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

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Abstract This paper presents a result of landslide inventory mapping at the Bednja Municipality and Lepoglava City study area in Hrvatsko Zagorje region, NW Croatia. The landslides were interpreted from the high resolution (30 cm) digital elevation model (DEM) and its derivatives (slope and contour map, hillshade). The DEM was interpolated from the point cloud obtained by airborne laser scanning undertaken in spring 2020. In the study area of 20.22 km2, the total number of interpreted landslides is 912, making the average density of 45.1 ls/km^2. The average size of the recorded landslides is 448 m^2. According to the spatial plans, most of the studied area is covered by forests, agricultural areas, pastures, and artificial areas. The highest density of landslides is also in the forest areas, while the lowest is in the artificial areas. Furthermore, almost 64% of the mapped landslides are located within 50 m of the roads, and more than 39% of the mapped landslides are located within 100 m of the buildings and residential houses. Due to the level of detail provided and its completeness, the presented landside inventory map is an important tool for risk management at the local level because it gives detailed information necessary for risk evaluation as well as to decide about feasible options for risk mitigation, e.g., stabilisation measures vs relocation of the development to a more favourable location.

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

Introduction

A landslide inventory presents a detailed register of the distribution and characteristics of past landslides (Hervás 2013) in some areas. Preparation of a landslide inventory is an essential part of any landslide zoning (AGS 2007). According to the Guzzeti et al. (2012), landslide inventory maps are prepared for: (i) documenting the extent of landslide phenomena in areas ranging from small to large watersheds and from regions to states or nations; (ii) as a preliminary step toward landslide susceptibility, hazard, and risk assessment; (iii) to investigate the distribution, types, and patterns of landslides in relation to morphological and geological characteristics; and (iv) to study the evolution of landscapes dominated by mass-wasting processes. Landslide maps, including the landslide inventory map, are an essential tool in landslide risk management, supporting authorities, practitioners and decision-makers in the more appropriate and sustainable land planning and risk mitigation strategy development (Roccati et al. 2021).

In recent years, Light Detection and Ranging (LiDAR) data have been commonly used to map landslide morphology and estimate landslide activity in areas that are partly or completely covered by dense vegetation (Razak et al. 2010). 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 kilometres (Shan and Toth 2009). The technique uses a laser sensor mounted on an aeroplane or helicopter to measure the distance from the instrument and multiple points on the topographic surface. According to Guzzetti et al. (2012), more than 100 points per square meter can be measured. From elevation point clouds obtained by laser scanning, a detailed digital elevation model (DEM) can be produced and different DEM derivatives such as slope, hillshade or contour maps. High resolution DEM (HRDEM), and its derivatives, enables a recognition of landside morphology and thus interpretation of landslides.

In this paper, a historical inventory map of the study area in NW Croatia, interpreted from LiDAR HRDEM derivates, is presented and analysed regarding land-use data. In the context of risk assessment, land-use is a useful indicator of elements at risk, because the overlap of landslide inventory with the basic land use categories (forests, agricultural areas, and artificial surfaces) gives us information on landslide impact (e.g., Bernat Gazibara et al. 2019) that is necessary for following up risk assessment.

Study area

The study area comprises 20.22 km^2 of the hilly terrain, located in the Hrvatsko Zagorje region (Fig. 1). The area belongs to the Varaždin County, i.e., to the Bednja Municipality (14.28 km^2) and Lepoglava City (5.94 km^2). According to the land use data from the Bednja Municipality and Lepoglava City, the study area is covered by forests (52%), agricultural areas and pastures (52%) and artificial areas (8%). Approximately 12% of the area have

