Random Forests machine learning method to derive landslide susceptibility maps (Table 1). Landslide inventory was split into two equal datasets considering the amount of landslide polygone presence, one for training and the other for validation. Both training and validation performance was measured with Area Under the ROC Curve (AUC) metric. The calculated AUC values were observed to determine the LCF importance and influence on the LSMs in the defined scenarios (Fig.1). Analyses showed that using only five properly selected LCFs is enough to derive LSMs having >96.0 training and >76.0 validation AUC values. On the other hand, the highest AUC validation values at >80.0 are possible by using 10 or more LCFs. Adding or removing single LCFs is neglectable when using a larger amount of LCFs, an exception being curvature and terrain dissection LCFs which are identified as the two most significant. Furthermore, minimal usage of two or three LCFs still keeps training AUC values higher than 90.0, whereas validation performance drops to 71.2 or lower. The absence of lithological units or proximity to geological contact LCFs leads to a slight increase in AUC validation. The combination of LCFs and the presence or absence of certain LCFs is less influential when a larger number of LCFs are used. On the contrary, using significantly fewer LCFs can be sufficient if a proper combination is selected, considering that the input data is of proper scale. In addition, a poor combination of a low number of LCFs can drastically decrease AUC validation values. Determining LCF influence is crucial in optimizing LSMs and can lead to deriving sufficient landslide susceptibility maps without having a variety of LCFs at disposal. In this study, LiDAR derivatives and anthropogenic LCFs proved enough to derive an LSM with training AUC values of 98.7 and 80.7 for training and validation, respectively. The latter AUC values are insignificantly lower than the highest possible we achieved by optimizing the combinations.

Keywords landslide susceptibility, landslide conditioning factor, large scale, Random Forests

Published in: Sinčić M, Bernat Gazibara S, Šarić G, Krkač M, Mihalić Arbanas S (2023) Influence of landslide conditioning factor selection on landslide susceptibility modelling in large scale. In Tofani V, Casagli N (eds) Abstract book of the 6th World Landslide Forum „Landslide science for sustainable development". OIC S.r.l., Firenze, pp 651-651.

Table 1 Landslide conditioning factors sorted according to influence defined with a Leave One Out test.

		S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15
SORTED BY INFLUENCE	proximity to geological contact														x
	proximity to all streams													x	x
	proximity to spring												x	x	x
	engineering formations											x	x	x	x
	elevation										x	x	x	x	x
	aspect									x	x	x	x	x	x
	prox. to traffic infastruc. and build.								x	x	x	x	x	x	x
	land-use							x	x	x	x	x	x	x	x
	contour density						x	x	x	x	x	x	x	x	x
	surface-area ratio					x	x	x	x	x	x	x	x	x	x
	slope				x	x	x	x	x	x	x	x	x	x	x
	compound topographic indeks			x	x	x	x	x	x	x	x	x	x	x	x
	proximity to drainage network		x	x	x	x	x	x	x	x	x	x	x	x	x
	terrain dissection	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	proximity to geological contact	x	x	x	x	x	x	x	x	x	x	x	x	x	x

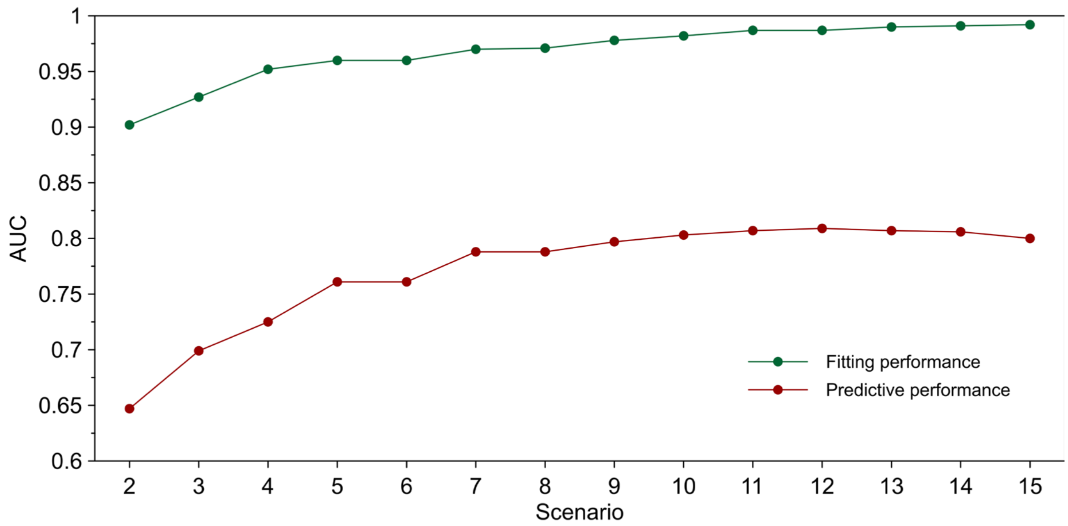


Figure 1 Landslide susceptibility fitting and predictive performance measured with Area Under the Curve metric in 14 derived landslide susceptibility models (S2 to S15).

Results of scientific research

Landslide susceptibility assessment: Modelling, evaluation, validation and zonation

Landslide susceptibility assessment of the City of Karlovac using the bivariate statistical analysis

Marko Sinčić[(1)], Sanja Bernat Gazibara[(1)], Martin Krkač[(1)], Snježana Mihalić Arbanas[(1)]

1) University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Zagreb, Pierottijeva 6, Croatia

Preliminary landslide susceptibility analysis on a regional scale of 1:100 000 using bivariate statistics was conducted for the City of Karlovac. A preliminary landslide susceptibility map was done on a small scale, using incomplete landslide inventory and limited input data about geofactors, for the application in spatial planning. The main tasks of the research were: (i) optimization of geofactors using pairwise conditional independence (CI) test; (ii) landslide susceptibility analyses for five scenarios using different combinations of landslide causal factor groups; (iii) verification of all susceptibility maps using AUC rates for defined scenarios. The research was organized to elaborate assumption that a limited amount of input data can be used for reliable prediction "where" landslides are likely to occur.

The landslide inventory used in this study was compiled based on information received from citizens or road patrol who informed the City administration responsible for landslide remediation or civil protection. Most reported landslides have damaged infrastructure, mainly roads and private properties. The landslide causal factors for the landslide susceptibility modelling in the City were selected expertly and based on data availability. Analyses included 17 geofactors relevant to landslide occurrence divided into four groups: geomorphological (elevation, slope gradient, slope orientation, terrain curvature, terrain roughness), geological (lithology-rock type, proximity to geological contacts, proximity to faults), hydrological (proximity to drainage network, proximity to springs, proximity to temporary, permanent and to all streams, topographic wetness) and anthropogenic (proximity to traffic infrastructure, land cover using two classifications). The existing data for this study area included topography in the form of a Digital Elevation Model (EU-DEM) with a resolution of 25 x 25 m downloaded from the Copernicus Land Monitoring Service. Based on the obtained input data five scenarios were defined using a different combination of geofactors weighted by the Weights-of-Evidence (WoE) method, resulting in five different landslide susceptibility maps and corresponding AUC success and prediction rate values as shown in Table 1.

The best landslide susceptibility map was selected based on the results of a ROC curve analysis, which was used to obtain success and prediction rates of each scenario. The novelty in the presented research is that a limited amount of thematic data and an incomplete landslide inventory map allow the production of a preliminary landslide susceptibility map for usage in spatial planning. Also, this study provides a discussion regarding the method used, geofactors, defined scenarios, and reliability of the results.

The final preliminary landslide susceptibility map, shown in Fig. 1, was derived using ten geofactors which satisfied the pairwise CI test and it is classified into four zones, low landslide susceptibility (57.05% of the area), medium landslide susceptibility (20.63% of the area), high landslide susceptibility (13.28% of the area), very high landslide susceptibility (9.03% of the area) and has a success rate of 94% and a prediction rate of 93% making it a highly accurate source of preliminary information for the study area. Analyses performed in this study resulted in a final version of the preliminary landslide susceptibility map that can be used for informative purposes as a basis to select areas for conducting further spatial analyses of landslide hazards.

Keywords landslide; susceptibility assessment; zonation; bivariate statistical analysis; City of Karlovac

Published in: Sinčić M, Bernat Gazibara S, Krkač M, Mihalić Arbanas S (2022) Landslide susceptibility assessment of the City of Karlovac using the bivariate statistical analysis. Rudarsko-geološko-naftni zbornik 37: 149–170. DOI: 10.17794/rgn.2022.2.13

Table 1 Weight maps and AUC rates for different scenarios applied in the study.

Group of landslide causal factor	Weight maps	Scenarios				
		0	I	II	III	IV
Geomorphological	Slope orientation	+	-	+	+	+
	Terrain roughness	+	-	+	+	+
Geological	Lithology (rock type)	+	+	-	+	+
	Proximity to geological contact	+	+	-	+	+
	Proximity to faults	+	+	-	+	+
Hydrological	Proximity to drainage network	+	+	+	-	+
	Proximity to springs	+	+	+	-	+
	Topographic wetness	+	+	+	-	+
Anthropogenic	Land cover (B)	+	+	+	+	-
	Proximity to traffic infrastructure	+	+	+	+	-
AUC success rate (%)		94	93	94	94	79
AUC prediction rate (%)		93	92	93	94	74

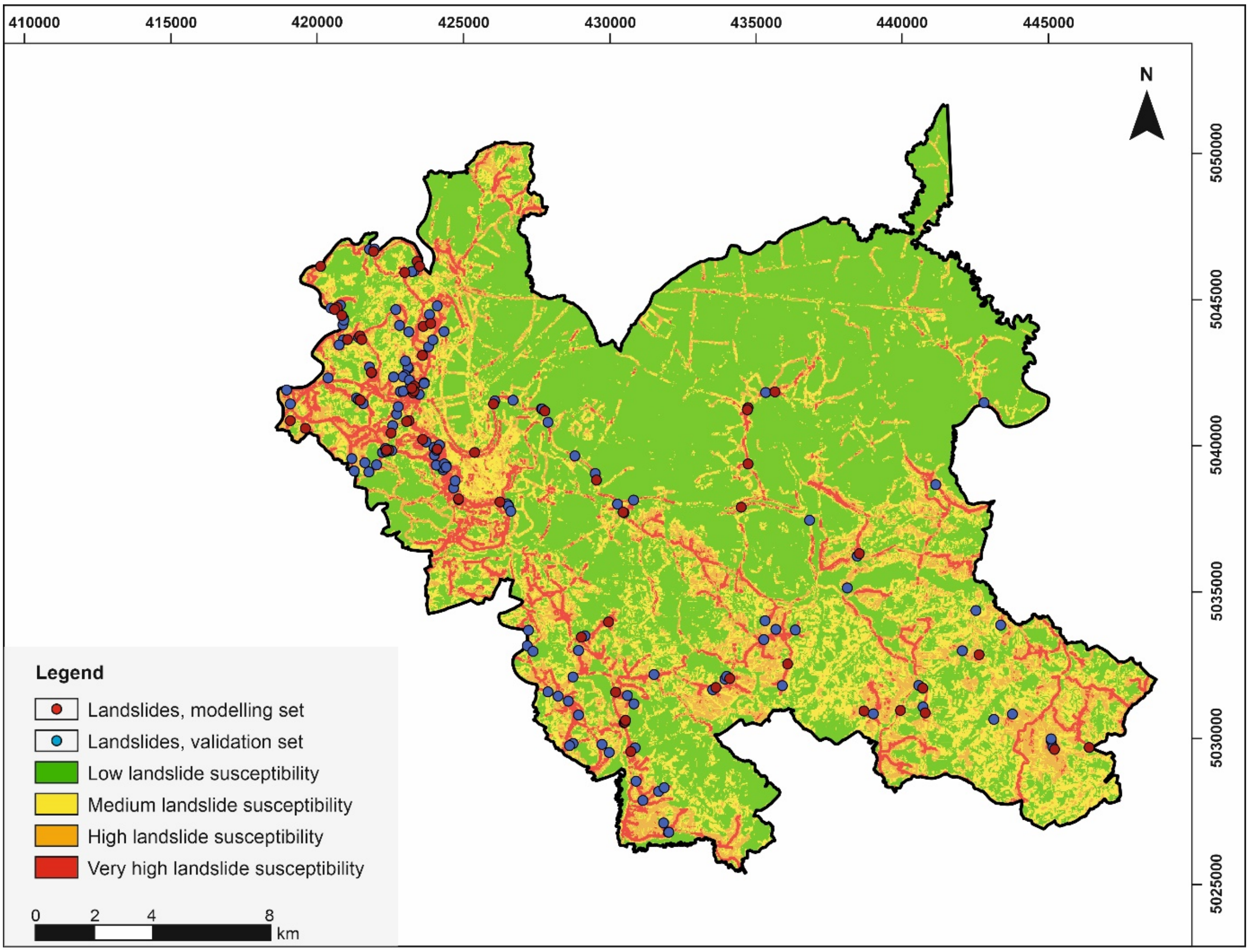


Figure 1 Landslide susceptibility map of the City of Karlovac in scale 1:250 000 created by the Weight of Evidence method.

