Landslide Detection and Spatial Prediction: Application of Data and Information from Landslide Maps

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Abstract

The need for landslide maps of wider areas has increased with the understanding that proper planning will considerably decrease the construction and maintenance cost of structures. The main objective of the paper is to present types of data and information on landslides that can be derived from landslide inventory and landslide susceptibility maps and their use for spatial and urban planning. Recent examples of landslide zonation maps from Croatia are given to show the possibility of the derivation of data about landslides by using LIDAR (Light Detection and Ranging) DTM (Digital Terrain Model) for the compilation of historical landslide inventory. The application of data about landslide phenomena is compared with the application of information from landslide susceptibility zonation maps. It is 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.

1 Introduction

The first review of landslide hazard zonation maps was compiled by Varnes and the IAEG Commission on Landslides and other Mass-Movements (Varnes 1984) as part of the landslide risk mitigation programme published by UNESCO. Given the content of these maps, there are two basic types that are fundamentally different: maps presenting records of landslide phenomena and maps showing a prediction of landslide processes in terms of spatial probability (i.e., landslide susceptibility) or temporal probability (i.e., landslide hazard). Landslide records in the form of landslide contours are collected by landslide detection and mapping. The results are displayed on the landslide inventory maps that are discussed in detail in the paper Guzzetti et al. (2012). Spatial prediction of landslides is the result of landslide susceptibility assessment and it is displayed on the landslide susceptibility zonation maps that present the distribution of resulting susceptibility in the form of a few zones. The most recent overview of the main methods to predict populations of landslides in space and time is given by Guzzetti et al. (2021).

During the period of more than 35 years, numerous attempts and unquestionable progress happened in landslide mapping and zonation. The most recent and revolutionary change in methods and techniques used to detect and map landslides is an application of high-resolution LiDAR (Light Detection and Ranging) bare earth DTM (Razak et al. 2011). The capability of the derivation of the detailed landslide inventory in highly vegetated areas with shallow landslides is enabling further development of landslide maps for application in spatial and urban planning. This will also have

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a positive impact on the enhancement of landslide zoning maps by offering new opportunities to prescribe provision of legislative action for the purpose of regulating the land use and the construction of buildings within the area under the jurisdiction of the legislative body concerned.

The main objective of the paper is to present types of data and information on landslides that can be derived from landslide inventory and landslide susceptibility maps and their use for spatial and urban planning. The paper is organized into three main chapters. Some methodological aspects of the preparation of landslide inventory maps are dealt with in the chapter "Landslide detection and mapping". Emphasis is on applying the LIDAR technology and ALS (Airborne Laser Scanning) to landslide inventory mapping. Examples of historical landslide inventories are given to illustrate the quality and quantity of data derived by visual identification of shallow landslides and by compilation of complete detailed landslide inventories. The chapter "Susceptibility modelling and zonation" introduces basic concepts related to landslide susceptibility assessment and resulting zonation maps. A multi-stage approach to landslide susceptibility mapping is noted, from small to large scale. Examples of landslide susceptibility maps derived from an assessment on

the national, regional and local levels are given to illustrate the quality of map information. The chapter "Application of landslide data and information" summarises general considerations of applying data and information from landslide maps in land use planning. Scale-related objectives are given for a hierarchical approach to producing landslide zoning maps. We have used examples of spatial planning documents of different levels from Croatia and landslide maps of multiple study areas (Fig. 1).

2 Landslide Detection and Mapping

Detecting or identifying landslide features on the ground surface is part of the landslide mapping, which precedes the cartographic representation of slope movements. The task of the expert performing mapping is the recognition of changes in the surface topography left by the occurrence of a landslide (or landslide signature, Pike 1988). The choice of the type and scale of the resulting map depends on many factors, primarily on the end user's requirements and the ultimate purpose of the landslide mapping (Mihalić Arbanas and Arbanas 2015).
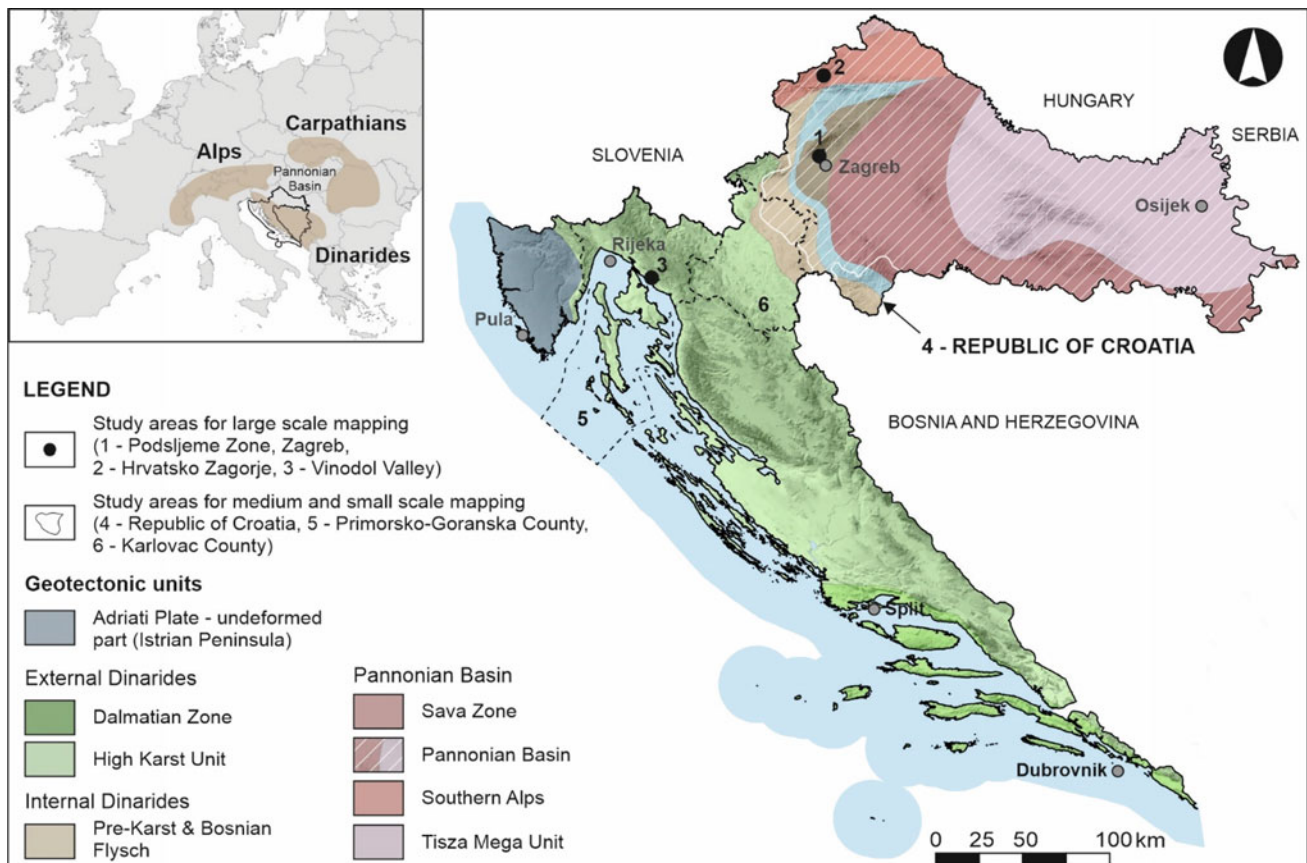
Fig. 1 Study areas used as pilot areas for landslide inventory mapping and landslide susceptibility mapping

Guzzetti et al. (2012) provide an overview of types of landslide inventory maps followed by a comprehensive description of methods and techniques for their preparation. There are two main types of inventory maps, archive and geomorphological maps. Methods of their preparation include some or all of the following: remote sensing, ground surveys and archive data from different sources (e.g., literature etc.). Generally, archive landslide inventories are of small scale (> 1:200,000), compiled based on literature or other archive sources (inquires to public organisations and private consultants, chronicles, journals, technical and scientific reports, interviews of landslide experts etc.) without involved procedures of landslide detection and mapping. Contrary, geomorphological landslide inventories contain landslide data derived through the process of interpretation of aerial photographs, very high-resolution satellite images or digital terrain models (DTM), followed by limited ground survey (i.e., field checks) to derive medium- (1:25,000–1:200,000) or large-scale (>1:25,000) landslide inventory maps. The types of geomorphological landslide inventories differ depending on the time-span of input data (photographs, images, DTM) that are used for landslide detection. Summarised overview of the main characteristics of historical, event, seasonal and multi-temporal landslide inventory maps, according to Guzzetti et al. (2012), is given in Table 1.