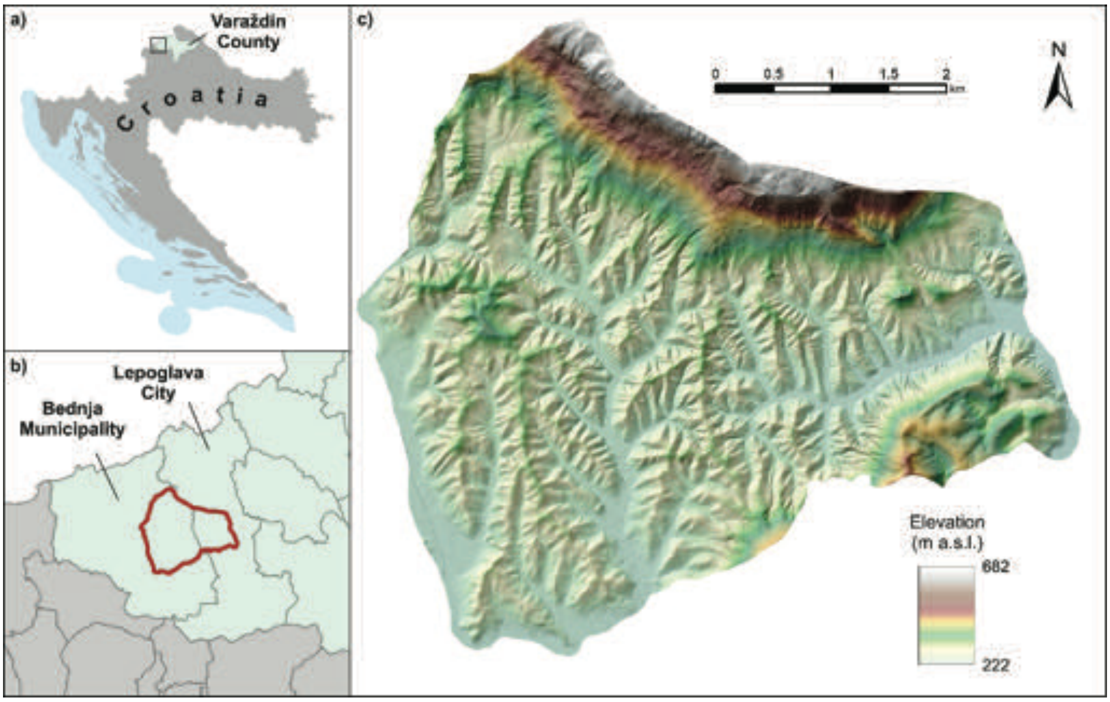

Figure 1 Location of the study area within the administrative units of the Republic of Croatia (a, b) and its relief conditions (c).

slope angles <5°, 15% of the area 5°–12°, 57% of the area 12°–32° and 14% of the area have slope angles >32°. The distribution of slope angels makes the study area potentially prone to sliding. The study area is composed of Miocene (78%), Quaternary (14%) and Triassic sediments (7%) according to the Basic Geological Map (Aničić and Juriša 1984; Šimunić et al. 1982). The Triassic sediments, located in the north-eastern part of the study area, are composed of Lower Triassic sandstones, shales, dolomites and limestones and Middle Triassic dolomites, limestones and dolomitised breccias (Šimunić et al., 1982). The Miocene sediments are composed of sandstones, marls, sands and tuffs (Burdigalian), and biogenic, sandy and marly limestones, calcareous marls and sandstones (Tortonian). The Triassic sediments incline mainly towards SW with dip angles 35°-60°. The Miocene sediments are subhorizontal (in W part of the study area) to steeply inclined (40°-55°) in NE and E parts of the study area (Aničić and Juriša 1984; Šimunić et al. 1982). The Quaternary sediments, composed of sands, silts and gravels, are located in the valleys around streams and rivers.

Precipitations and human activity are the primary triggers of landslides in NW Croatia (Bernat et al. 2014a). For example, abundant landslide events (Multiple-Occurrence Regional Landslide Events, MORLE) in the hilly areas of NW Croatia occurred in winter 2012/2013 due to the prolonged heavy rainfall periods and the rapid melting of a thick snow cover (Bernat et al. 2014b). Generally, the climate of the study area is continental with a mild maritime influence. The mean annual precipitation for the period of 1949-2020 is 873.7 mm, according to the data from the meteorological station in the City of Varaždin, located approximately 30 kilometres to the east (DHMZ 2022). The majority of precipitations (approx. 70%) falls mainly from May to November.