Influence of the landslide inventory completeness on the accuracy of the landslide susceptibility modelling: A case study from the City of Zagreb (Croatia)

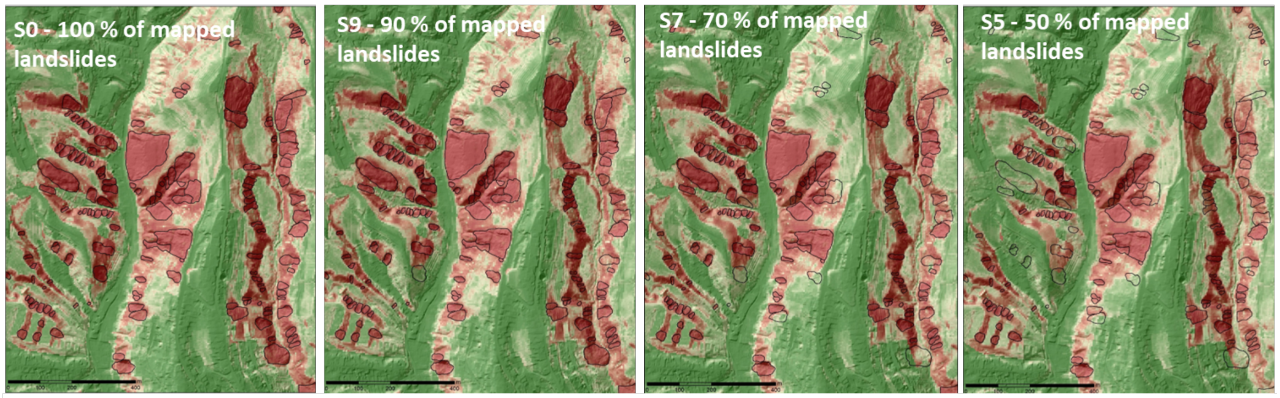
Sanja Bernat Gazibara[1], Marko Sinčić[1], Martin Krkač[1], Petra Jagodnik[2], Hrvoje Lukačić[1], Snježana Mihalić Arbanas[1]

1) University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Zagreb, Pierottijeva 6, Croatia
2) University of Rijeka, Faculty of Civil Engineering, Rijeka, Radmile Matječić 3, Croatia

The quality of landslide susceptibility maps depends on the quality of the input data, i.e. the spatial resolution and accuracy of the landslide conditioning factor maps and the completeness and accuracy of the landslide inventory map. For the pilot area (21 km^2) in the City of Zagreb (NW Croatia) a detailed landslide mapping was done based on visual interpretation of high-resolution LiDAR DTM. The result was the LiDAR-based inventory with 702 landslides (min = 43 m^2, max = 8,064 m^2, median = 400 m^2). The purpose of this study is to test the relevance of landslide inventory completeness and its influence on the landslide susceptibility model (LSM). Moreover, by analysing different scenarios, i.e. different ratios of landslides for model training and validation, we aim to provide new insight into the need for detailed landslide mapping for large-scale susceptibility modelling, as well as the impact on the final landslide susceptibility map. Landslide susceptibility modelling was performed based on 5 m pixel-based analysis, Random Forests machine learning method and 10 landslide conditional factors. The landslide susceptibility analysis consists of nine scenarios that were defined considering the percentage of landslide polygons in the inventory for model training (S0 = 100%, S9 = 90%, S8 = 80 %, S7 = 70%, etc.), while the rest of the landslides were used for model validation (S9 = 10%, S8 = 20 %, S7 = 30%, etc.). The performance of landslide susceptibility model training and validation was measured with the Area Under the ROC Curve (AUC) metric (Fig. 1). The results are part of the scientific research project "Methodology development for landslide susceptibility assessment for land-use planning based on LiDAR technology" (LandSlidePlan, HRZZ IP-2019-04-9900). Presented analyses showed that using 90% of inventory landslides for model training and the rest of the 10% of landslides for model validation resulted in LSM with a training AUC value of 98.1 % and validation AUC of 93.0 %. Using landslide inventory split into two equal datasets considering the number of landslides, one for training and the other for validation, keeps training AUC value higher than 98 %, and validation AUC slightly decreased to 88.4 %. Furthermore, LSM trained with only 10 % on inventory landslides resulted in training AUC value higher than 99 %, and validation AUC dropped to 85.1 %. Based on the conducted landslide susceptibility analysis, using a significantly small percentage of landslides for model training can result in LSM with high validation AUC (> 85 %). Moreover, in the presented study, detailed and completed geomorphological LiDAR-based inventory, LiDAR DTM morphometric derivatives, small-scale geological data, and high-resolution land use data proved to be enough to derive an LSM with validation AUC values higher than 85 %, respectively. However, the analysis of absolute differences between model S0, in which we used 100% of inventory landslides, and the rest of the derived models indicate significant differences in the model's spatial accuracy (Fig. 2). The research highlights the importance of qualitative assessment, alongside commonly used quantitative metrics, to verify spatial accuracy and test the applicability of derived LSM in the spatial planning system. There is an open question of minimising the influence of the landslide data sampling on the final large-scale landslide susceptibility zonation maps.

Keywords landslide inventory completeness, LiDAR DTM morphometric derivatives, landslide susceptibility, Random Forests, training, validation

Published in: Bernat Gazibara S, Sinčić M, Krkač M, Jagodnik P, Lukačić H, Mihalić Arbanas S (2023) Influence of the landslide inventory completeness on the accuracy of the landslide susceptibility modelling: A case study from the City of Zagreb (Croatia). In Tofani V, Casagli N (eds) Abstract book of the 6th World Landslide Forum „Landslide science for sustainable development". OIC S.r.l., Firenze, pp 644-644.



ROC curve – Area Under the Curve

VERIFICATION

input Scenario	TRAINING UNSTABLE % polygons	VALIDATION UNSTABLE % polygons	AUC Training	AUC Validation	AUC Validation with fixed 10% of mapped landslides	AUC Validation with fixed 30% of mapped landslides	AUC Validation with fixed 50% of mapped landslides
S0	**100**	**0**	**98,0**	×	×	×	×
S9	**90**	**10**	**98,1**	**93,0**	**93,0**	×	×
S8	80	20	98,2	91,5	93,1	×	×
S7	70	30	98,4	89,4	92,7	89,4	×
S6	60	40	98,6	88,8	92,4	89,0	×
S5	**50**	**50**	**98,8**	**88,4**	**92,5**	**89,0**	**88,4**
S4	40	60	99,0	87,9	92,3	89,0	87,9
S3	30	70	99,2	87,3	**92,4**	**89,2**	**87,8**
S2	20	80	99,4	87,1	92,0	88,8	87,7
S1	**10**	**90**	**99,6**	**85,1**	**90,1**	**87,0**	**86,5**

Figure 1 Derived probabilistic landslide susceptibility models for scenarios S0, S9, S7 and S5, and training and validation AUC values for all ten scenarios regarding different landslide percentages used for modelling and validation.

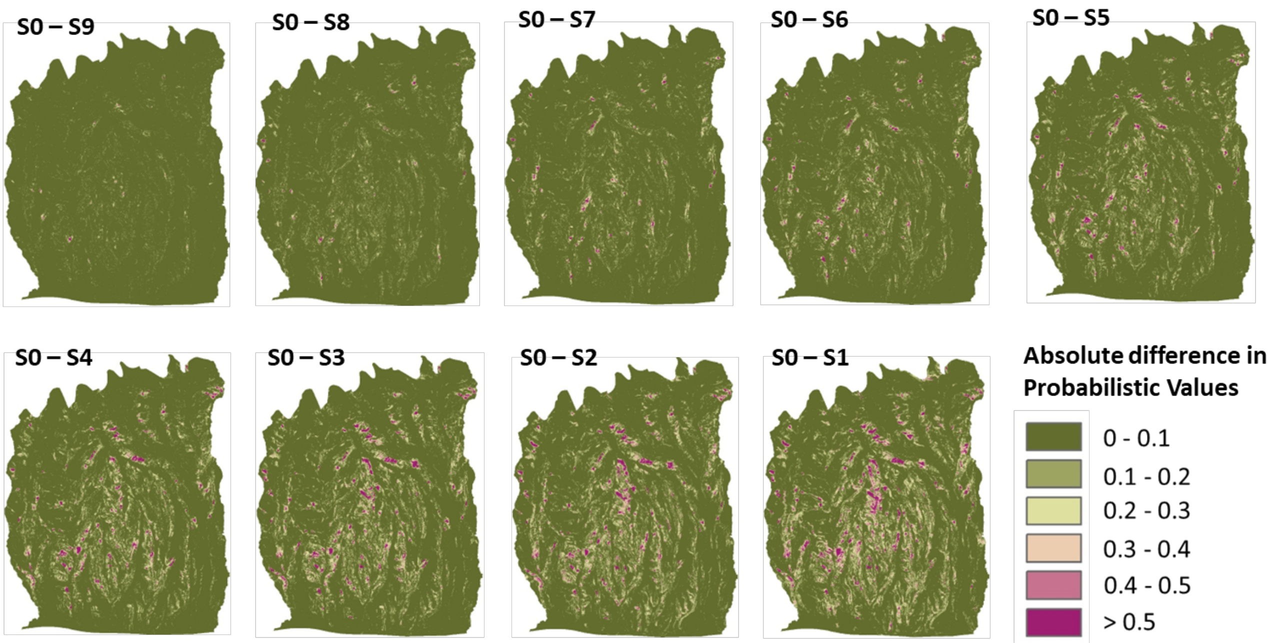


Figure 2 Absolute differences in probabilistic values of derived landslide susceptibility models, which differ regarding the percentage of landslides used for modelling, compared to model S0 - 100% of landslides in inventory used for modelling.

Influence of the landslide inventory sampling on the accuracy of the susceptibility modelling using Random Forests: A case study from the NW Croatia

Marko Sinčić[(1)], Sanja Bernat Gazibara[(1)], Mauro Rossi[(2)], Martin Krkač[(1)], Hrvoje Lukačić[(1)], Snježana Mihalić Arbanas[(1)]

1) University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Zagreb, Pierottijeva 6, Croatia
2) Research Institute for Geo-Hydrological Protection, Perugia, Via Madonna Alta 126, Italy

The quality of landslide susceptibility maps depends on the quality of the input data, i.e. the spatial resolution and accuracy of the landslide conditioning factor maps and the completeness and accuracy of the landslide inventory map. For the pilot areas (40 km^2) in NW Croatia, a detailed landslide mapping was done based on visual interpretation of high-resolution LiDAR DTM. This study aims to test the relevance of landslide inventory completeness and sampling on the landslide susceptibility model (LSM). Moreover, by analysing different scenarios, i.e. different ratios of landslides for model training and validation and sampling of landslide location and morphological conditions, we aim to provide new insight into the need for detailed landslide mapping for large-scale susceptibility modelling, as well as the impact on the final landslide susceptibility map. Landslide susceptibility modelling was performed based on 5 m pixel-based analysis and Random Forests machine learning method. The landslide susceptibility analysis consists of nine scenarios that were defined considering the percentage of landslide polygons in the inventory for model training (S1 = 90%, S2 = 80 %, S3 = 70%, etc.), while the rest of the landslides were used for model validation (S1 = 10%, S2 = 20 %, S3 = 30%, etc.) (Table 1). Furthermore, three more scenarios were defined based on sampling strategy, i.e. original terrain inside landslide polygon, smooth terrain inside landslide polygon and original buffer around landslide boundary (Fig. 1). Landslide susceptibility model training and validation performance were measured with the Area Under the ROC Curve (AUC) metric. The results are part of the scientific research project "Methodology development for landslide susceptibility assessment for land-use planning based on LiDAR technology" (LandSlidePlan, HRZZ IP-2019-04-9900). The purpose of comparing landslide susceptibility models is to define the most suitable methodology for application in the Croatian spatial planning system at the local level.

Keywords landslide susceptibility, landslide sampling strategy, large scale, Random Forests, landslide inventory

To be published in: Sinčić M, Bernat Gazibara S, Rossi M, Krkač M, Lukačić H, Mihalić Arbanas S (2024) Influence of the landslide inventory sampling on the accuracy of the susceptibility modelling using Random Forests: A case study from the NW Croatia. In Abolmasov et al. (eds) Abstract proceedings of the 6th ReSyLAB. University of Belgrade Faculty of Mining and Geology, Belgrade, In publ

Table 1 Fitting and predictive performance measured with Area Under the Curve metric for nine scenarios defined with different training and validation landslide ratio.