The objective of landslide detection aims to determine landslide boundaries at the ground surface. Regardless of the adopted technique, detecting and mapping landslides are complex, time-consuming, and error-prone task (Galli et al. 2008). Over the last decade, airborne laser scanning has been made available and has been used to identify and map landslide morphology in areas partially or completely covered by dense vegetation (Carter et al. 2001; Razak et al. 2011). Airborne laser scanning (ALS) is also known as airborne LiDAR or airborne laser swath mapping (ALSM). LiDAR elevation data prove particularly effective where the terrain is forested, a condition where old and very old, deep-seated landslides are difficult to identify using traditional aerial photography or satellite imagery (Eeckhaut et al. 2007; Razak et al. 2011), and perform well also in arid and sub-arid regions where the vegetation cover is sparse or inexistent. Recognition of small cracks and detailed geomorphological features might be the best surface landslide characteristics that can be interpreted from these images (Fig. 2), which provides additional information compared with other types of images or photos.

A relatively new remote-sensing tool uses airborne mounted lasers to obtain digital representations of the topographic surface for areas ranging from a few hectares to thousands of square kilometers (Shan and Toth 2017). Visual analysis and interpretation of the topographic surface remain the most common and most promising application of a very-high-resolution (metric to decametric) DEM captured by airborne LiDAR sensors for detecting and mapping landslides over large areas (Guzzetti et al. 2012). The required resolution of a bare-earth LiDAR DEM for identifying landslides primarily depends on the landslide size.

Table 1 Geomorphological landslide inventories classified by their scale and the type of mapping (Guzzetti et al. 2000, 2012, 2021; Malamud et al. 2004; Galli et al. 2008)

| Type (Guzzetti et al. 2004, 2005; Galli et al. 2008; Fiorucci et al. 2011)	Landslide map data	Landslide age
Historical	Many landslide events throughout tens, hundreds or thousands of years	The age of the landslides is not differentiated or is given in relative terms, i.e., recent, old or very old
	Examples: Brabb and Pampeyan (1972), Antonini et al. (1993), Cardinali et al. (2001), and Galli et al. (2008)	
Event	Landslides caused by a single trigger, such as an earthquake, rainfall event or snowmelt event	The landslides' date corresponds to the triggering event's date (or period)
	Examples: Harp and Jibson (1996), Buckman and Jeffrey (2001), Lin et al. (2004), Guzzetti et al. (2004), Cardinali et al. (2006), Tsai et al. (2010), Dai et al. (2011), Parker et al. (2011), and Gorum et al. (2011)	
Seasonal	Landsides triggered by single or multiple events during a single season, or a few seasons identified by exploiting multiple sets of aerial or satellite images of different dates	The date (or periods) of the landslides is attributed based on the date (or periods) of the triggers and the date of the imagery or the field surveys carried out to compile the inventories
	Examples: Guzzetti et al. (2004, 2005), Galli et al. (2008), and Fiorucci et al. (2011)	
Multi-temporal	Landslides triggered by multiple events over more extended periods (e.g., years to decades) identified by exploiting multiple sets of aerial or satellite images of different dates	The date (or periods) of the landslides is attributed based on the date (or periods) of the triggers and the date of the imagery or the field surveys carried out to compile the inventories
	Examples: Guzzetti et al. (2004, 2005), Galli et al. (2008), and Fiorucci et al. (2011)	
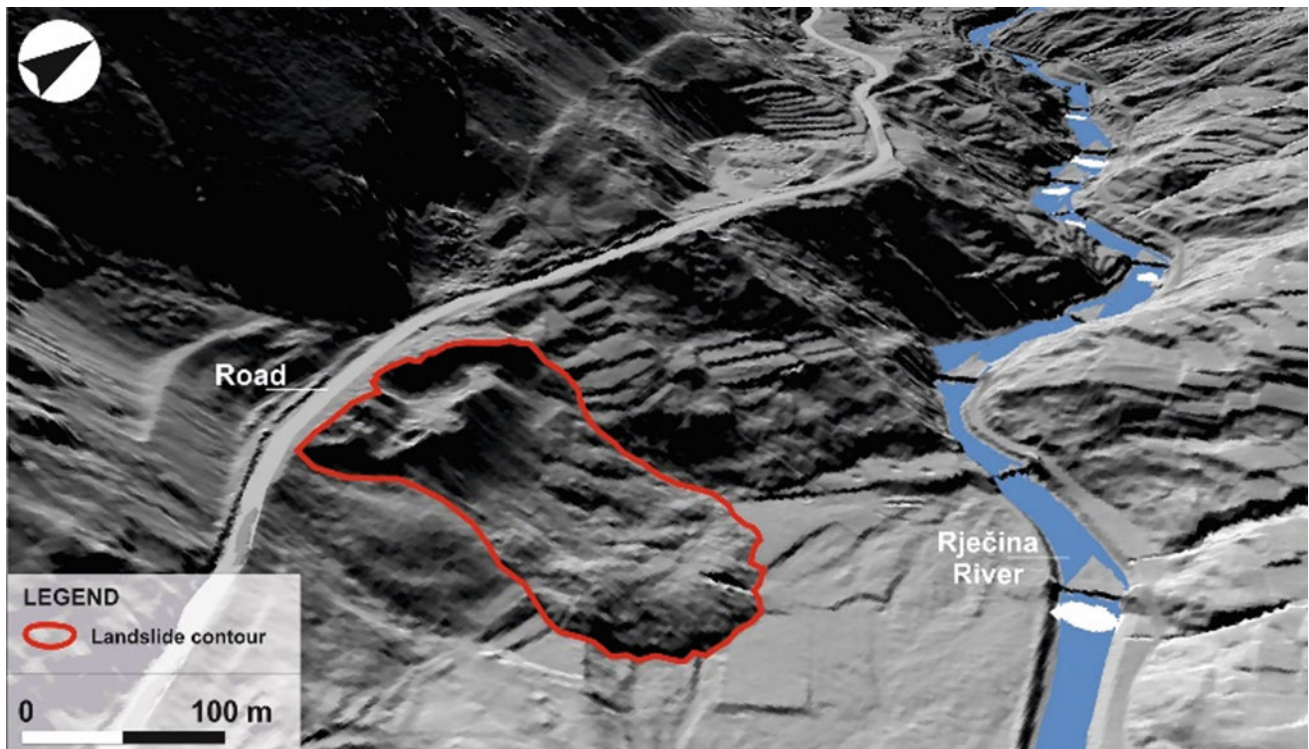
Fig. 2 Oblique aerial view prepared from the LIDAR-derived bare-earth DTM of the Rječina River Basin (Croatia) (Mihalić Arbanas and Arbanas 2015)

Examples from the literature reveal that investigators have used 5-m resolution DEM (Glenn et al. 2006; Eeckhaut et al. 2007), 2-m resolution DEM (Ardizzone et al. 2007), 1.8-m resolution DEM (Schulz 2007), 1-m resolution DEM (McKean and Roering 2004; Chen et al. 2006; Mihalić et al. 2013; Đomlija et al. 2014; Đomlija 2018) and 30-cm resolution DEM (Bernat Gazibara 2019; Sinčić et al. 2022).