Data and methods

Lidar data

LiDAR data for the study area was acquired in the framework of the project „Methodology development for landslide susceptibility assessment for land-use planning based on LiDAR technology (LandSlidePlan)“ financed by the Croatian Science Foundation. Airborne laser scanning (ALS) was undertaken in March 2020, which corresponds to the winter leaf-off period in Croatia. The LiDAR system used in this study captured data at a pulse rate of 400 kHz with a surface point horizontal accuracy of 3 cm and vertical accuracy of 4 cm.

The total number of points in the LiDAR point cloud for the area of 20.22 km^2, 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. Those points were used for the creation of the bare-earth digital elevation model (DEM) with a 0.3 m resolution.

Visual interpretation of landslides on LiDAR DEM

The topographic derivative datasets used to interpret the landslide morphology were hillshade maps, slope maps and contour lines (Fig. 2). In addition, orthophoto images from 2014-2016 were used to check the morphological forms along roads and houses, such as artificial fills and cuts, similar to landslides on DEM derivatives. Derivatives of the LiDAR DEM were computed in ArcGIS 10.8.

Landslide identification on the LiDAR DEM derivatives was manual and GIS-assisted, based on recognising landslide features (e.g., concave main scarps, hummocky landslide bodies and convex landslide toes).

Hillshade maps calculated with different azimuth angles (45°, 135° and 315°) were used to avoid shades covering landslide features hindering the delineation of the landslide boundary (Schulz 2007). A slope map (Fig. 2b) was used to interpret steep areas, which may also indicate scarps, ridges, or landslide toes (Ardizzone et al., 2007). Contour lines with a spacing of 0.5 m were helpful for the identification of concave and convex features such as landslide accumulation and depression zones, respectively. The mapping was performed at a large scale (1:100–1:500) to ensure the correct delineation of the landslide boundaries. Each mapped landslide polygon was assigned with the certainty of landslide identification and precision of mapping.

Anthropogenic landslide conditioning factors analysed in this study were land use data, transport infrastructure network (roads) and buildings (Fig. 3). Land use data were obtained from the official spatial plans of the Municipality of Bednja (2019) and the City of Lepoglava (2017). Land use classes from both spatial plans were firstly merged using ArcMap 10.8 and then simplified into three categories (artificial areas, agricultural areas and pastures, and forests) as described in Table 1. According to the land use data, 10.5 km² (52%) of the study area is covered by forests, 8.07 km² (40%) of the area is covered by agricultural areas and pastures and 1.63 km² (8%) of the area are artificial surfaces.

Traffic infrastructure was partly obtained from spatial plans and partly by digitising the roads from aerial photos and hillshade maps derived from LiDAR DEM. The total length of the roads covering the study area is 165 km.

The buildings in the study area were obtained from the LiDAR point cloud points classified as buildings according to the ASPRS (2011). The points classified as buildings were converted to polygon shapefiles in ArcMap 10.8 and checked on aerial photos. The total number of mapped buildings in the study area is 1849.