SCENARIO	training unstable			validation			AUC training	AUC validation
	N poly	% poly	N pix	N poly	% poly	N pix		
S1	638	90	20246	71	10	1729	98.1	93.0
S2	567	80	18452	142	20	3569	98.2	91.5
S3	496	70	15971	213	30	5957	98.4	89.4
S4	425	60	13822	284	40	8107	98.6	88.8
S5	354	50	11581	355	50	10344	98.8	88.4
S6	283	40	8655	426	60	13270	99.0	87.9
S7	212	30	6211	497	70	15714	99.2	87.3
S8	141	20	3962	568	80	17963	99.4	87.1
S9	70	10	1947	639	90	19978	99.6	85.1

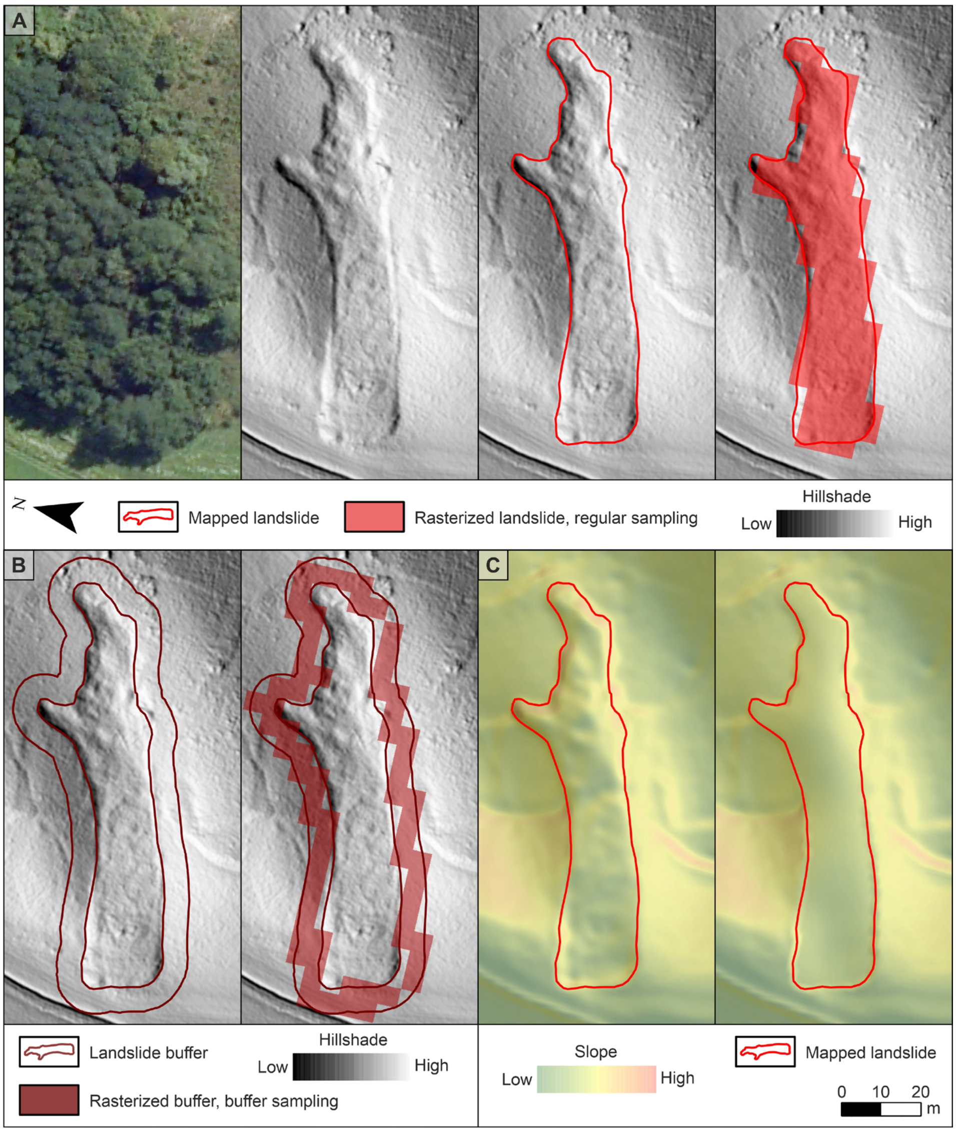


Figure 1 An example of three landslide sampling strategies: (A) original terrain inside landslide polygone); (B) original buffer around landslide boundary and (C) smooth terrain inside landslide polygon.

Comparison of conditioning factors classification criteria in large-scale statistically-based landslide susceptibility models

Marko Sinčić[(1)], Sanja Bernat Gazibara[(1)], Mauro Rossi[(2)], Snježana Mihalić Arbanas[(1)]

HRZZ

1) University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Zagreb, Pierottijeva 6, Croatia
2) Research Institute for Geo-Hydrological Protection, Perugia, Via Madonna Alta 126, Italy

The large-scale landslide susceptibility assessment (LSA) is an important tool for reducing landslide risk through the application of resulting maps in spatial and urban planning. The existing literature more often deals with LSA modelling techniques and the scientific research very rarely focuses on acquiring relevant thematic and landslide data, necessary to achieve reliable results. Therefore, the paper focuses on the crucial step of classifying continuous landslide conditioning factors (LCF) for susceptibility modelling by presenting an innovative comprehensive analysis that resulted in 54 landslide susceptibility models (LSM) to test 11 classification criteria (scenarios which vary from stretched values, partially stretched classes, heuristic approach, classification based on studentized contrast and landslide presence, and commonly used classification criteria, such as Natural Neighbor, Quantiles and Geometrical intervals) in combination with five statistical methods, i.e. Information Value (IV), Logistic Regression (LR), Neural Network (NN), Random Forests (RF), and Support Vector Machine (SVM). The large-scale LSMs were derived for small and shallow landslides in the pilot area (21 km^2) located in the City of Zagreb (Croatia), which occur mainly in soils and soft rocks.

The main conclusion derived from the presented research of large-scale landslide susceptibility modelling is that the LCF classification criteria and selected statistical method significantly influence modelling outcomes. Some of the novelties in LSA are the following: (i) due to using relevant input data with sufficient spatial accuracy, landslide susceptibility modelling performed by any statistical method or any LCF classification scenario in this paper resulted in a highly reliable LSM (Fig. 1); (ii) any of the suggested scenarios to classify continuous LCFs is appropriate if it resulted in roughly ten or unlimitedly more classes in the LCF, suggesting the higher importance of the number of classes in LCFs, rather than the method of how the classes were created. In other words, a low number of classes in LCFs, such as <5, is likely to perform poorly and should be avoided; (iii) applying input data layers as stretched rasters (scenario S11) and line vectors as buffers with >10 buffer zones, simplifies the susceptibility modelling process and provides a uniform solution to preparing LCFs; (iv) quantitative classification parameters and uncertainty metrics, as well as qualitative comparison (e.g. close up views to verify spatial accuracy) applied in this study, are necessary metrics to evaluate optimal settings for large-scale landslide susceptibility modelling as they depict LSM characteristics unidentified by standard quantitative fitting and/or prediction metrics (Fig. 2); (v) optimal method selection remains an open question and generally should be considered regarding the final applicability of the LSA, whereas in this study LR method presents the most stable and representative option, and the RF method offers optimal performance when appropriately applied, achieving the finest performance comparing to other methods (Fig. 1), and (vi) NN and RF methods are more sensitive to the LCF classification criteria than IV, LR, and SVM. The research highlights the importance of qualitative assessments, alongside commonly used quantitative metrics, to verify spatial accuracy and to test the applicability of derived landslide susceptibility maps for spatial planning purposes.

Keywords landslide susceptibility modelling, landslide conditioning factor, large-scale, machine learning, LiDAR

To be published in: Sinčić M, Bernat Gazibara S, Rossi M, Mihalić Arbanas S (2024) Comparison of conditioning factors classification criteria in large-scale statistically-based landslide susceptibility models. In publ

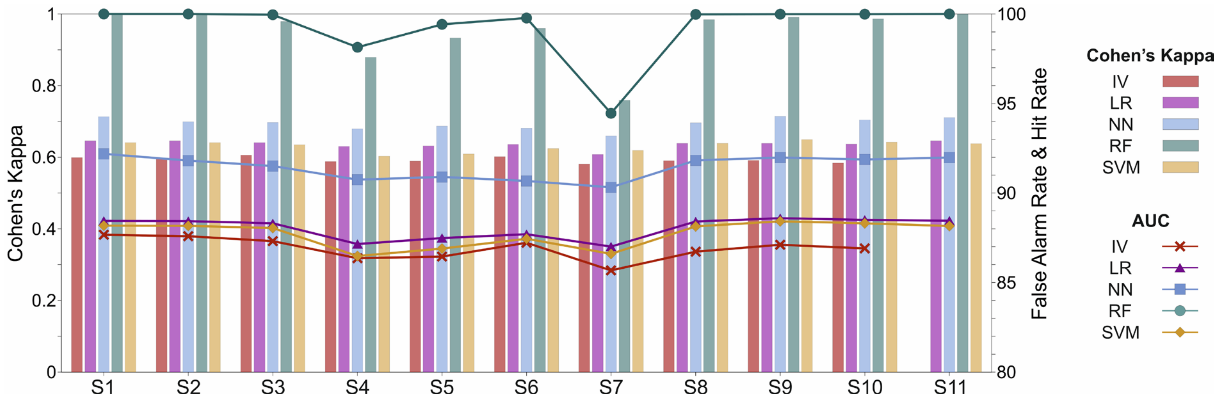


Figure 1 AUC and Cohen's Kappa quantitative parameters describing fitting performance of 54 derived landslide susceptibility models.

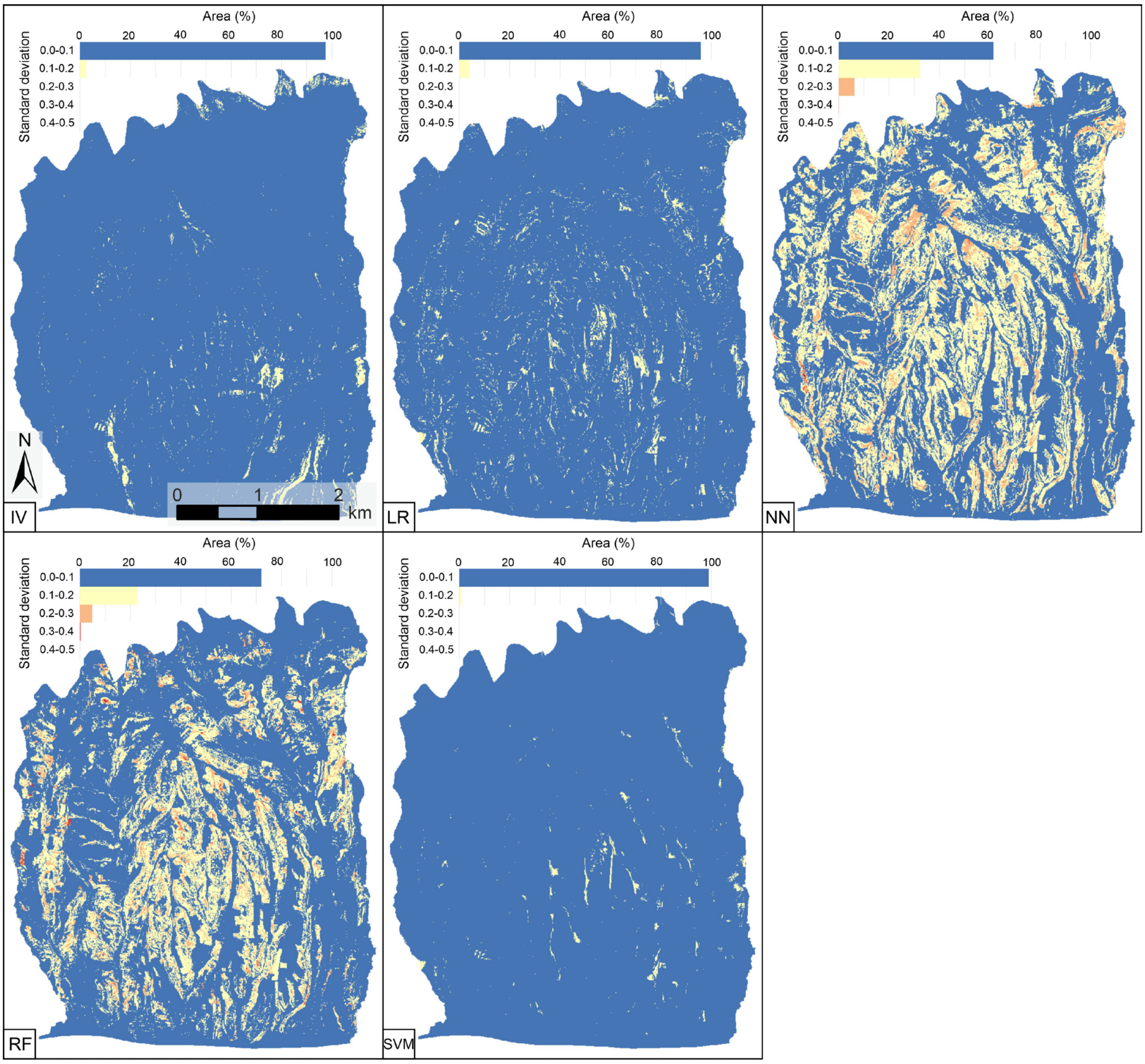


Figure 2 Standard deviation maps and class area distribution defined through 11 scenarios for each method (i.e. IV, LR, NN, RF, SVM).

Application of LAND-SUITE for landslide susceptibility modelling using different mapping units. A case study in Croatia

Sanja Bernat Gazibara[(1)], Marko Sinčić[(1)], Mauro Rossi[(2)], Paola Reichenbach[(2)], Martin Krkač[(1)], Hrvoje Lukačić[(1)], Petra Jagodnik[(3)], Gabrijela Šarić[(1)], Snježana Mihalić Arbanas[(1)]

1) University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Zagreb, Pierottijeva 6, Croatia
2) Research Institute for Geo-Hydrological Protection, Perugia, Via Madonna Alta 126, Italy
3) University of Rijeka, Faculty of Civil Engineering, Rijeka, Radmile Matječić 3, Croatia

In this study, the LAND-SUITE software was applied for large-scale landslide susceptibility zonation, with the main objective to analyze its usefulness to support application in a spatial planning system. The study was carried out in the study area of 20 km^2 located in the Hrvatsko Zagorje in Croatia, where numerous small and shallow soil slides predominantly occur. Five statistical methods in LAND-SUITE were used to carry out the landslide susceptibility analysis, including four single statistical models, i.e., Logistic Regression model (LRM), Linear Discriminant Analysis (LDA), Quadratic discriminant analysis (QDA), and Neural network analysis (NNM); and one combined (CFM)model, for two types of mapping units: 5 m x 5 m regular grid cells and slope units.