2.1 Historical Inventories Derived from LiDAR Images

A geomorphological historical inventory shows the cumulative effects of many landslide events throughout tens, hundreds or thousands of years (Guzzetti et al. 2012). This chapter presents the experience gained in Croatia, collected through detecting and mapping landslides from high-resolution LiDAR images produced based on ALS in different landslide-prone geomorphological settings in Croatia. Recognition of landslides was performed through the visual analysis of a series of LiDAR derivatives by experienced and trained landslide scientists, using a systematic methodology and well-defined interpretation criteria (Bernat Gazibara et al. 2019a; Jagodnik et al. 2020a; Krkač et al. 2022).

The first study area, located in the hills of the Zagreb city (known as the Podsljeme area), belongs to the continental part of Croatia in the Pannonian Basin (Fig. 1). The study area (of 21 km^2), at the southeastern-facing slope of the Medvednica Mt., is urbanized and densely populated, with prevailing artificial surfaces (about 56%) and equally represented agricultural areas and forests (both about 22%). The area is composed of Quaternary soils (heterogeneous mixtures of unfoliated, mostly impermeable clayey-silty soils) and stratified upper Miocene soils and soft rocks (sands, silts and marls) (Šikić 1995). Gentle relief combined with geomechanical properties of the abovementioned soils is a preparatory causal factor for shallow soil slides, as it is confirmed by the landslide inventory presented in Fig. 3. Intense precipitation is the main triggering factor (Bernat Gazibara et al. 2019a). In total, the landslide inventory from the Zagreb city consists of 702 landslides with a non-uniform distribution across the pilot area (Bernat Gazibara et al. 2019a). The prevailing types are shallow soil slides; only ten landslides were classified as earth flows. Nearly 65% of all the identified landslides were evaluated as 'high confidence' due to the visible landslide features on the LiDAR derivatives, and almost 60% of all mapped landslides were evaluated as 'high precision' due to the fresh and clearly visible landslide boundaries on the LiDAR
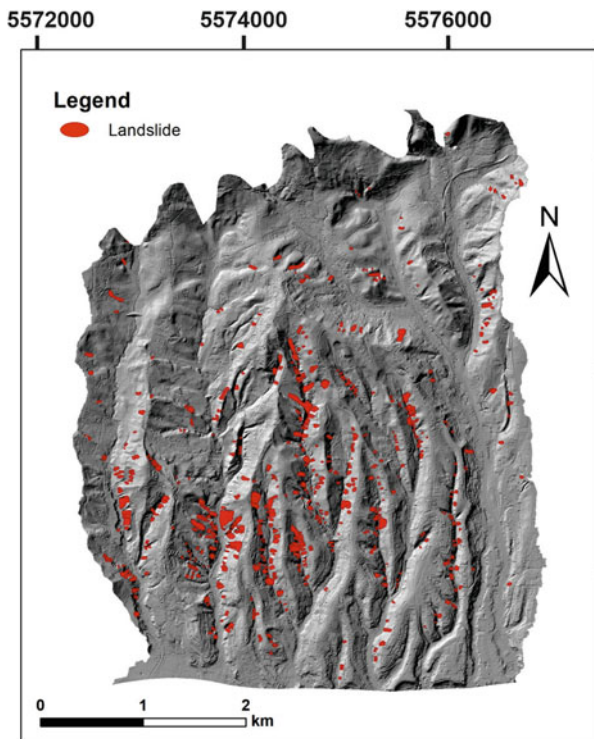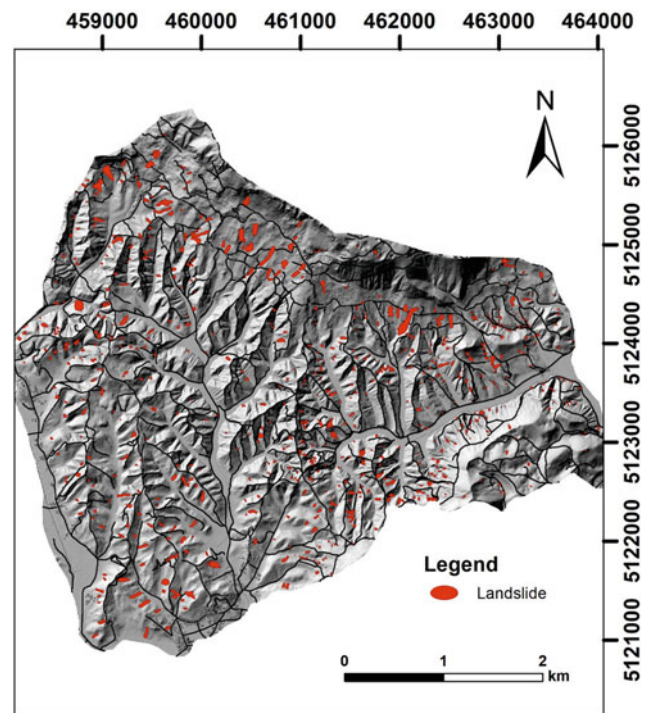
Fig. 3 Landslide inventory of the study area in the Zagreb city (area 21 km^2) derived by visual interpretation of LiDAR DTM morphometric maps (modified from Bernat Gazibara et al. 2019a, b)

Fig. 4 Landslide inventory of the study area in the Hrvatsko Zagorje (area 20.22 km^2) derived by visual interpretation of LiDAR DTM morphometric maps (modified from Sinčić et al. 2022)

derivatives. Based on the landslide inventory, the total landslide area is 0.5 km^2 (about 2.43% of the pilot area). The mean landslide density is 33.4 slope failures per square kilometer.

The second study area is located in the hills of the Hrvatsko Zagorje region in the Pannonian Basin (Fig. 1). The study area (20.22 km^2) differs from the previous one based on geomorphological settings and land use. According to Krkač et al. (2022) this study area is covered with forests (52%), agricultural areas and pastures (40%) and sporadic artificial areas (8%). Slopes are composed chiefly of Miocene soils, soft- and hard rocks (sandstones, marls, sands, tuffs and biogenic, sandy and marly limestone, calcareous marls and sandstones) and Triassic hard rocks (sandstones, shales, dolomites, limestone and dolomitized breccias) (Šimunić et al. 1982; Aničić and Juriša 1984). The inclination of bedding in Miocene and Triassic rocks vary depending on structural geological settings. Quaternary soils cover only flat areas in valleys around superficial streams.

Non-uniform distribution across the pilot area is caused by changes in relief types (from steeper to more gentle slopes) and lithologies (soft rocks and hard rocks). In total, the landslide inventory from the Hrvatsko Zagorje region consists of 912 landslides (Fig. 4), mainly shallow soil slides and earth flows (Sinčić et al. 2022). Nearly 58% of all the

identified landslides on the LiDAR DTM were evaluated as 'high confidence' due to the clearly visible landslide features on the LiDAR derivatives. Based on the landslide inventory, the total landslide area is 0.408 km^2 or 2.02% of the pilot area. The mean landslide density is 45.1 slope failures per square kilometer.