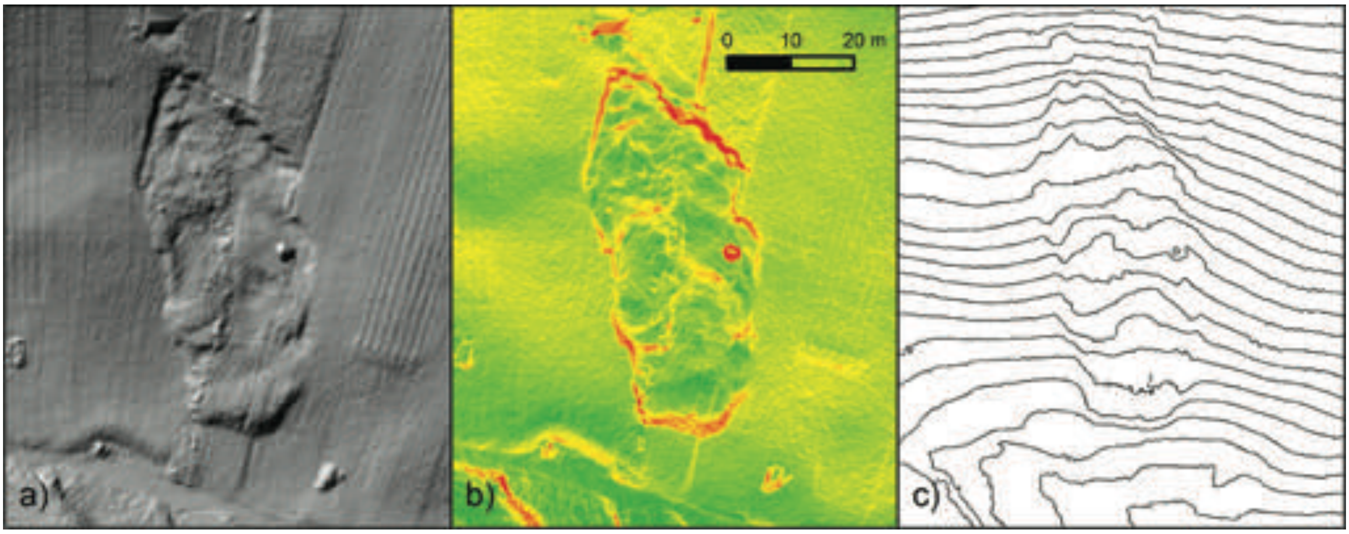

Figure 2 Landslide identified on the three different topographic derivative DTM maps: (a) hillshade map; (b) slope map; and (c) contour map (0.5 m spacing).

Table 1 Land use classes from spatial plans of Municipality of Bednja, City of Lepoglava and merged land use classes of the study area.

Merged classes	Municipality of Bednja	City of Lepoglava
Artificial areas	Settlement area with constructions	Settlement area with constructions
	Construction site	Construction site outside of the settlement area
	Graveyard	Graveyard
		Tourist area
Agricultural areas and pastures	Valuable agricultural areas	Valuable agricultural area
	Other agricultural areas	Other agricultural area
	Other agricultural areas and forests	Other agricultural areas and forests
	Settlement area without constructions	Settlement area without constructions
		Areas and buildings related to agricultural activities
Forest areas	Commercial forest	Commercial forest
	Commercial forest under management of the Republic of Croatia	Other forests