For the purpose of developing landslide susceptibility models (LSM) geomorphological landslide inventory map of the Hrvatsko Zagorje was produced based on the visual interpretation of high-resolution LiDAR DTM derivate maps. The LiDAR DTM for landslide mapping was derived at 0.3 m resolution from a point cloud with a density of 16 pt./m2. As a result, 904 landslides were mapped and dominantly classified as shallow soil slides. Randomly selected 24 % were checked in the field in order to ensure reliability of produced landslide inventory. A total of 2 994 slope units were distinguished in the study area using the *r.slopeunits* software for the automatic and adaptive delineation of slope units based on a digital terrain model and a set of user-defined input parameters. Delineated slope units were were classified into two categories: stable or unstable slopes. Furthermore, 22 landslide causal factor maps of geomorphological, geological, hydrological, and anthropogenic type were derived from 5 m resolution LiDAR DTM and/or modified using the high-resolution remote sensing data. Significant landslide causal factors included slope orientation, terrain curvature, engineering formations, proximity to engineering formation contact, proximity to drainage network, proximity to permanent and temporary streams, and proximity to land use boundary.

As the result of the modelling, ten susceptibility maps were obtained and classified into five susceptibility zones, based on the modelled landslide probability. Among the pixel training samples, the best model fitting performance was obtained for the NNM (AUC = 0.793 and k = 0.431) and the combined (CFM) models (AUC = 0.79 and k = 0.432). Similarly, the best model fitting performance for the slope-unit was obtained for the NNM (AUC = 0.854 and k = 0.364) and the combined (CFM) models (AUC = 0.837 and k = 0.383). The pixel and slope unit-based maps displayed differences in the information detail (Fig. 1), indicating that pixel-based susceptibility models are more appropriate for the local-level spatial planning system, although such an approach requires "post-processing" of the susceptibility zones to produce clustered and homogeneous information. On the other hand, slope-based susceptibility maps have a higher relation with the topography and reduced mapping errors, but the size of the slope units derived for this analysis does not correspond well with the scale of landslide susceptibility assessment, and therefore can be considered as more appropriate for LSM at the regional level. The study has also proven the LAND-SUITE as a valuable tool for testing numerous landslide susceptibility hypotheses, with the most valuable advantage of the selection of the appropriate causal factor maps using simple decisions based on multiple analyses, including multicollinearity tables and correlograms.

Keywords landslide, susceptibility zonation, LAND-SUITE

Published in: Bernat Gazibara S, Sinčić M, Rossi M, Reichenbach P, Krkač M, Lukačić H, Jagodnik P, Šarić G, Mihalić Arbanas S (2023) Application of LAND-SUITE for Landslide Susceptibility Modelling Using Different Mapping Units: A Case Study in Croatia. In Alcántara-Ayala I, Arbanas Ž, Huntley D, Konagai K, Mihalić Arbanas S, Mikoš M, Ramesh MV, Sassa K, Tang H, Tiwari B (eds) Progress in Landslide Research and Technology, Volume 2 Issue 2. Springer, Cham, pp 343-354. https://doi.org/10.1007/978-3-031-44296-4_19

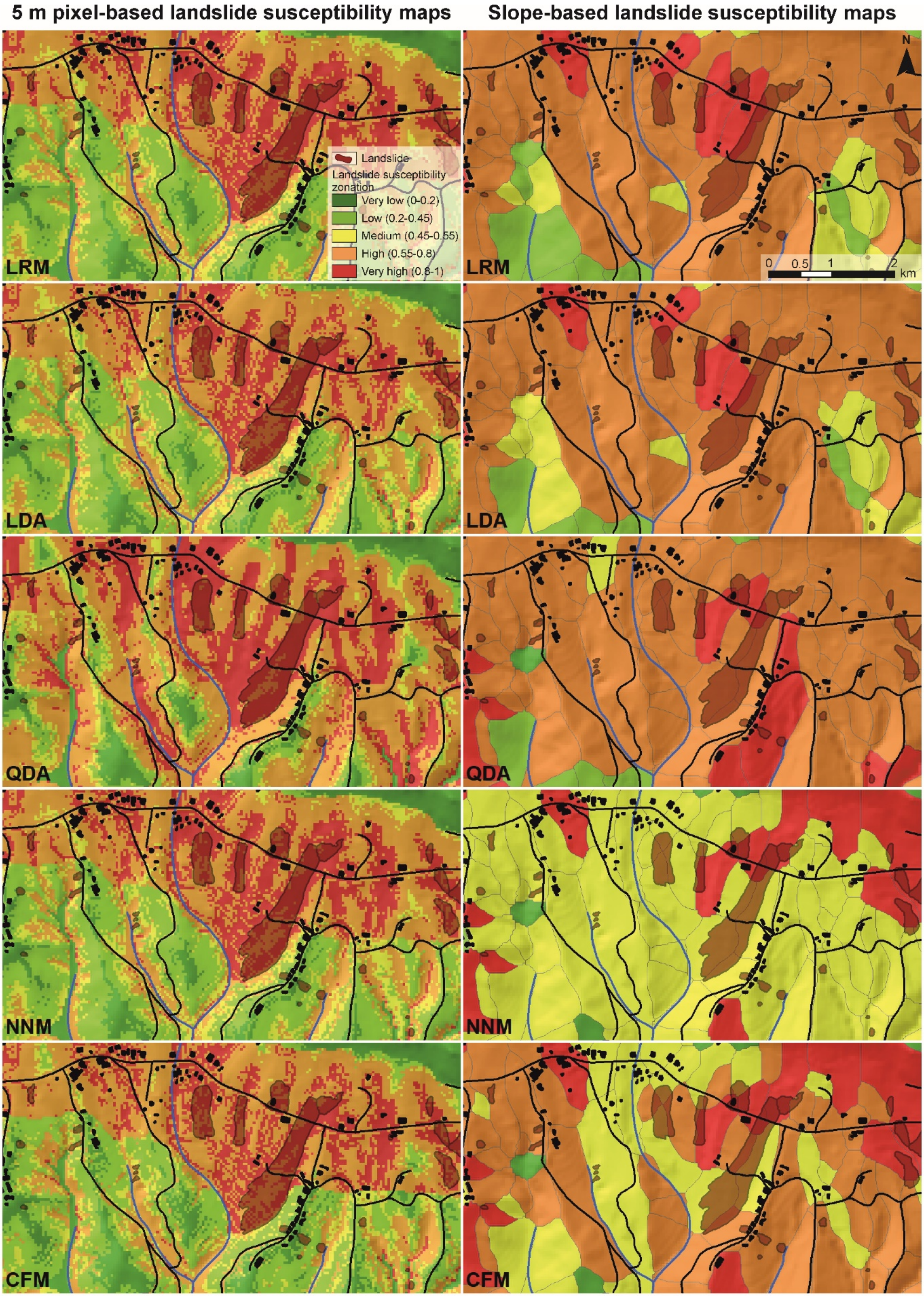


Figure 1 Close-up views for pixel and slope unit-based landslide susceptibility maps of the study area in Hrvatsko Zagorje prepared using LAND-SUITE. Legend: LDA = Linear discriminant analysis; LRM = Logistic regression model; QDA = Quadratic discriminant analysis; NNM = Neural network analysis; CFM = Combined model.

Large-scale landslide susceptibility models: Examples and conclusions from the modelling of small and shallow landslides

Sanja Bernat Gazibara[(1)], Marko Sinčić[(1)], Mauro Rossi[(2)], Martin Krkač[(1)], Hrvoje Lukačić[(1)], Petra Jagodnik[(3)], Snježana Mihalić Arbanas[(1)]

1) University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Zagreb, Pierottijeva 6, Croatia
2) Research Institute for Geo-Hydrological Protection, Perugia, Via Madonna Alta 126, Italy
3) University of Rijeka, Faculty of Civil Engineering, Rijeka, Radmile Matječić 3, Croatia

The main motivation to research the large-scale landslide susceptibility modelling for application in land use planning and civil protection arises from the national landslide risk assessment (BERNAT GAZIBARA et al., 2019), which recognised landslides as a second natural risk in Croatia (CNPDRR, 2019). Furthermore, the preliminary regional landslide susceptibility analysis showed that approx. 20% of the Republic of Croatia area is potentially prone to sliding. Therefore, large-scale landslide susceptibility modelling was carried out in the frame of two scientific projects: *Methodology development for landslide susceptibility assessment for land-use planning based on LiDAR technology* (LandSlidePlan, HRZZ IP-2019-04-9900) and project *Applied landslide research for the development of risk mitigation and prevention measures* (PRI-MJER, KK.05.1.1.02.0020).

Large-scale landslide susceptibility modelling was carried out on three pilot areas in the City of Zagreb, Hrvatsko Zagorje and Karlovac City using different mapping units and statistical methods (e.g. Information Value method, Weights of Evidence method, Logistic Regression and Discriminant Analysis, and machine learning methods, including Support Vector Machine, Artificial Neural Network and Random Forest). Moreover, landslide susceptibility models were computed using different scenarios of high-resolution input data, i.e. geometrical types of LiDAR-based inventory and variations of causal factors. Finally, all landslide susceptibility models were evaluated based on model fitting performance, model prediction performance, and model uncertainty. The purpose of comparing landslide susceptibility models is to define the most suitable methodology for application in spatial planning system at a local level. Application of the landslide susceptibility model requires zoning into several landslide susceptibility classes and generalization of susceptibility zones so that the final map is unambiguous and straightforward to apply in a spatial planning system (Fig 1.). The research was based on innovative technologies, limitations related to the availability of spatial data in Croatia (limited amount of geological data), and urgent needs for efficient solutions applicable in the Croatian spatial planning system in line with European and global requirements related to sustainable development, human and environmental protection.

Keywords large-scale landslide susceptibility modelling, landslide susceptibility zonation

To be published in: Bernat Gazibara S, Sinčić M, Rossi M, Krkač M, Lukačić H, Jagodnik P, Mihalić Arbanas S (2024) Large-scale landslide susceptibility models: Examples and conclusions from the modelling of small and shallow landslides. In Abolmasov et al. (eds) Abstract proceedings of the 6th ReSyLAB. University of Belgrade Faculty of Mining and Geology, Belgrade, In publ

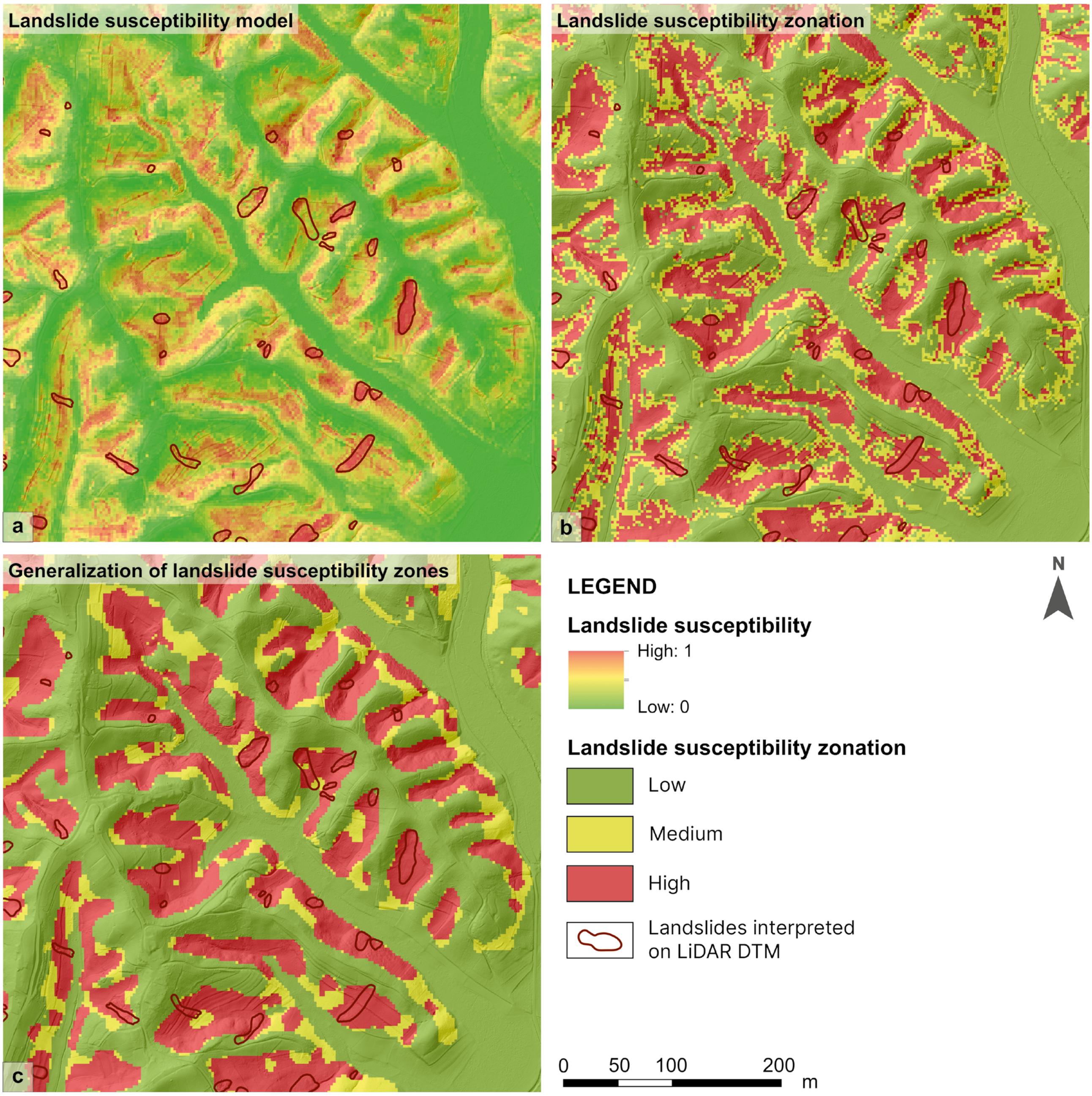


Figure 1 Example of landslide susceptibility zonation and generalization for application in spatial planning system.