The third study area is in the Vinodol Valley (area of 64.57 km^2), situated in Dinarides (Fig. 1), in the NW coastal part of the Adriatic Sea (Jagodnik et al. 2020a, b, c). The geomorphological settings of the area is controlled by the valley's tectonic origin that resulted in an elongated shape stretched the in Dinaric NW–SE direction. The area is predominantly rural, with approximately 30 settlements connected by a network of county and local or unnamed roads. Comparing to the two abovementioned study areas, the valley is characterized by higher precipitation. The valley flanks are composed of Upper Cretaceous and Palaeogene hard rocks (carbonates), while the lower parts and the bottom of the valley are built of Palaeogene flyschoid rock (Šušnjar et al. 1970). Superficial deposits in the valley are formed by various geomorphological processes on slopes, such as rock falls, debris flows, debris slides, and gully erosion. Fluvial deposits cover flat areas around the Dubračina river and its tributes. Heterogenous geological settings of the valley resulted in numerous landslide types. Đomlija (2018)
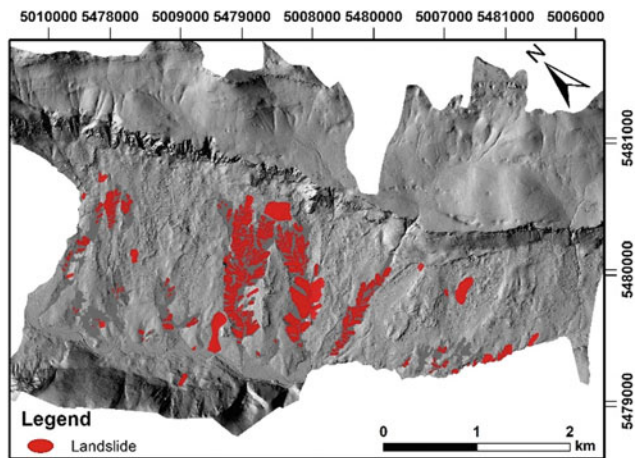
Fig. 5 Details from the historical landslide inventory of the Vinodol Valley (modified from Đomlija 2018) for the southeastern part of the Dubračina River Basin

identified 10 types of landslides using a modified Varnes classification (Hungr et al. 2014). The five landslide types were identified and mapped using LiDAR DTM morphological derivative maps: rotational rock and soil slide, debris slide and avalanche, and debris slide-debris flow. Figure 5 presents part of the landslide inventory. In total, the inventory consists of 631 landslides with a non-uniform distribution across the area (Đomlija 2018). The most abundant landslide phenomena are shallow debris slides (approx. 98%) of all activity styles (complex, composite, successive, single, multiple), typically activated along the contact between the flysch bedrock and superficial deposits. Regardless on the landslide type, about 80% are developed within the gully landforms (Jagodnik et al. 2020a). Because of that, 236 gullies are also mapped, with a total area of 1.89 km^2. The smallest gully channel has an area of 317 m^2, the largest 0.48 km^2, while the average has an area of 6700 m^2. The smallest mapped landslide is debris slide of 65 m^2 and the largest is rotational rock slide of 63,708.5 m^2. Nearly 24% of all the identified landslides (394 phenomena), which could be outlined in their entirety by visual interpretation of the LiDAR DTM, were evaluated as 'clearly expressed', and nearly 76% as 'poorly expressed'. Based on the landslide inventory, the total landslide area is 1.51 km^2 or 2.3% of the pilot area. The mean density of landslides is 9.77 slope failures per square kilometer. Besides abundant debris slides, there are only 11 phenomena determined and mapped as rock and soil slides and rock avalanche. The remaining six landslide types identified by Đomlija (2018) were impossible to map as separate phenomena. Most of them are phenomena of processes on steep rocky slopes.

2.2 Landslide Statistics and Completeness of the Inventory

This chapter presents the landslide statistics obtained from three inventory maps that represent hilly areas in Zagreb city, the Hrvatsko Zagorje region and Vinodol Valley. The quality, reliability and completeness of the landslide inventory affect (i.e., control) the quality of the resulting susceptibility assessment (Carrara et al. 1992; Ardizzone et al. 2002). The characteristics and the quality of the three inventories was evaluated using the methodology proposed by Malamud et al. (2004).

In the first study area in Zagreb city, with the mean landslide density of 33.3 slope failures per square kilometer, the smallest identified landslide has a planimetric area (A_L) of 43 m^2 (Bernat Gazibara et al. 2017). The mapped landslides extend in size to a maximum of 8064 m^2, while the mean landslide area is approx. 700 m^2 (mean = 704 m^2, median = 411 m^2, std. dev. = 921 m^2). The most frequent landslides in the inventory have an area of approx. 400 m^2, and 90% of the landslide bodies showed a size between 100 and 2000 m^2. The frequency–size distribution of all mapped landslides in the pilot area (Fig. 6a) shows two regimes: a positive power-law behavior for small landslides and a negative power-law behavior 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 maximum value at approximately A_L = 400 m^2, 48% of the mapped landslides are small (A_L < 400 m^2) in size.

In the study area of the Hrvatsko Zagorje region, the mean landslide density is 45.1 slope failures per square kilometre. The size of the identified landslides ranges from a minimum value of 3.3 m^2 to a maximum of 13,779 m^2, whereas the average area is 448 m^2 (median = 173 m^2, std. dev. = 880 m^2). The most frequent landslides in the inventory have an area of approx. 200 m^2, and almost 85% of the landslide bodies showed a size between 40 and 2000 m^2. The frequency–size distribution of all mapped landslides in the pilot area (Fig. 6b) shows two regimes: a positive power-law behavior for small landslides and a negative power-law behavior 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 maximum value at approximately A_L = 200 m^2, 48% of the mapped landslides are small (A_L < 200 m^2) and 52% are medium and large (A_L > 200 m^2) in size. The prevailing dominant types of landslides are shallow soil slides.