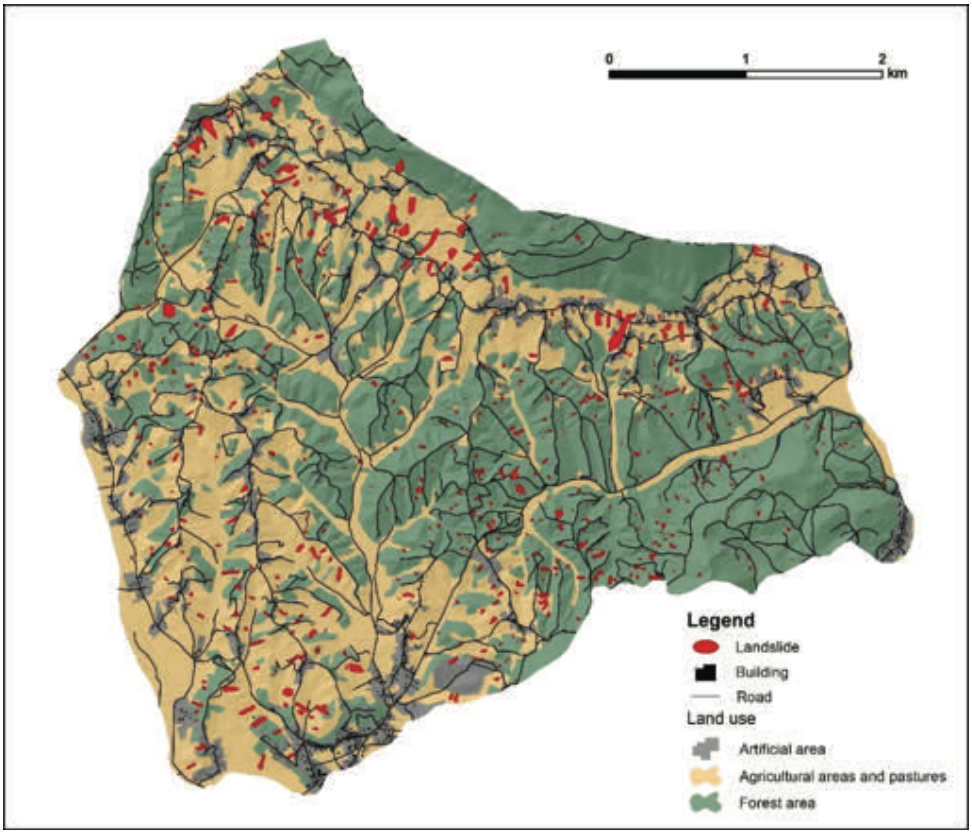

Figure 3 Spatial distribution of the anthropogenic landslide causal factors in the study area and landside inventory mapped on the LiDAR DEM.

Results

Landslide inventory map

Initially, 904 landslides were mapped on the LiDAR DEM derivatives of the study area. 24% (214) of randomly selected landslides were checked on the field. From the 214 checked phenomena, 20 phenomena were rejected as landslides. Additionally, 28 phenomena were mapped in the field and added to the landslide inventory, making the total number of landslides in the inventory 912 (Fig. 3).

The total area of mapped landslides is 0.408 km², or 2.02% of the study area. The mean landslide density is 45.1 slope failures per square kilometre. The size of the recorded landslides ranges from a minimum value of 3.3 m² to a maximum of 13,779 m², whereas the average area is 448 m² (median = 173 m², std. dev. = 880 m²). The most frequent landslides in the inventory have an area of approx. 200 m², and almost 85% of the landslide bodies showed a size between 40 and 2,000 m². 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 frequency–size distribution of all mapped landslides in the pilot area (Fig. 4) shows two scaling regimes: a positive power-law scaling for small landslides and a negative power-law scaling for medium and large landslides. The transition between the positive and the negative power-law relations can be used to distinguish between small and medium landslides. Based on the rollover at approximately 200 m², 48% of the mapped landslides are small (<200 m²) and 52% are medium and large (>200 m²) in size. The prevailing dominant types of landslides are probably shallow soil slides.

The relative relationship between landslides and types of land-use

The analyses of landslide statistics relative to land-use types were performed by using points, which represent landslide polygon centroids. The landslide density per land-use unit (Tab. 2) shows that 73.8% of the mapped landslides appear in forest areas, 23.6% on agricultural areas and pastures, and only 2.6% on artificial surfaces. The mean landslide density in forests is 64 ls/km², more than two times higher than in agricultural areas and pastures (26.7 ls/km²) and almost five times higher than in artificial areas (14.7 ls/km²). One of the possible explanations is that LiDAR-based landslide inventories can often be incomplete on settlements and arable lands due to frequent anthropogenic influences (Bell et al. 2012; Bernat et al. 2019; Petschko et al. 2015; Steger et al. 2016). 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°).

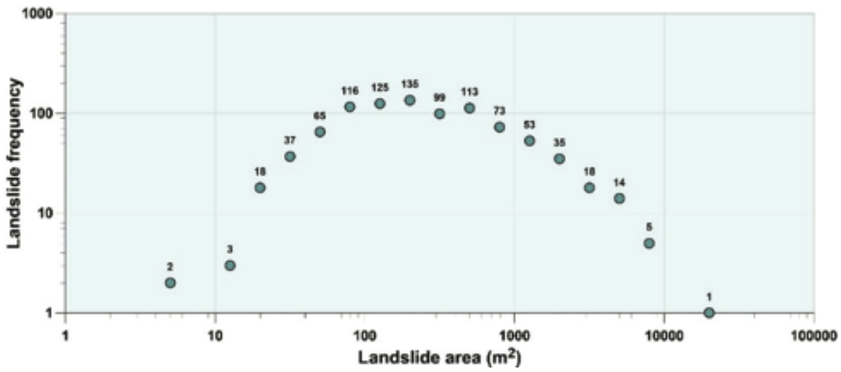

Figure 4 Frequency–size distribution of all mapped landslides in the study area (20.22 km²) of the Hrvatsko Zagorje region.