Landslide susceptibility assessment on a large scale in the Podsljeme area, City of Zagreb (Croatia)

Sanja Bernat Gazibara[1], Marko Sinčić[1], Martin Krkač[1], Hrvoje Lukačić[1], Snježana Mihalić Arbanas[1]

1) University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Zagreb, Pierottijeva 6, Croatia

This study presents the landslide susceptibility assessment on a large scale in the City of Zagreb (Croatia). The analysis was performed for the hilly area of the Podsljeme in the City of Zagreb, which is prone to small to medium-sized soil slides. For the first time, the landslide susceptibility map for the part (130 km^2) of the Podsljeme area was prepared (Fig. 1), based on available input data at a large scale. First, the landslide susceptibility analysis using the Weight of Evidence (WoE) model was performed for the representative pilot area (21 km^2), and then the landslide susceptibility map for the entire study area (130 km^2) was derived based on susceptibility analysis of the input data layers for the pilot area. Hence, the study also tested the potential of defining susceptibility conditions in smaller pilot areas based on detailed LiDAR DTM input datasets and applying them for large-scale landslide susceptibility assessment of large research areas with similar geomorphological and geological conditions. The input data for the analysis were the LiDAR-based landslide inventories, and six landslide conditioning factors derived from 5 m LiDAR DTM, 5 m SfM DEM, and geological and land-use maps.

The landslide inventory for the pilot area (21 km^2), consisting of 702 landslides (Fig. 1), was used for landslide susceptibility modelling and defining weight values for each factor map class that was further used for the landslide susceptibility assessment of the entire study area (130 km^2). The landslide inventory for the susceptibility verification of the study area consists of 507 landslides (Fig. 1) depicted with the point in the centre of the identified landslide feature. Among landslide conditioning factors used for modelling, the slope gradient classes proved to have the highest impact on the landside susceptibility. Landslide susceptibility maps for the pilot area (21 km^2) and the study area (130km^2) were derived by summing the factor maps according to the assigned weight values. As a result, the W_{map} value for the WoE model in the pilot area ranges from –12.14 to 6.03, and for the study area from –12.45 to 6.03. The success rate of the derived landslide susceptibility map (21 km^2) is AUC=85.3%, while the prediction rate is AUC= 86.9% (Fig. 1). Validation of the resulting susceptibility map for the study area (130 km^2) showed a high prediction rate, i.e. the AUC is 84.4% (Fig. 1). The landslide susceptibility map of the study area was classified into four susceptibility zones (Fig. 1). The proposed method for large-scale landslide susceptibility assessment, where susceptibility conditions are defined in smaller pilot areas, can be applied to larger research areas where similar geomorphological and geological conditions prevail. Therefore, landslide susceptibility assessment in the Podsljeme area can provide necessary information for disaster loss reduction and serve as an example and guideline for sustainable land use planning at a local level in the City of Zagreb and northwestern Croatia.

Keywords landslide susceptibility modelling, large scale, bivariate statistical method, LiDAR, Croatia

Published in: Bernat Gazibara S, Sinčić M, Krkač M, Lukačić H, Mihalić Arbanas S (2023) Landslide susceptibility assessment on a large scale in the Podsljeme area, City of Zagreb (Croatia). Journal of Maps.
https://doi.org/10.1080/17445647.2022.2163197

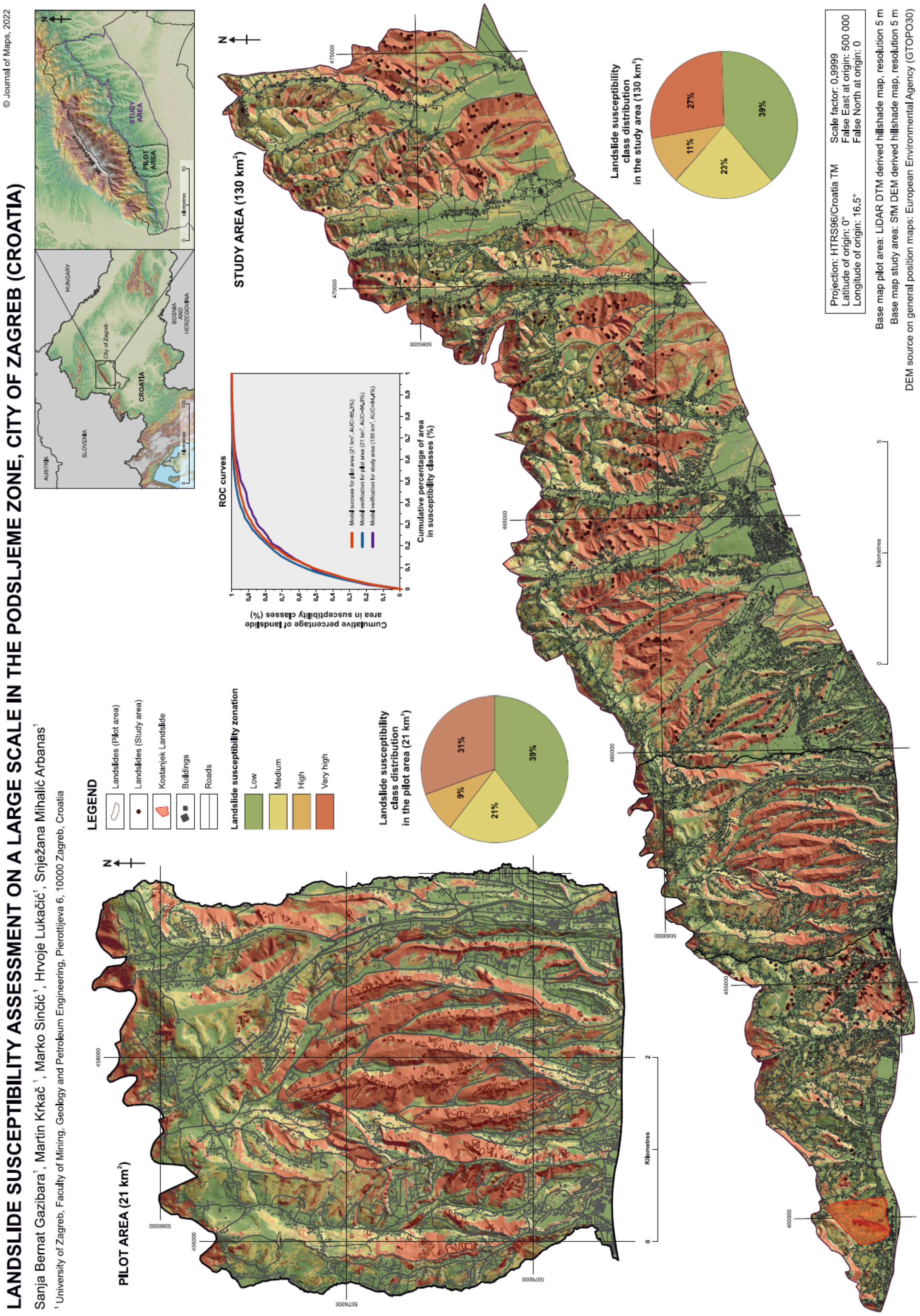


Figure 1 Landslide susceptibility map for the part of the Podsljeme area (130 km²) in a large scale, derived by summing the factor maps according to the assigned weight values of the representative pilot area (21 km²).

Application of scientific research results

Landslide maps for spatial planning

The landslide susceptibility assessment for application in the spatial planning system: From national to local scale

Sanja Bernat Gazibara[(1)], Marko Sinčić[(1)], Martin Krkač[(1)], Hrvoje Lukačić[(1)], Gabrijela Šarić[(1)], Petra Jagodnik[(2)], Snježana Mihalić Arbanas[(1)],

1) University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Zagreb, Pierottijeva 6, Croatia
2) University of Rijeka, Faculty of Civil Engineering, Rijeka, Radmile Matječić 3, Croatia

The main motivation to research the landslide susceptibility assessment for application in land use planning arises from the national landslide risk assessment which recognised landslides as a second natural risk in Croatia. Furthermore, the preliminary regional landslide susceptibility analysis showed that approx. 20% of the Republic of Croatia area is potentially prone to sliding. Therefore, landslide susceptibility assessment for national, county and local levels was carried out in the frame of two scientific projects *Methodology development for landslide susceptibility assessment for land-use planning based on LiDAR technology* (LandSlidePlan, HRZZ IP-2019-04-9900) and project *Applied landslide research for the development of risk mitigation and prevention measures* (PRI-MJER, KK.05.1.1.02.0020). The national landslide susceptibility map at a small scale is created to give a general overview of critical areas for an entire country, and its purpose is to inform policymakers and the general public (Fig. 1). County-level landslide susceptibility assessment on a medium scale synthesizes available data and identifies wider areas with landslide problems and can be used to define areas for more detailed research on a local level. The third level is the local-scale landslide mapping and zonation that includes specific areas of local administrative units (municipality or city) or complex critical areas. The results were landslide susceptibility maps for seven study areas: (i) the Republic of Croatia; (ii) City of Zagreb, Karlovac County and Primorje-Gorski Kotar County; and (iii) the study areas in the Zagreb City, Hrvatsko Zagorje, Karlovac City and Istria.

Methodology development for landslide susceptibility assessment on national and county scales was carried out using a heuristic approach, i.e. Fuzzy Logic method, and available topographical and geological data. Given that the validation of the final landslide susceptibility map is mandatory, and systematic landslide inventories at the national or county level do not exist, we used the landslide database conducted by the University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering. The database consists of 2,186 landslides with the exact location of the occurrence. All landslide susceptibility maps showed high accuracy and were classified into three susceptibility zones, considering The Area Under the Receiver Operating Characteristic Curve (AUC_{ROC}).

Methodology development for landslide susceptibility assessment on a local scale was carried out using different mapping units and statistical methods (e.g. Information Value method, Weights of Evidence method, Logistic Regression and Discriminant Analysis, and machine learning methods, including Support Vector Machine, Artificial Neural Network and Random Forest). Moreover, landslide susceptibility models were computed using different scenarios of high-resolution input data, i.e. geometrical types of LiDAR-based inventory and variations of causal factors. Finally, all landslide susceptibility models were evaluated based on model fitting performance, model prediction performance, and model uncertainty. The purpose of comparing landslide susceptibility models is to define the most suitable maps for application in spatial planning at national, regional, and local levels (Fig. 2). The research was based on innovative technologies, limitations related to the availability of spatial data in Croatia (limited amount of geological data), and urgent needs for efficient solutions applicable in the Croatian spatial planning system in line with European and global requirements related to sustainable development, human and environmental protection.

Keywords landslides, landslide susceptibility assessment, Croatia

Published in: Jagodnik P, Bernat Gazibara S, Sinčić M, Krkač M, Lukačić H, Šarić G, Jagodnik P, Mihalić Arbanas S (2023) The landslide susceptibility assessment for application in the spatial planning system: From national to local scale. In Fio Firi K (ed) Book of Abstracts of the 7th Croatian Geological Congress with international participation. Croatian Geological Survey, Zagreb, pp 22-23.

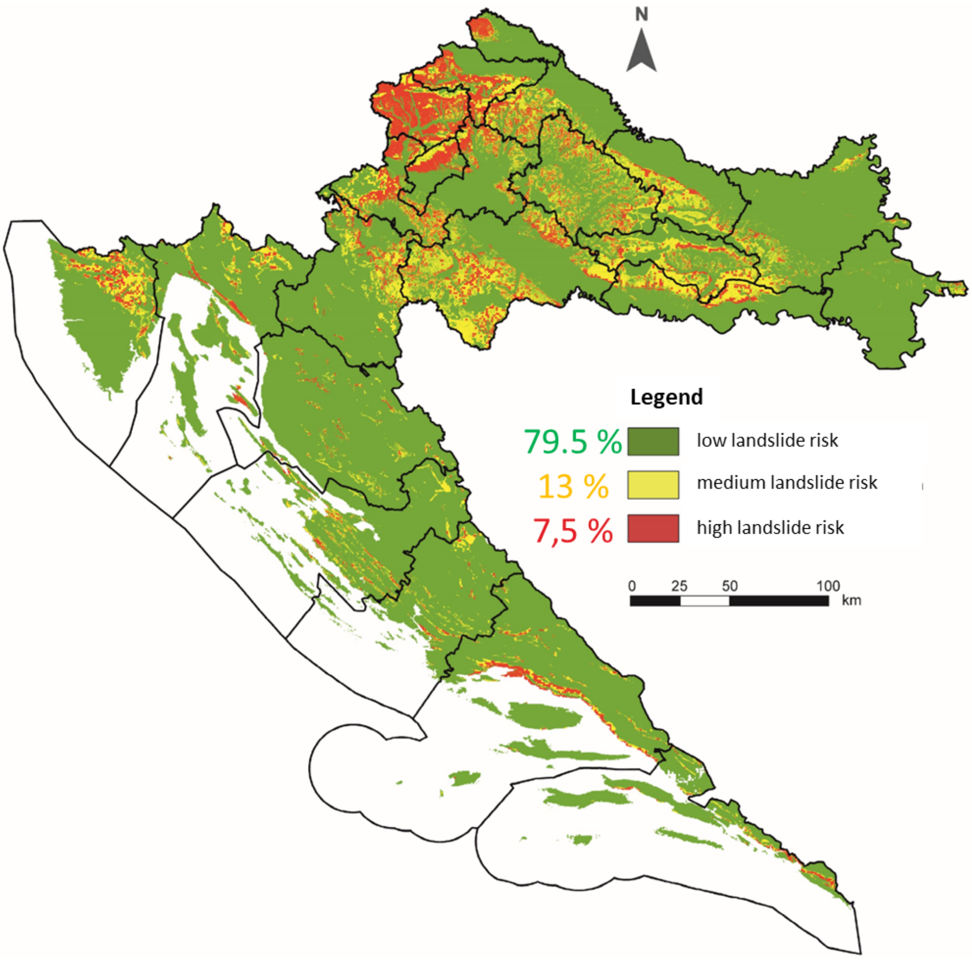


Figure 1 The landslide susceptibility map of the Republic of Croatia at a small scale (1:100.000).