Fig. 6 Frequency–size distribution of all mapped landslides in: (1) the study area (21 km^2) of the Podsljeme area (Zagreb city in Pannonian Basin); (2) the study area (20 km^2) of the Hrvatsko Zagorje region in Pannonian Basin; (3) the study area (64.57 km^2) of the Vinodol Valley in the Dinarides
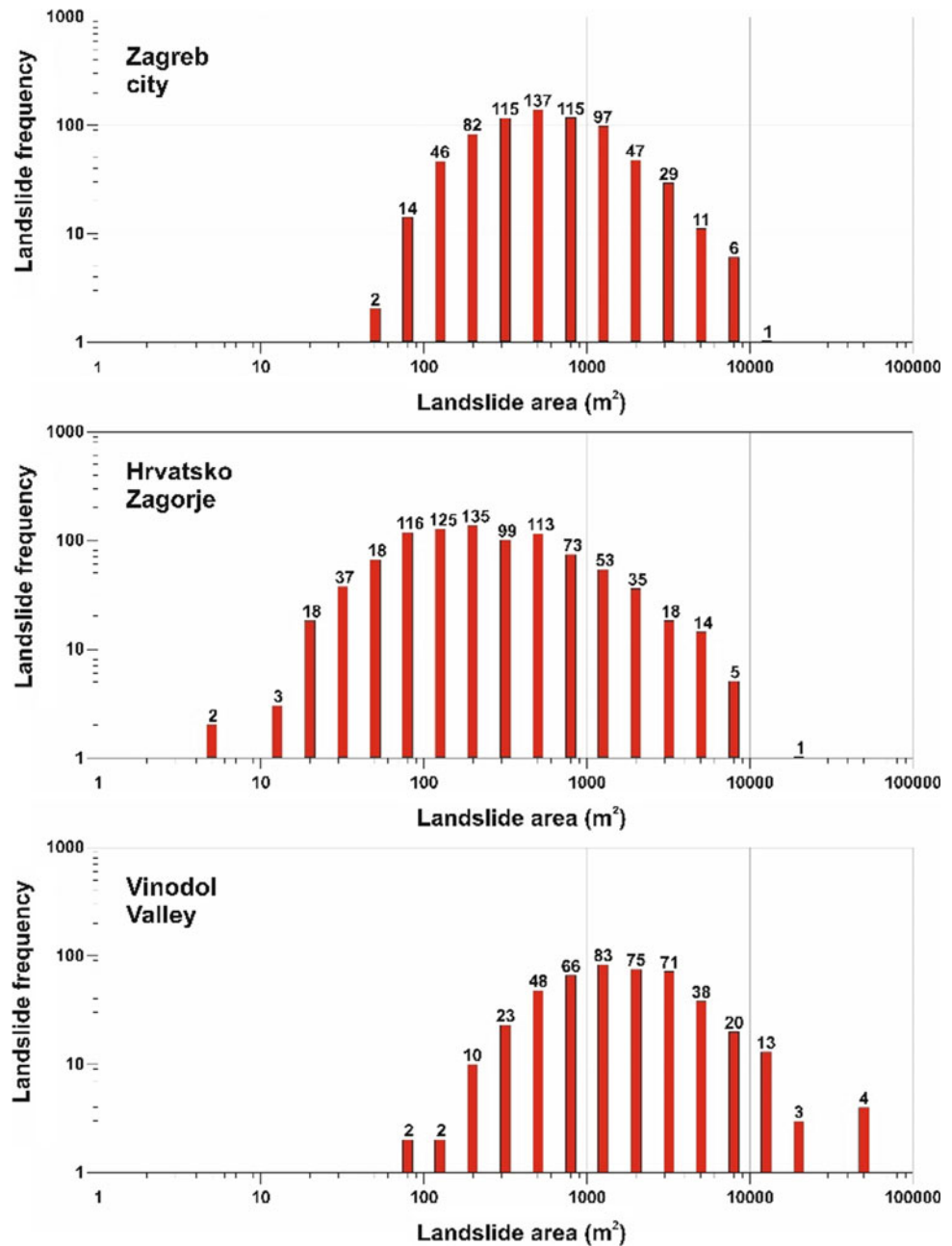
In the study area of Vinodol Valley, the mean landslide density is 9.77 slope failures per square kilometer. The size of the identified landslides ranges from a minimum value of 64.8 m^2 to a maximum of 49,461.62 m^2, whereas the average area is 2336.70 m^2 (median = 1218.17 m^2, std. dev. = 4,498.11 m^2). The most frequent landslides in the inventory have an area of approx. 1200 m^2, and almost 80% of the landslide bodies showed a size between 500 and 20,000 m^2. The frequency–size distribution of all mapped landslides in the pilot area (Fig. 6c) shows two regimes: a positive power-law behavior for small landslides and a negative power-law behavior 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 maximum value at approximately A_L = 1500 m^2, 58% of the mapped landslides are small (A_L < 1500 m^2), and 52% are medium-large (A_L > 1500 m^2) in size. The dominant types of landslides are debris slide and debris slide-debris flow (Jagodnik et al. 2020a).

The distribution obtained for the mapped landslides in the two study areas in Pannonian Basin and in one in the Dinarides can be explained by the 'universal distribution' described by Malamud et al. (2004), which implies that the occurrence of a landslide in the pilot area is a result of either

natural triggering factors (e.g., rainfall or rapid snowmelt) or human actions with regional impacts (e.g., widespread deforestation and urbanisation). Frequency–size distribution of all mapped landslides in Zagreb city (Fig. 6a), the Hrvatsko Zagorje region (Fig. 6b) and the Vinodol Valey (Fig. 6c) are complete landslide inventory maps because they include a substantial fraction of all landslides at all scales.

3 Susceptibility Modelling and Zonation

The identification and map portrayal of areas highly susceptible to damaging landslides is the first and necessary steps toward loss reduction. This section uses several essential terms, such as 'hazard', 'susceptibility' and 'zonation'. The terminology used in this work is consistent with the landslide hazard and risk definitions proposed by such international committees as Varnes (1984), Fell et al. (2008), United Nations Human Settlements Programme (2012) and ISSMGE TC32 (2004). Predicting where, when, how many, and how large landslides are expected in an area and during a particular period is the main aim of landslide hazard assessment (Varnes 1984; Guzzetti et al. 2005, 2021). Landslide hazard zonation is commonly portrayed on maps. Landslide susceptibility assessment and modelling are limited to the spatial prediction of landslides. Landslide susceptibility maps present spatial, time-independent probability of landslides occurring in an area depending on local terrain conditions (Guzzetti et al. 1999, 2005). The most frequent input data about terrain conditions belong to the categories of geomorphological, geological, hydrological and anthropogenic landslide factors.

The first extensive papers on the use of digital spatial data for landslide susceptibility mapping date back to the late seventies and early eighties of the last century. Among the pioneers in this field were (Brabb et al. 1972) in California and Carrara et al. (1977) in Italy. All research on landslide susceptibility and hazard mapping uses Geographic Information System (GIS) as digital tools for handling spatial data. Van Westen's dissertation (Van Westen 1993) is the first comprehensive overview of the application of GIS technology to landslide susceptibility assessment followed by a classification of analysis methods. Thirteen years later, a dissertation by Guzzetti (2006) provided numerous examples of analysis, assessment, and zonation of landslide susceptibility, hazard, and risk in Italy, which have been subjects of numerous scientific studies. Soon after that, 'Guidelines for Landslide Susceptibility, Hazard and Risk Zoning for Land Use Planning' (Fell et al. 2008) was prepared by the Joint Technical Committee on Landslides and Engineered Slopes of three international societies. Simultaneously, an overview of the types of spatial data required for

landslide susceptibility, hazard, and vulnerability assessment and the methods for obtaining these data was published in van Westen et al. (2008). The most recently published recommended methodologies for the quantitative analysis of landslide hazard, vulnerability, and risk at different scales (site-specific, local, regional, and national) are from Corominas et al. (2013). These methodologies primarily include quantitative approaches developed worldwide during the preceding decade. Reichenbach et al. (2018) performed critical review of statistical methods for landslide susceptibility modelling and associated terrain zonations based on compiled extensive database of 565 peer-review articles from 1983 to 2016. They also provide recommendations for the preparation, evaluation, and use of landslide susceptibility models and associated terrain zonations. Results can be exploited for different purposes that are spatial and urban planning, identification of the most suitable scenarios of risk mitigation measures, prioritization of the areas that require control works in tandem with their design, and the use of funds earmarked for mitigating the risk. Landslide susceptibility assessment can be considered the initial step towards a landslide hazard and risk assessment, but it can also be an end-product that can be used in land-use planning and environmental impact assessment.

Landslide susceptibility zonation involves a degree of interpretation aimed at the prediction of spatial distribution and rating of the terrain units according to their propensity to produce landslides. Moreover, landslide susceptibility is defined as the tendency of a specific area to be affected by a particular type of landslide in the future (Brabb 1984; Guzzetti et al. 2005). The value of susceptibility is usually a relative one and the quality of landslide susceptibility models is known to be highly dependent on the quality of input data (Sinčić et al. 2022), such as the landslide inventory (Guzzetti et al. 2012) and the terrain attributes (predictors) (van Westen et al. 2008). The possibility of obtaining the required input data strongly affects the type of assessment method that can be used and the scale of analysis. All the susceptibility assessment approaches and methods proposed in the literature can be grouped into five broad categories (Reichenbach et al. 2018), namely: (i) geomorphological mapping; (ii) analysis of landslide inventories; (iii) heuristic or index-based approaches; (iv) process-based, or physically based numerical modelling methods; and (v) statistically based modelling methods. Qualitative approaches are subjective, ascertain susceptibility heuristically, and portray susceptibility levels using descriptive (qualitative) terms. Quantitative methods produce numerical estimates for susceptibility zones, resulting in more precise probabilities of occurrence of landslide phenomena (Guzzetti et al. 1999).