In contrast, the artificial areas and agricultural areas and pastures in the study area are likely to be associated with the less favourable conditions for landslide initiation, i.e. on the surfaces with more gentle slope angles (average slope angle for artificial areas is 14°, and for agricultural areas and pastures 16°).

Analysis of the landslide distribution in the study area shows that more than 56% of the mapped landslides are located within 25 to 75 m from the roads (approx. 45% of the study area). Additionally, more than 39% (314) of the mapped landslides are located within 100 m of the buildings (approx. 34% of the study area).

Table 2 Landslide density per land-use unit in the study area.

Anthropogenic factors	Area (km²)	Area (%)	Landslide number (%)
Land use			
Forest areas	10.5	52.1	73.8
Agricultural areas and pastures	8.1	39. 9	23.6
Artificial areas	1.6	8.1	2.6
Distance from roads			
0-10 m	3.2	15.7	7.9
10-25 m	4.2	20.8	19.7
25-50 m	5.6	27.5	32.9
50-75 m	3.6	18.0	23.5
75-100 m	2.0	10.0	10.9
>100 m	1.6	8.1	5.2
Distance from buildings			
0-10 m	0.9	4.6	0.8
10-25 m	1.3	6.4	3.3
25-50 m	2.1	10.1	10.0
50-75 m	2.0	9.6	10.6
75-100 m	1.7	8.4	9.8
>100 m	12.3	60.9	65.6

Conclusions

LiDAR DEM map and its derivatives were used for detailed landslide mapping of the hilly area in the Hrvatsko Zagorje region, NW Croatia. Visual interpretation of the 20.22 km² area resulted in a landslide inventory map with 912 landslides and a mean landslide density of 45.1 ls/km². LiDAR DEM map with a resolution of 0.3 m, and its derivatives, proved to be a valuable tool for mapping landslides in the Hrvatsko Zagorje region, even for landslides of the small area. The area of the smallest mapped landslide is 3.3 m², and almost 50% of the landslides are smaller than 200 m². The frequency-size distribution shows that the landslide inventory of the study area is substantially complete. Most of the mapped landslides are historical landslides. However, the presence of small landslides and landslides with a significant degree of preserved morphology indicates that the inventory map includes relatively recent seasonal landslides. This seasonal inventory probably represents landslides (re)activated in winter 2012/2013 and in spring 2018.

Most of the mapped landslides are located in forest areas, showing one of the advantages of using LiDAR in the Hrvatsko Zagorje region that enables mapping landslides under dense vegetation cover. Only 26% of landslides are located in artificial areas, agricultural areas and pastures. The difference in landslide density (frequency) between land use classes indicates that landslide inventories in artificial areas, agricultural areas, and pastures are often incomplete due to frequent anthropogenic influences and changes in natural morphology. However, these areas are also less favourable for landslide initiation because of more gentle relief with prevailing smaller slope angels.

Even though the landslide density is two to five times higher in forest areas than in agricultural areas, pastures and artificial areas, the landslides still present a significant threat to transportation infrastructure and buildings. Spatial analyses show that almost 64% of the mapped landslides are located within 50 m from the roads, and more than 39% of the mapped landslides are located within 100 m from the buildings and residential houses.

Due to the level of detail provided and its completeness, presented landside inventory presents an important tool for the following risk mitigation measures: (i) avoid the risk by measures applied in the process of spatial and urban planning; (ii) reduce the frequency of sliding and its consequences by stabilisation measures; (iii) manage the risk by establishing monitoring and warning systems; and (iv) transfer the risk by, e.g., by the provision of insurance to cover potential property damage.

Because of a variety of possible applications, the presented landslide inventory map is intended for numerous users from spatial and urban planning, construction, and civil protection. In addition, the same map also provides valuable and necessary data for preparing a landslide susceptibility map in the detailed scale for local application, another essential tool for spatial development and land-use planning.

Acknowledgments

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