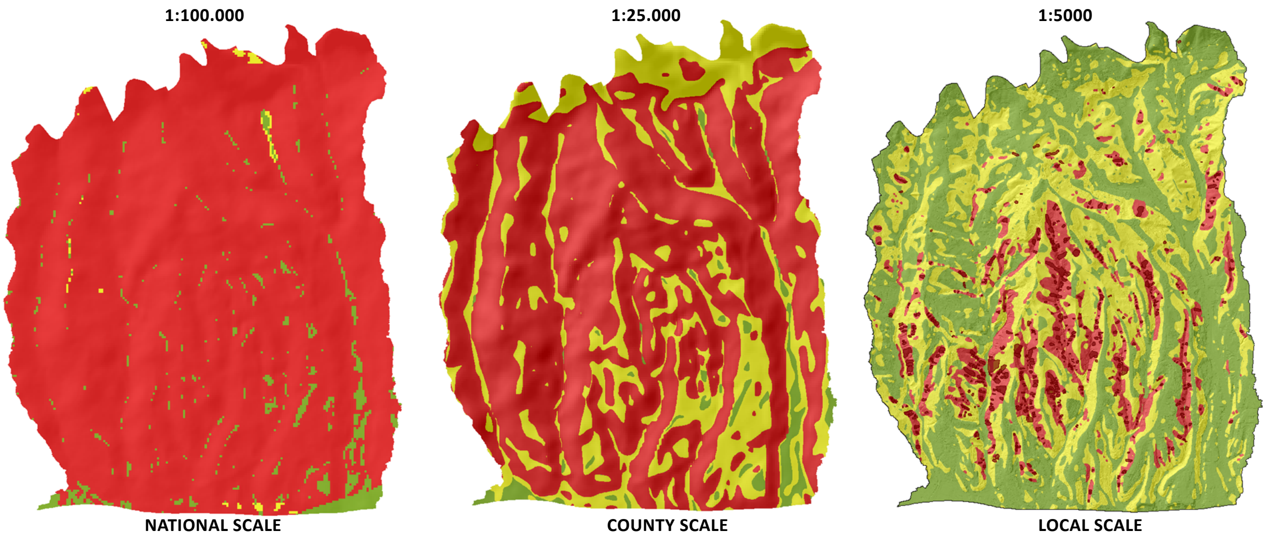


Figure 2 Comparison of the landslide susceptibility models in a national, regional (county), and a local scale for the pilot area in the City of Zagreb (21 km^2).

Landslide detection and spatial prediction: Application of data and information from landslide maps

Snježana Mihalić Arbanas[(1)], Sanja Bernat Gazibara[(1)], Martin Krkač[(1)], Marko Sinčić[(1)], Hrvoje Lukačić[(1)], Petra Jagodnik[(2)], Željko Arbanas[(2)]

1) University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Zagreb, Pierottijeva 6, Croatia
2) University of Rijeka, Faculty of Civil Engineering, Rijeka, Radmile Matječić 3, Croatia

The main objective of this review paper is to present types of data and information on landslides that can be derived from landslide inventory and susceptibility maps and their use for spatial and urban planning. The paper is organized into three main chapters regarding: (i) landslide detection and mapping, where LIDAR technology for landslide inventory mapping was presented; (ii) susceptibility modelling and zonation, where basic concepts related to landslide susceptibility assessment and resulting zonation maps were presented; and (iii) application of landslide data and information, where general considerations of applying data and information from landslide maps in land use planning are given. Furthermore, scale-related objectives and examples from Croatia are given for a hierarchical approach to producing landslide zoning maps.

Study areas for large-scale landslide inventory and susceptibility mapping in Croatia are located in the Podsljeme zone in the City of Zagreb (Fig. 1), Hrvatsko Zagorje and Vinodol Valley. Landslide inventory mapping was done based on visual interpretation of high-resolution LIDAR (Light Detection and Ranging) DTM (Digital Terrain Model) derivatives. Examples of detailed and complete landslide inventories (Fig. 1) in combination with large-scale susceptibility zonation maps compiled for three pilot areas proved that they could be used for all significant mitigation approaches: restricting development in landslide-prone areas; enforcing codes for excavation, construction, and grading; engineering for slope stability; deploying monitoring and warning systems; and providing landslide insurance. Medium-scale landslide susceptibility maps, derived from low-resolution and low-quality small-scale data that are widely available, are sufficient for land use planning at a regional level as well as for the development of county disaster management plans. In the paper, we presented the medium-scale susceptibility maps of Primorsko-Goranska County and Karlovac County (1:25,000) (Fig. 2a) obtained by the heuristic assessment, which has obtained satisfactory reliability for defining areas where a more detailed susceptibility mapping is needed. The small-scale landslide susceptibility map created for the whole territory of the Republic of Croatia (1:100,000) (Fig. 2b) gives preliminary information about landslide susceptibility for all counties. Unlike medium-scale landslide maps, it is intended to be used only for informative purposes at the national level, giving an indication to the counties that need to implement zoning on a medium scale.

It can be concluded that a multi-level and hierarchical approach is necessary to reach the cost-effectiveness of nationwide production of landside maps for land-use planning. Staging will allow better process control and may reduce the zoning costs by limiting the more detailed zoning only to areas where it is necessary. Officials and planners need to reduce landslide risk and potential losses based on data and information in large-scale landslide susceptibility assessments, which require defining national standards and guidelines for landslide hazard assessments.

Keywords landslide detection, landslide maps, landslide susceptibility zonation, land use planning

Published in: Mihalić Arbanas S, Bernat Gazibara S, Krkač M, Sinčić M, Lukačić H, Jagodnik P, Arbanas Ž, (2022) Landslide detection and spatial prediction: Application of data and information from landslide maps. In Alcántara-Ayala I, Arbanas Ž, Huntley D, Konagai K, Mikoš M, Sassa K, Sassa S, Tang H, Tiwari B (eds) Progress in Landslide Research and Technology, Volume 1 Issue 2, 2022. Springer, Cham, pp 195–212. https://doi.org/10.1007/978-3-031-18471-0_16

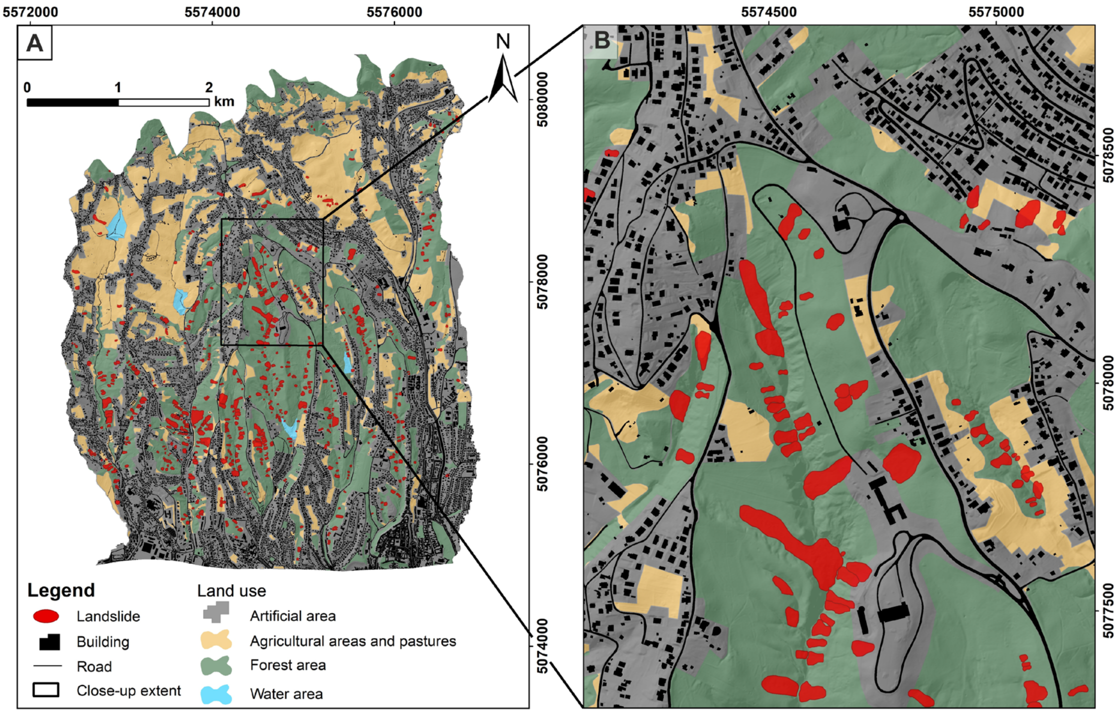


Figure 1 Detailed landslide inventory map of the study area in the Podsljeme Zone (21 km^2) in Zagreb overlapped with land use categories from the Spatial Plan of the City of Zagreb.

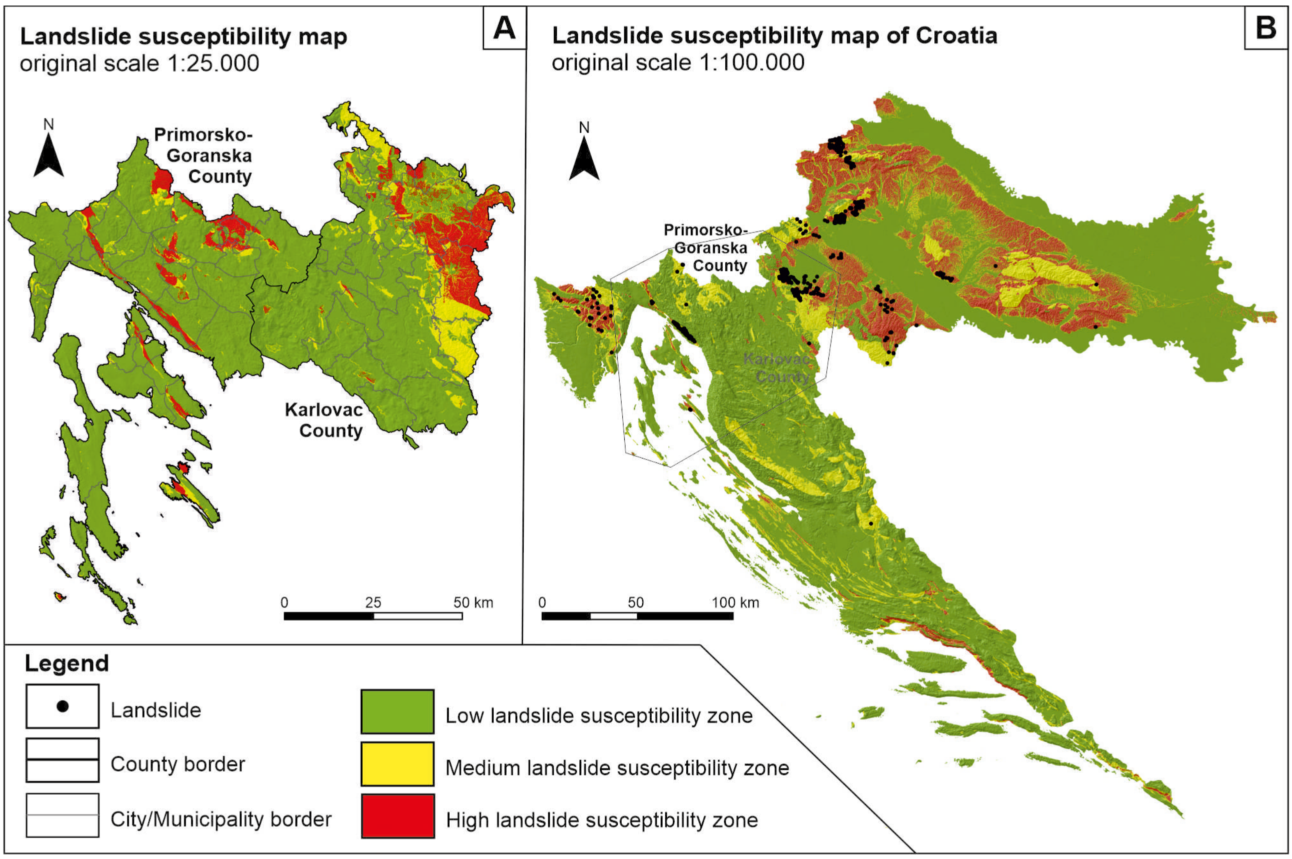


Figure 2 Landslide maps in medium and small-scale: (A) Regional-level landslide susceptibility maps of Primorsko-Goranska County and Karlovac County, original scale 1:25 000; (B) Landslide susceptibility map of Croatia, original scale 1:100.000.