Maps are a useful and convenient tool for presenting information on landslide susceptibility. They can present

many kinds and combinations of information at different levels of detail. Susceptibility maps used in conjunction with land-use maps are a valuable planning tool. The development of a clear hierarchical methodology in hazard zonation is necessary to obtain an acceptable cost–benefit ratio and to ensure the practical applicability of the zonation (Soeters and Van Westen 1996). The working scale for a susceptibility analysis is determined by the requirements of the user for whom the assessment or zonation is executed. Because planners and engineers form the most important user community, the following scales of analysis can be differentiated for landslide hazard zonation (IAEG 1976): Small scale maps (<1:100,000); Medium scale maps (1:10,000 to 1:100,000); Large scale maps (>1:10,000). The current practice in Europe (Corominas and Mavrouli 2010) shows that the scale of the landslide zoning maps required by state or local authorities varies significantly from country to country, depending on the coverage, input data and methods that are used as well as the information provided (qualitative or quantitative). Commonly, there is a multi-stage approach to landslide susceptibility and hazard mapping, from national maps on a small scale to local maps on a large scale. If resources are limited, it may be more prudent to bypass small-scale mapping and concentrate on a few known areas of concern (Highland and Bobrowsky 2008).

3.1 National and Regional Level Assessment

National landslide zoning maps at a small scale are created to give a general overview of critical areas for an entire country and can be used to inform national policymakers and the public (Soeters and Van Westen 1996). The next stage is regional mapping, which synthesizes available data and identifies general problem areas at the regional level to produce small- or medium-scale susceptibility maps. The third stage is the local-level mapping, a more detailed susceptibility mapping program on a large scale that includes areas of local administrative units (municipality or city) or complex critical areas. We present here two types of susceptibility mapping performed in Croatia that resulted from national and regional level landslide susceptibility modelling and zonation. This presented experience is gained through heuristic modelling of landslide susceptibility for the whole territory of Croatia and for two counties, Karlovac County and Primorsko-Goranska County (Fig. 1). Susceptibility zonation was performed by experienced landslide scientists, using knowledge to decide about the relative influence of factor maps (van Westen et al. 2008).

The Republic of Croatia covers an area of 56,594 km^2 and has about 4 million inhabitants. As it is depicted in Fig. 1, 49% of the Croatian area belongs to the Pannonian Basin, 51% to the Dinarides and Adriatic Plate (Istrian

Peninsula) (Mihalić Arbanas et al. 2017). Mean annual rainfall ranges from 300 to 1000 mm/year in the Pannonian part of Croatia to more than 3000 mm/year in the Adriatic region. Multiple-Occurrence Regional Landslide Events (MORLE) have been triggered by intense precipitation events during very wet seasons in 2006, 2010, 2013, 2014, and 2018. There are no systematic landslide inventories at the country level, neither archival nor geomorphological. Risk assessment of the Republic of Croatia (Mihalić Arbanas et al. 2019) showed that the MORLE with the greatest consequences happened in 2013 (Bernat et al. 2014a, b), and the most likely MORLE is from 2018 (Bernat Gazibara et al. 2019b). In the winter period of 2012/2013, more than 900 (re)activated landslides were recorded in NW Croatia, and the largest number was in the Krapina-Zagorje County, with 521 landslides in total.

To develop a national landslide susceptibility map (Fig. 7), the fuzzy logic method has been applied to 15 different combinations of causal factors, because of lack of complete landslide inventory. The Area Under the Receiver Operating Characteristic Curve (AUROC) was used to validate all derived landslide susceptibility maps and the best was selected as the final one for further classification into three susceptibility zones (Table 2, Fig. 7) based on natural breaks classification method. With over 90% of mapped landslides falling in high and very high susceptibility zones, the results are considered satisfactory for national scale landslide modelling. The analysis showed that approximately 28% of the area of Croatia is potentially prone to sliding. Particularly landslide-prone areas in Croatia are
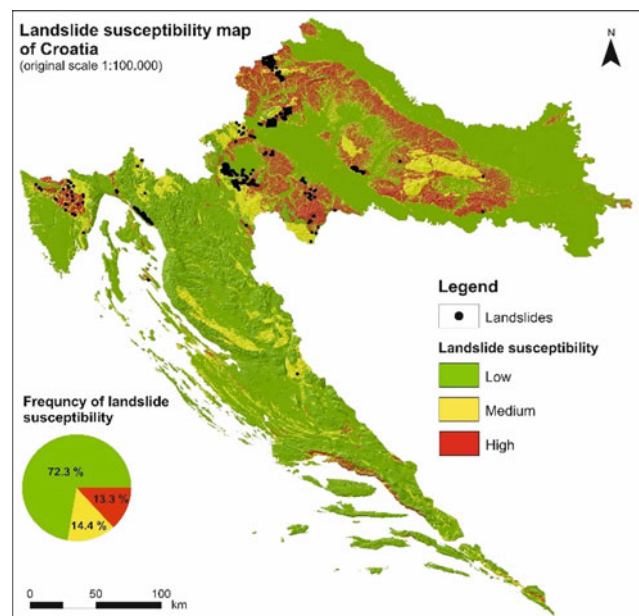
Fig. 7 Landslide susceptibility map of Croatia, original scale 1:100,000 (Bernat Gazibara et al. 2022)
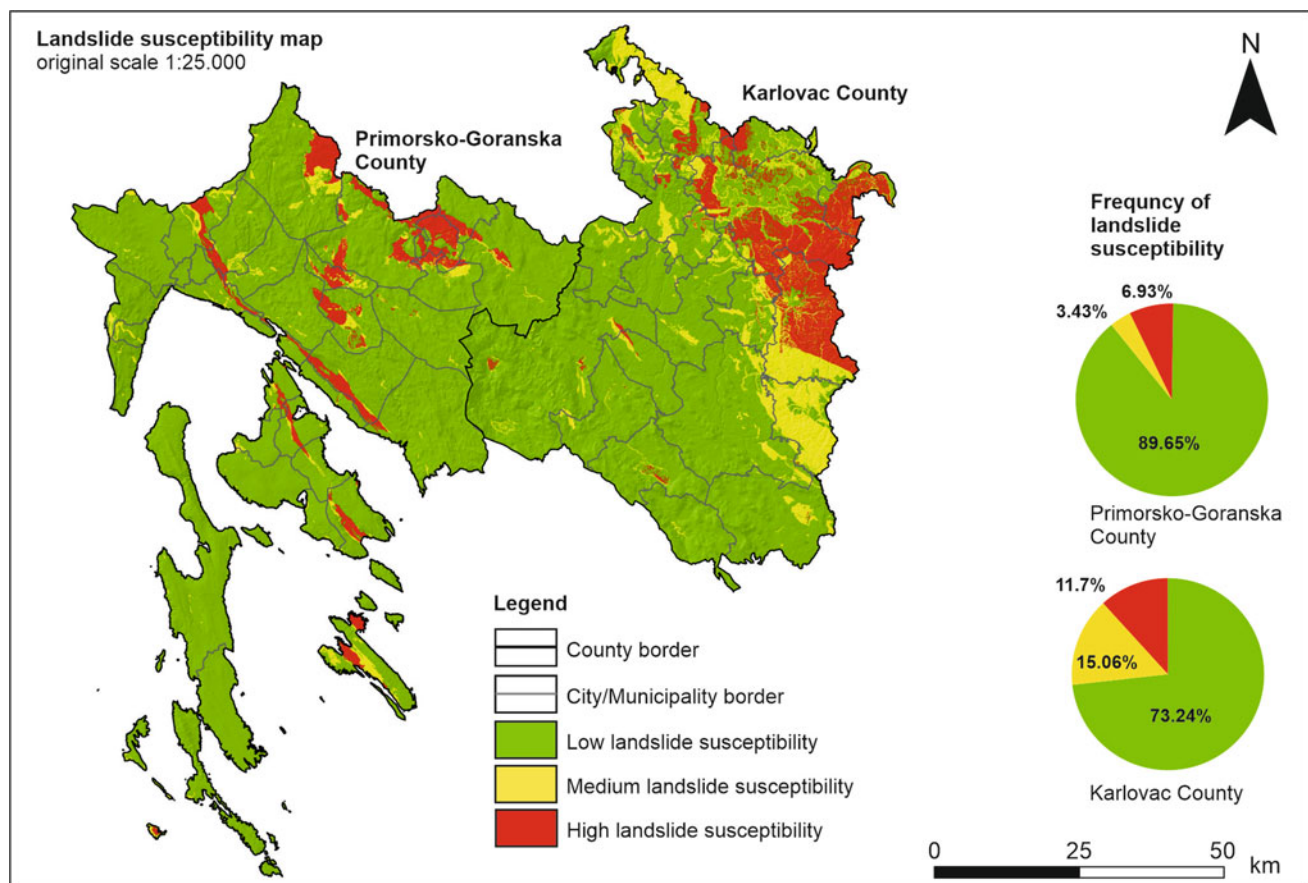
Table 2 Spatial distribution of landslide susceptibility zones in the Republic of Croatia

Landslide susceptibility zone	Area (km^2)	Area (%)
Non-susceptible	40,922.37	72.33
Low susceptibility	8144.12	14.39
High susceptibility	7512.43	13.28

lowlands and hills in the Pannonian Basin, the hills of the Istrian Peninsula and isolated narrow valleys in the Dinarides, such as Rječina River Valley and Vinodol Valley in Primorje.

To develop a regional-scale landslide susceptibility map of the Karlovac County (Fig. 8a) and of the Primorsko-Goranska County (Fig. 8b) on a medium scale (1:25,000), the same Fuzzy heuristic approach was used. It was applied for both counties because of the lack of representative landslide inventory using the same factor maps were analyzed for geomorphological and anthropogenic factors. The main difference in the methodology assessment, compared to the abovementioned assessment on a national scale, is the

use of a more detailed geological map, i.e., the Basic Geological Maps on the scale of 1:100,000. Results are more detailed susceptibility zonations on the county level. Based on AUROC, several derived landslide susceptibility maps were validated to select the final one for both counties, which were classified into three susceptibilities. With over 89% of mapped landslides falling in high and very high susceptibility zones, the results are considered satisfactory for regional scale landslide modelling. The analysis showed that approximately 27% of the area of Karlovac County and approx. 10% of the area of Primorsko-Goranska County is potentially prone to sliding (Table 3, Fig. 8a and b). The highest susceptible areas in Karlovac County are in the western and north-western part that belongs to the lowlands and hills of the Pannonian Basin. In Primorsko-Goranska County located in the Dinarides, several isolated zones throughout almost whole the county are highlighted, either in the form of narrow or otherwise relatively small, isolated zones. A comparison of both county maps with the national landslide susceptibility map shows that there is more detailed elaboration on the county map.

Fig. 8 Regional-level landslide susceptibility maps of the Primorsko-Goranska County and the Karlovac County, original scale 1:25,000

Table 3 Spatial distribution of landslide susceptibility zones in Primorsko-Goranska County and Karlovac County

Landslide susceptibility class	Karlovac County		Primorsko-Goranska County	
	Area (km^2)	Area (%)	Area (km^2)	Area (%)
Non-susceptible	2816.33	73.24	3216.04	89.65
Low	579.02	15.06	122.91	3.43
High	450.24	11.71	248.58	6.93

3.2 Local Level Assessment

Landslide zoning maps at a large scale can be used for the determination of hazard zones in areas affected by urbanization or large engineering structures and roads. The areas to be investigated may cover upward of a few hundreds of square kilometers, yet a considerably higher level of detail is required at this scale. The detail should be such that adjacent slopes in the same lithology are evaluated separately and may obtain different hazard scores depending on their characteristics, such as slope angle or form and type of land use. Within the same terrain unit, a distinction should be made between different slope segments. For example, a concave slope should receive a different rating, when appropriate, then an adjacent straight or convex slope. We present here one example of preliminary large-scale susceptibility mapping performed for the urbanized hilly area in the Zagreb city (Croatia) that resulted from local level landslide susceptibility modelling and zonation. The presented experience is obtained by Bernat Gazibara et al. (2019a) through statistical modelling of landslide susceptibility at the pilot area of 21 km^2 (Fig. 1) that is representative for the whole Podsljeme area (Bernat Gazibara et al. in press). Susceptibility zonation was performed by experienced landslide scientists, using high-resolution LiDAR morphometric derivative maps and univariate statistical analysis. Landslide susceptibility analysis on a large scale of 1:5000, conducted for the pilot area of the Podsljeme zone using bivariate statistics, is fully described in the doctoral thesis by Bernat Gazibara (2019) and here is shortly presented only necessary information to enable comparison of input data and resulting information with susceptibility assessment performed in medium and small scale for national and regional level zonation.

Podsljeme area of 180 km^2 is described in the previous chapter together with its geomorphological historical landslide inventory map. In the densely populated area with 56% settlement construction area, most of the terrain remained in a natural condition or has been slightly modified by urbanization. This enabled the derivation of a complete detailed inventory (Bernat Gazibara et al. 2019a) by visual interpretation of LiDAR DTM derivative maps.

The landslide susceptibility assessment on a large scale was performed based on the described landslide inventory and on a series of geofactors relevant to landslide occurrence

Table 4 Spatial distribution of landslide susceptibility zones in the Podsljeme area

Landslide susceptibility zone	Area (km^2)	Area (%)
Non-susceptible	9.03	42.75
Low susceptibility	4.36	20.63
Medium susceptibility	3.04	14.40
High susceptibility	4.69	22.22

divided into the following main groups: geomorphological (elevation, slope gradient, slope orientation), geological (lithology-rock type, proximity to geological contacts, proximity to faults), hydrological (proximity to drainage network) and anthropogenic (proximity to traffic infrastructure and buildings, land cover). The final preliminary landslide susceptibility model was derived using nine geofactors selected based on weights evaluated by the Weights-of-Evidence (WoE) model. The cut-off values of landslide susceptibility were defined based on classification of the ROC curve according to the criteria from Bernat Gazibara (2019), based on cumulative number of landslides: $\geq$ 85% —very high susceptibility; 15%—high susceptibility; 5%— medium susceptibility; 1% low susceptibility. The resulting susceptibility zonation (Table 4, Fig. 9) has a success and prediction rate of 88% making it a highly accurate source of preliminary information for the study area.