Landslide information for land management and planning: Examples from Italy and Croatia

Paola Reichenbach[(1)], Snježana Mihalić Arbanas[(2)], Mauro Rossi[(1)], Sanja Bernat Gazibara[(2)]

1) Research Institute for Geo-Hydrological Protection, Perugia, Via Madonna Alta 126, Italy
2) University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Zagreb, Pierottijeva 6, Croatia

Landslide information and derived mapping products are relevant tools to support local authorities in land use management and planning. Landslide inventory maps are the basis for determining landslide susceptibility, hazard, and risk at different scales. Accurate landslide mapping and geotechnical characterization can be of paramount importance for the comprehension and set-up of landslide forecast models. In addition, information on landslide spatial occurrence (i.e., susceptibility) is fundamental to evaluate the instability of the territory when is hit by a triggering event and can be a relevant component of early warning systems, which focuses on the forecast of multiple or populations of landslides over large areas based on the monitoring of a potential landslide trigger (e.g., rainfall).

In Italy, there are several examples of inventory maps prepared at different scales using diverse mapping techniques. At the National level, the IFFI catalogue compiled by the Italian Institute for Environmental Protection and Research (Fig. 1), represents the most detailed inventory available for the entire Italian territory. In addition, a mosaic of landslide hazard maps, originally prepared by the regional administrations following national criteria, show areas classified into five levels (Fig. 2). The PAI landslide hazard maps were prepared for the Italian regions in the framework of a national project (www.isprambiente.gov.it) that was focused on identifying areas of possible evolution of existing landslides and areas where new landslides potentially may occur.

As an example of the use of landslide maps, the prototype SANF system (Sistema per l'Allertamento Nazionale da Frana) developed by CNR IRPI for the Italian Civil Protection Department, integrated two different landslide susceptibility zonation derived with statistically based methods. The first, at the municipality level, was polygon-based and used the AVI landslide archive and morphology, land use, geo-lithology, and climatic information as explanatory variables. The second was carried at a pixel level with a resolution of 25 m, successively down-sampled at 1 000 m with similar explanatory information.

In Croatia, there are several recent examples of landslide maps prepared in large and medium scales (Fig. 3). Inventory maps prepared at large scale (1:2 000) using visual interpretation of LiDAR DTM (Digital Terrain Model) morphometric derivatives. The large-scale inventory maps for different study areas were compiled in the framework of the EU-funded project PRI-MJER (KK.05.1.1.02.0020, https://pri-mjer.hr/) aimed at the development of the most detailed inventory required at the municipal level (Fig. 3a). In the same period, large-scale landslide susceptibility zonations (Fig. 3b) were derived using statistically based methods in the framework of the scientific research project LandSlidePlan (HRZZ IP-2019-04-9900, https://landslideplan.eu/), funded by the Croatian Scientific Foundation. To ensure a rational approach to landslide mapping in the entire Croatian territory, a prototype of a landslide susceptibility map was produced at a medium scale (1:25 000) with areas classified into three levels (Fig. 3c,d). The prototype map, in the form of a mosaic, covers three Croatian counties (total area approx. 8 000 km^2; Fig. 3d), and it is intended for regional administration to recommend cities and municipalities for the preparation of large-scale maps in zones of high and medium susceptibility. It is a pixel-based map with a 25-m resolution and it is based on a heuristic approach because of the lack of national landslide inventory. Despite the small number of explanatory variables used for modelling (morphology and geo-lithology), the spatial information about zones for more detailed landslide mapping is satisfactory.

Keywords landslide mapping, susceptibility, planning, early warning system

To be published in: Reichenbach P, Mihalić Arbanas S, Rossi M, Bernat Gazibara S (2024) Landslide information for land management and planning: Examples from Italy and Croatia. In Abolmasov et al. (eds) Abstract proceedings of the 6th ReSyLAB. University of Belgrade Faculty of Mining and Geology, Belgrade, In publ.

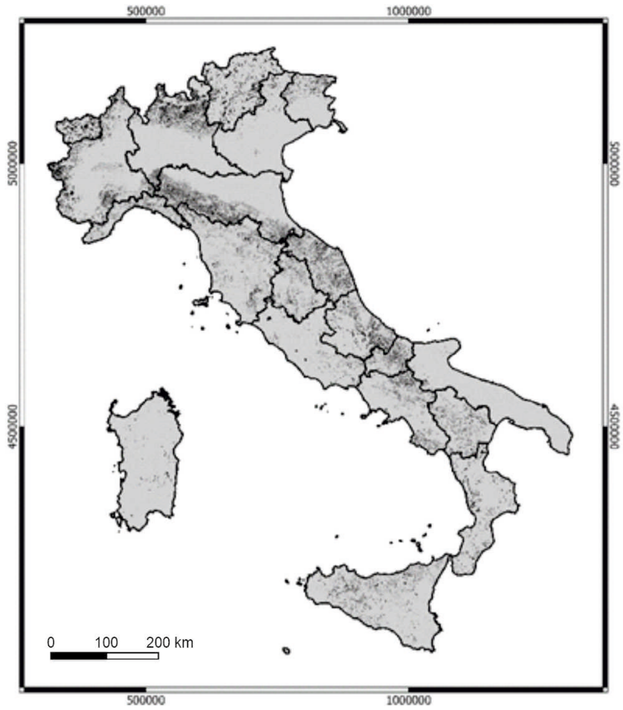


Figure 1 The map shows the IFFI landslide data (black polygons) for the Italian regions (black lines).

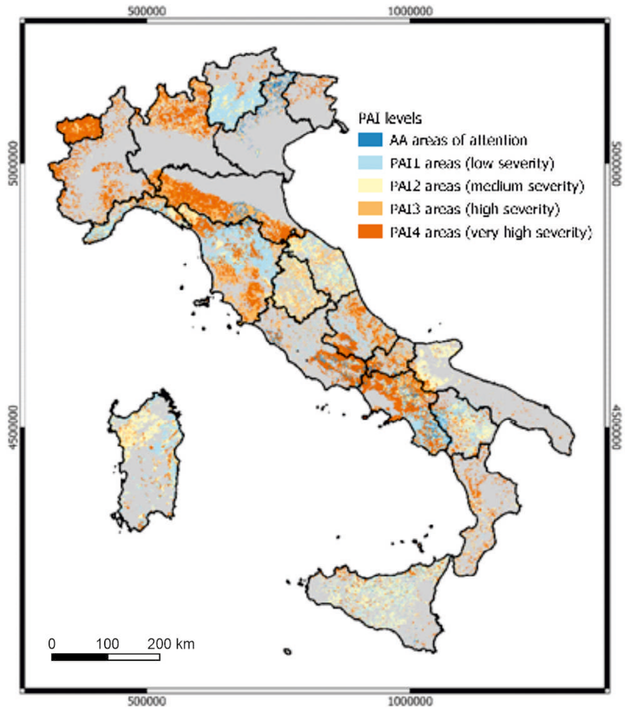


Figure 2 The map shows the distribution of the five PAI hazard levels (AA, H1, H2, H3, and H4) for the Italian regions (black lines).

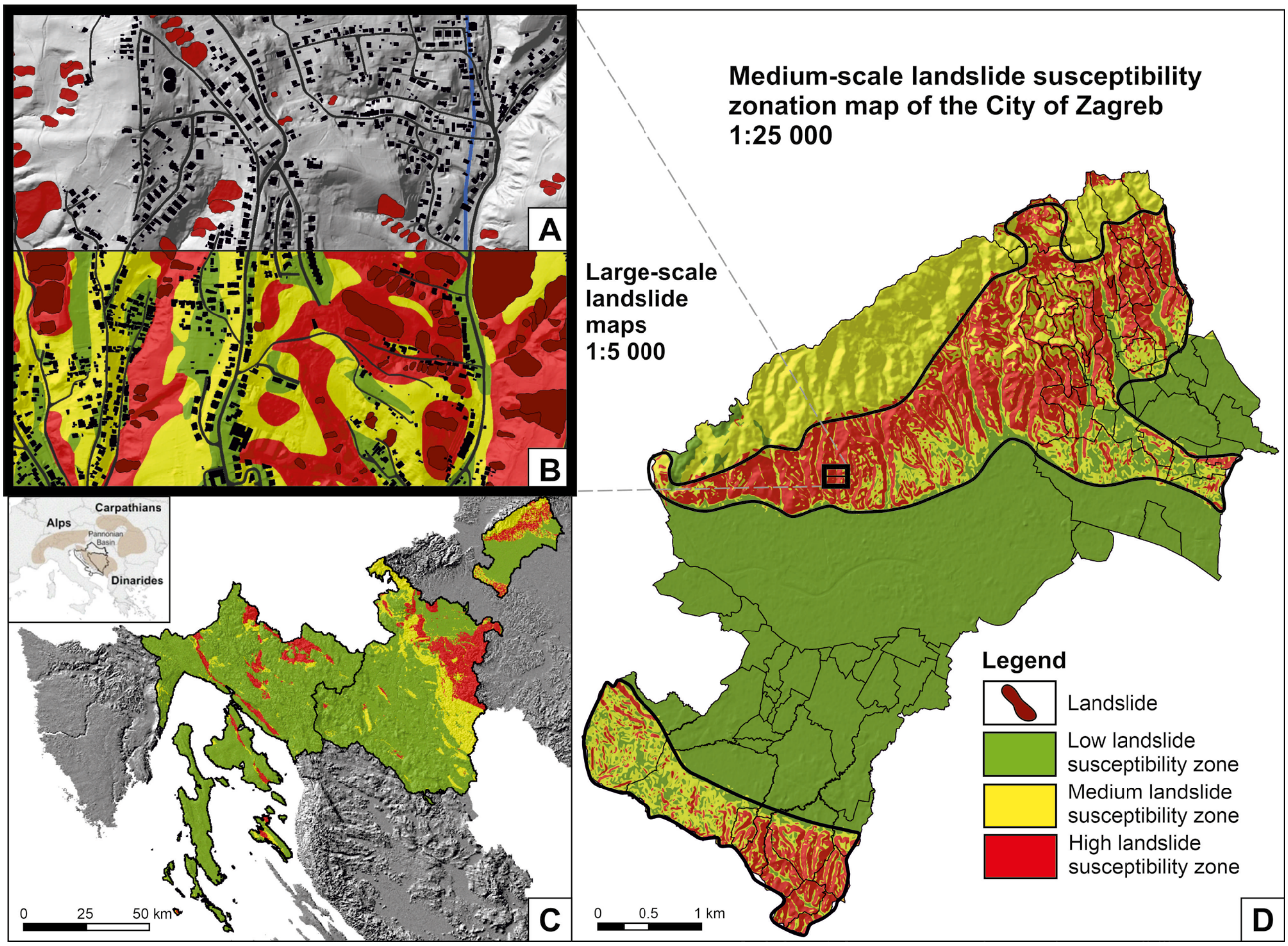


Figure 3 Examples of landslide maps prepared on large and medium scale: (a) large-scale landslide inventory map; (b) large-scale landslide susceptibility zonation map; (c) mosaic of medium-scale landslide susceptibility zonation maps; (d) medium-scale landslide susceptibility zonation map of the City of Zagreb.

Application of landslide susceptibility maps in spatial planning at the local level

Željko Arbanas[(1)], Snježana Mihalić Arbanas[(2)], Gorana Ljubičić[(3)], Petra Jagodnik[(1)], Sanja Bernat Gazibara[(2)]

1) University of Rijeka, Faculty of Civil Engineering, Rijeka, Radmile Matječić 3, Croatia
2) University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Zagreb, Pierottijeva 6, Croatia
3) The Institute for Physical Planning of Primorje-Gorski Kotar County Public Institution, Rijeka, Splitska 2/II, Croatia

Landslides, as one of the most common and worldwide present natural hazard phenomena, would expectedly become an increasing threat due to climate change. The severe socioeconomic and environmental damage and losses, as well as human fatalities caused by landslides, require a considerable variety of techniques and practices to mitigate the potential losses arising from landslide occurrence. The approach to completely avoid landslide-prone areas and exclude human activities from them is rarely feasible, and it is neither possible nor desirable to limit development in all landslide-prone areas. The solution lies in the determination and selection of effective mitigation approaches that include land management through spatial planning. The landslide hazard mitigation strategies include the following major mitigation approaches: restricting development in landslide-prone areas; enforcing codes for excavation, construction, and grading; engineering for slope stability; deploying monitoring and warning systems; and providing landslide insurance. To enable the application of landslide hazard mitigation approaches, a necessary condition is providing landslide inventory and landslide susceptibility maps in landslide-prone regions. These maps must be created based on standards and guidelines for landslide hazard mapping to ensure sufficiently detailed assessments which will support mitigation action at the local level.

In this paper, we will present a landslide hazard mitigation approach applied through land-use planning at the local level, i.e., through the Spatial Plan of the Jelenje Municipality. The Jelenje Municipality is located near the City of Rijeka, Croatia, in the Rječina River valley, known for large, deep-seated fossil landslides. Determination and selection of effective mitigation approaches were based on large-scale landslide inventory and landslide susceptibility maps created using high-resolution LiDAR morphometric derivative maps. The large-scale landslide inventory map 1:2 000 and the landslide susceptibility zonation map 1:5 000 for the Rječina River valley were compiled in the framework of the EU-funded project PRI-MJER (KK.05.1.1.02.0020, https://pri-mjer.hr/) (Fig. 1). Large-scale landslide susceptibility zonation was derived using statistically based methods developed in the framework of the scientific research project LandSlidePlan (HRZZ IP-2019-04-9900, https://landslideplan.eu/), funded by the Croatian Scientific Foundation. Data about landslides and information on landslide susceptibility zones from both landslide maps were integrated into the Spatial Plan as cartographic information was used in two ways. Firstly, to restrict development in landslide-prone areas, whether there exists a large number of densely distributed small landslides or a large fossil landslide, i.e., in zones of high susceptibility to sliding. The second group of mitigation measures were related to conditions of land use, focusing on construction (enforcing codes for excavation, construction, and grading) and protection of the environment (prohibition of forest cutting, etc).

Keywords landslide, inventory, susceptibility, spatial planning, landslide hazard mitigation

To be published in: Arbanas Ž, Mihalić Arbanas S, Ljubičić G, Jagodnik P, Bernat Gazibara S (2024) Application of landslide susceptibility maps in spatial planning at the local level. In Abolmasov et al. (eds) Abstract proceedings of the 6th ReSyLAB. University of Belgrade Faculty of Mining and Geology, Belgrade, In publ.

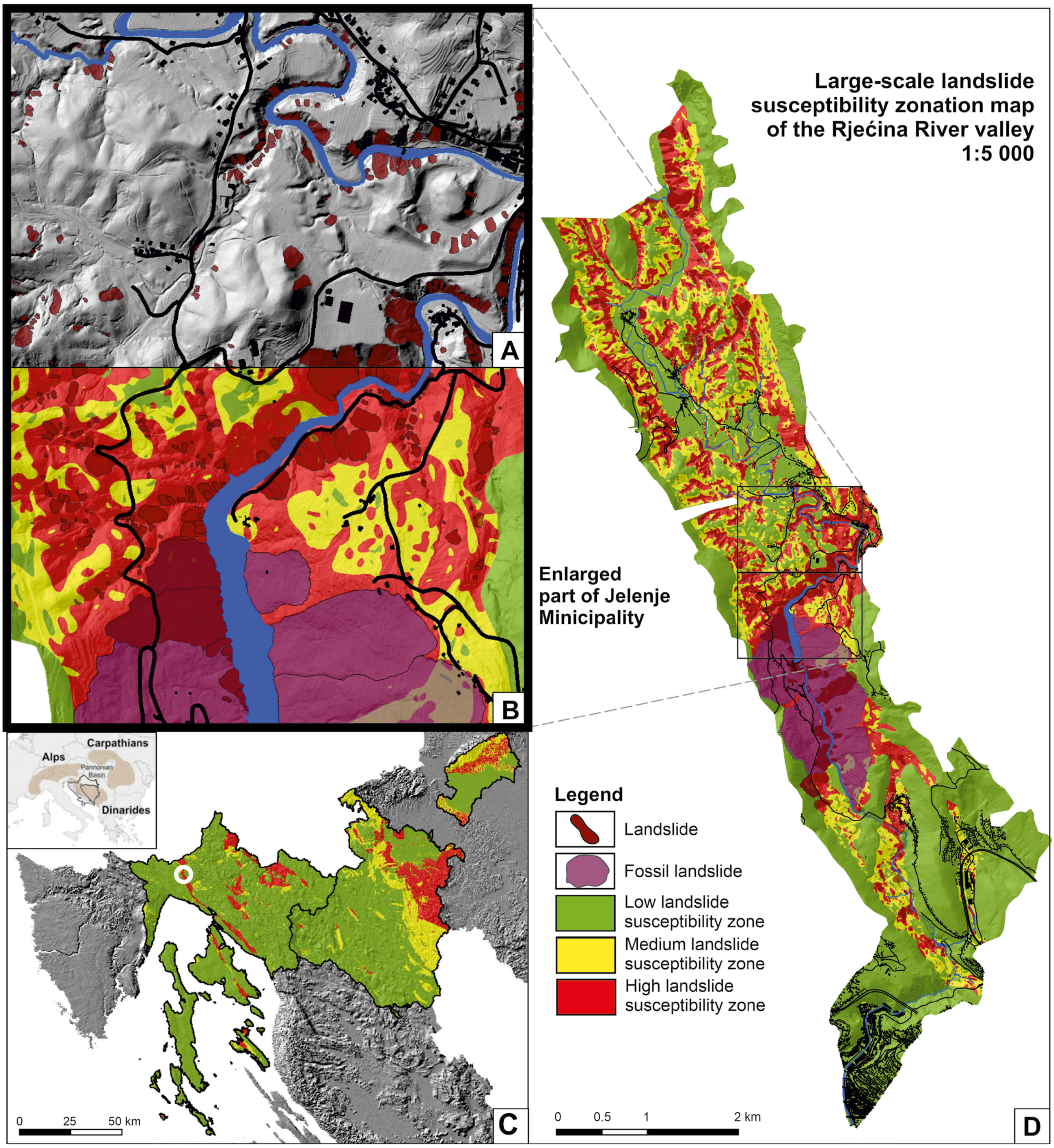


Figure 1 Examples of landslide maps prepared on a large scale for the Jelenje Municipality: (a) large-scale landslide inventory map; (b) large-scale landslide susceptibility zonation map; (c) location of the study area (white circle) on the mosaic of medium-scale landslide susceptibility zonation maps; (d) large-scale landslide susceptibility zonation map of the Rječina River valley (area of about 19 km² encompassing part of the City of Rijeka, Čavle Municipality and Jelenje Municipality). Spatial analysis showed that there are 37 buildings, and 3.4 km of roads endangered by landslides. The total number of landslides along superficial water courses is 287.

Landslides as areas of special restrictions in space: Advancement of physical planning by application of innovative technologies in thematic map development

Snježana Mihalić Arbanas[(1)], Gorana Ljubičić[(2)], Sanja Bernat Gazibara[(1)], Petra Jagodnik[(3)], Željko Arbanas[(3)]

1) University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Zagreb, Pierottijeva 6, Croatia
2) The Institute for Physical Planning of Primorje-Gorski Kotar County, Rijeka, Splitska ulica 2, Croatia
3) University of Rijeka, Faculty of Civil Engineering, Rijeka, Radmile Matječić 3, Croatia

The characteristics of the land and its landforms are strongly influenced by geomorphological processes (i.e., mass movements) because they leave traces or scars in the form of geomorphological phenomena. The processes are most common on inclined terrains or slopes (i.e., slope movements), e.g., in the form of sliding of soil, falling of rock or linear erosion. Landslide is the common term for 'footprint' or phenomenon resulting from a particular process(es). Landslides present geohazards because of their damaging effects on people and other goods and services. The land with a landslide is considered damaged because it requires additional investment for any kind of use, if that is even possible. Consequently, landslides need to be treated in physical planning as areas of special restrictions in use, which are related to the soil. Thus, the development of thematic maps based on available landslide data is necessary for the inclusion of information on landslides to obtain special restrictions for the development and implementation of spatial plans. The objective of the paper is to provide a comprehensive overview of the connection between the landslide topic and physical planning in Croatia and determine recommendations for efficient and reliable use of information about landslides to ensure safe and sustainable development, which is of special importance regarding climate change.

The first part of the paper provides the legislative status of landslides in Croatia, including legislative acts, and strategies from spatial planning, as well as from related sectors, such as environmental protection and risk management. The analysis has shown low recognition of the importance of spatial limitation due to landslide hazard and risk in Croatia. Protection from landslides in Croatia has been dealt with from the perspective of different sectors and several legislative acts that interpret landslides differently. Unfortunately, separate sector approaches, such as environmental protection, civil protection and physical planning, with partial involvement of landslides, result in negligible application of preventive measures. Moreover, the national document Disaster Risk Assessment of the Republic of Croatia has recognized physical planning as a common and integrative sector against landslide protection. The second part of the paper gives two examples of the application of thematic landslide maps available for cities and municipalities. One representative example is the City of Zagreb because of the longest tradition of landslide maps used in physical planning for the development as well as the implementation of the Spatial Plan of the City of Zagreb. This example shows the multiple landslide map developments in the last 60 years as proof of the continuous need for landslide information. Over this period, different approaches have been applied to mapping methodology and the use of landslide cartographic information. On the other hand, for most other cities and municipalities, landslide maps were not developed for that purpose at all. The analysis of spatial plans in Primorje-Gorski Kotar County shows a variety of thematic information used to compensate for the lack of landslide information in spatial planning (Table 1).

Recommendations for efficient and reliable use of information about landslides in physical planning are given based on the newest scientific results and innovative technologies. Today, in the 21st century, new technologies are available that enable obtaining high-quality and reliable data on landslides, that must be applied in spatial planning. Thanks to the use of new technologies and new knowledge gained through applied scientific research within the framework of the HRZZ LandSlidePlan Project (HRZZ IP-2019-04-9900, https://landslideplan.eu/) and EU Project PRI-MJER (KK.05.1.1.02.0020, https://pri-mjer.hr/), new findings clearly define a new direction in the development of landslide maps for applications on regional as well as local levels of spatial planning.

Keywords Croatia, landslides, physical planning, area of special, legislative, recommendations

To be published in: Mihalić Arbanas S, Ljubičić G, Bernat Gazibara S, Jagodnik P, Arbanas Ž (In prep) Landslides as areas of special restrictions in space: Advancement of physical planning by application of innovative technologies in thematic map development. Prostor: scientific journal for architecture and urban planning.

Table 1 Thematic information used in spatial plans in Primorje-Gorski Kotar County to compensate for the lack of landslide information. The grey box indicates that the theme is present in the graphical part of the spatial plan of the city/municipality.

Type of cartographic unit according to geological map (rock type) or geomorphological process(es) (derived from geological maps)	CITIES													
	Bakar	Cres	Crikvenica	Čabar	Delnice	Kastav	Kraljevica	Krk	Mali Lošinj	Novi Vinodolski	Opatija	Rab	Rijeka	Vrbovsko
Zone of magmatic rocks														
Zone of karst	■	■			■	■	■		■	■		■		■
Zone of Triassic clastic-carbonate rocks	■													
Zone of Palaeozoic clastic rocks	■													
Zone of Triassic clastic rocks and dolomites														
Zone of karst overlain by superficial deposits	■	■			■	■	■		■	■		■		
Carbonate rocks overlain by *Terra-Rossa*				■										
Zone of flysch														
Mostly unstable areas			■		■			■						■
Terrains of localised erosion with rare instability phenomena				■										
Area of potential erosion														
Area of intensive erosion			■	■					■					■
Area of intensive erosion – low risk											■			
Area of intensive erosion – moderate risk											■			
Area of intensive erosion – high risk											■			
Area of intensive erosion – very high risk											■			
Area of intensive erosion – flysch zone	■	■					■	■		■		■		
Deluvial (colluvial) deposit on flysch												■		
Fluvial deposits on carbonate rocks												■		
Fluvial deposits on flysch												■		
Zone of fluvial deposits	■	■					■							
Zone of alluvial deposits				■										
Zone of fluvioglacial deposits				■										
Zone of proluvial-alluvial deposits														
Zone of alluvial deposits										■				
Zone of torrent deposits										■				
Zone of marine origin sediments – sandy mud														
Embankment														
Estuary sediment														
Active of possible landslides or fall					■									
Erosion phenomena														

Type of cartographic unit according to geological map (rock type) or geomorphological process(es) (derived from geological maps)	MUNICIPALITIES																					
	Baška	Brod Moravice	Čavle	Dobrinj	Fužine	Jelenje	Klana	Kostrena	Lokve	Lopar	Lovran	Malinska-Dubašnica	Matulji	Mošćenička Draga	Mrkopalj	Omišalj	Punat	Ravna Gora	Skrad	Vinodolska općina	Viškovo	Vrbnik
Zone of magmatic rocks					■																	
Zone of karst	■		■	■	■	■		■	■	■	■		■							■		■
Zone of Triassic clastic-carbonate rocks																						
Zone of Palaeozoic clastic rocks									■													
Zone of Triassic clastic rocks and dolomites									■													
Zone of karst overlain by superficial deposits			■		■			■		■	■									■		■
Carbonate rocks overlain by *Terra-Rossa*																						
Zone of flysch										■												
Mostly unstable areas	■				■							■		■			■		■			
Terrains of localised erosion with rare instability phenomena																						
Area of potential erosion				■																		
Area of intensive erosion	■			■					■			■		■		■			■	■		
Area of intensive erosion – low risk																						
Area of intensive erosion – moderate risk																						
Area of intensive erosion – high risk																						
Area of intensive erosion – very high risk																						
Area of intensive erosion – flysch zone			■			■					■		■				■			■		■
Deluvial (colluvial) deposit on flysch																						
Fluvial deposits on carbonate rocks										■												
Fluvial deposits on flysch										■												
Zone of fluvial deposits																						■
Zone of alluvial deposits													■									
Zone of fluvioglacial deposits					■																	
Zone of proluvial-alluvial deposits			■					■												■		
Zone of alluvial deposits					■				■													
Zone of torrent deposits						■					■											■
Zone of marine origin sediments – sandy mud											■											
Embankment								■														
Estuary sediment								■														
Active of possible landslides or fall																				■		
Erosion phenomena							■															

Project Members

Full Professor
Snježana Mihalić Arbanas

University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering

Project Leader

Assistant Professor
Sanja Bernat Gazibara

University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering

Deputy of Project Leader

Marko Sinčić,
MSc.

University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering

Junior Researcher – Assistant
PhD fellow

Associate Professor
Martin Krkač

University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering

Researcher

Assistant Professor
Petra Jagodnik

University of Rijeka, Faculty of Civil Engineering

Researcher

Full Professor
Željko Arbanas

University of Rijeka, Faculty of Civil Engineering

Researcher

Hrvoje Lukačić,
MSc.

University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering

Researcher

Scan QR code and visit our web-site

www.landslideplan.eu