4 Application of Landslide Data and Information

Due to the severe socioeconomic and environmental damage and losses that result from landslides, a considerable variety of techniques and practices have been employed to mitigate the potential losses arising from landslide occurrence. The approach of avoiding landslide-prone areas is rarely feasible, and it is neither possible nor desirable to proscribe development in all landslide-prone areas. The question then becomes one of identifying the most effective of the various mitigation approaches and obtaining funding to apply the best. The USGS proposal for a national landslide hazards mitigation strategy (Spiker and Gori 2000) clearly summarizes the major mitigation approaches, including: Restricting development in landslide-prone areas; Enforcing codes for
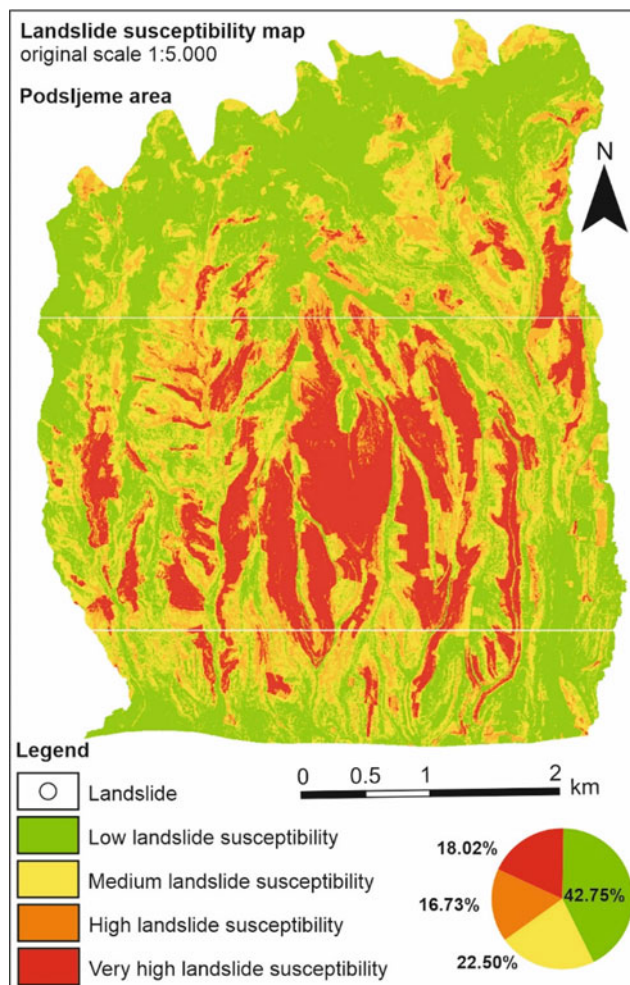
Fig. 9 Local-level landslide susceptibility map, original scale 1:5000, of the Podsljeme area (21 km^2) derived by statistical univariate analysis using landslides represented by points from a complete landslide inventory map depicting 702 phenomena (modified from Bernat Gazibara 2019)

excavation, construction, and grading; Engineering for slope stability; Deploying monitoring and warning systems; and Providing landslide insurance.

The USGS proposal for a national strategy aimed at mitigation of landslide hazard (Spiker and Gori 2000) also states that "landslide inventory and landslide susceptibility maps are critically needed in landslide-prone regions of the nation". These maps must be sufficiently detailed to support mitigation action at the local level. The identified three activities that will be required to provide the landslide maps, assessments, and other information needed by officials and planners to reduce landslide risk and losses are:

1. Develop and implement a plan for mapping and assessing landslide and other ground failure hazards nationwide;

2. Develop an inventory of known landslide and other ground failure hazards nationwide;
3. Develop and encourage the use of standards and guidelines for landslide hazard maps and assessments.

Members of users of landslide data and information differ widely in the kinds of information they need and, in their ability, to use that information (Wold et al. 1989). There are four general categories of these potential users:

1. Scientists and engineers who use the information directly;
2. Planners and decision-makers who consider landslide hazards among other land-use and development criteria;
3. Developers, builders, and financial and insuring organizations; and
4. Interested citizens, educators, and others with little or no technical experience.

4.1 General Considerations

The most comprehensive overview of the application of data and information from landslide maps in land use planning is given by the JTC-1 Joint Technical Committee on Landslides and Engineered Slopes in the form of Guidelines for Landslide Susceptibility, Hazard and Risk Zoning for Land Use Planning (Fell et al. 2008). They use the term "landslide zoning" for the creation of the multiple types of maps: landslide inventory; susceptibility; hazard and risk zoning maps. The practical value of the Guidelines is for those who are considering the introduction of land use management controls for landsliding. The Guidelines provide recommendations to decide the type of the zoning (inventory, susceptibility, hazard, risk) and level of detail (preliminary, intermediate, advanced) which they require based on the purpose of the zoning (information, advisory, statutory, design). They may choose to scale the zoning (regional, local, site-specific) and implementation of land use controls. Landslide zoning for land use planning is most commonly required at the local government level for planning urban development but may be required by state or federal governments for regional land use planning or disaster management planning. It may also be required by land developers, those developing major infrastructure such as highways and railways or managing recreational areas.

In some countries, landslide inventory, susceptibility, hazard and risk maps are introduced across the country. Fell et al. (2008) point out examples of the PPR (Plans de Prevention des Riques Naturels Previsibles) in France (Ministère de l'Aménagement du Territoire et de l'Environnement, 1999) and the Cartes de Dangers or

Gefahrenkarten in Switzerland which are carried out at the Canton level but with Federal funding support (Leroi et al. 2005). Lateltin et al. (2005) state that the Federal regulation introduced in 1991 in Switzerland required the 26 Cantons to establish hazard maps and landslide zoning for all types of mass movements to restrict development on hazard-prone land. The cantonal authorities have been participating actively in this hazard mapping to prevent and reduce the potential losses and the number of victims, through better land use planning. After 14 years, mapping works were still in progress to cover the Swiss territory by landslide hazard maps at different scales. Based on the nationwide experience, Lateltin et al. (2005) consider that the application of a strict management policy, carried out with the approval of the citizens, allows for a significant decrease in landslide risks.

In practice, those considering landslide zoning for land use management would be well advised to seek advice from an Engineering Geologist or a Geotechnical Professional who is familiar with landslide zoning and risk management to provide advice in planning the landslide zoning study and applying the outcomes to land use planning. Moreover, the scales for landslide susceptibility zoning maps must be harmonized with the scales and requirements of spatial plans.

4.2 Scale-Related Objectives

This chapter presents the experience gained in Croatia, collected through the production of detailed landslide inventory maps from high-resolution ALS LiDAR images (Figs. 3, 4 and 5) as well as landslide susceptibility maps on a small, medium and large scales (Figs. 7, 8 and 9). Proposed possibilities for application of the presented landslide maps are derived based on numerous discussions with Croatian planners and decision-makers who consider landslide data and information together with other land-use criteria. There are three levels of spatial plans in Croatia. Table 5 shows types of spatial and urban plans at the State, Regional and Local levels. The largest scale required will determine the level and scale of landslide zoning.

Generally, the small scale landslide susceptibility map of Croatia (1:100,000) is more likely to be used in the preliminary stages of development at the national level. In the case of a medium scale landslide susceptibility map of the county (1:25,000), the use of mapping which defines a planning control area may be sufficient to identify where a more detailed landslide risk assessment is needed. Detailed stages of development require a large scale landslide susceptibility map and a landslide inventory map of the city or municipality (1:5000).

Figures 10 and 11 present part of the previously described detailed landslide inventory maps on a large scale overlapped with land use in the urban area in Zagreb and in the rural area in Hrvatskoj Zagorje (NW Croatia). Both examples prove that they are large scale maps containing data at appropriate levels of input for proposing statutory land use planning constraints. These examples of zoning in terms of landslide inventory could be used to manage landslide hazard in urban areas by excluding development in areas endangered by registered landslides. This landslide inventory map in combination with a landslide susceptibility map on a large scale provides detailed boundaries of higher hazard areas to propose requirements for geotechnical engineering assessment of slope stability before development is approved in these areas.

In this regard, it should be noted that State and County governments have significantly different requirements from Local governments. The use of landslide zoning maps at the National and Regional levels in Croatia will provide information for areas where more detailed data and information about landslides are necessary. In addition to planners and developers, the information and data about landslides built into spatial and urban plans are intended for designers and other Engineering geologists or Geotechnical professionals involved in construction, as preliminary information about geohazards that is necessary to define site investigation requirements.

Table 5 Levels and scale of spatial plans in Croatia

Spatial plan level	Spatial plan type	Scale
National level	National spatial development plan	1:300,000
	UPU of state importance	1:100,000
	Spatial plans of areas of special features	1:100,000 or 1:25,000 or 1:10,000 or 1:5,000
Regional level	County spatial plans	1:100,000, 1:25,000 (PPGZ[a])
	UPU of county importance	1:25,000
Local level	Spatial plans of cities/municipalities	1:25,000 (1:5000 for determination of construction areas of settlements)
	General urban plan (GUP)	1:5000 or 1:10,000
	Urban development plan (UPU)	1:5000 or 1:1000 or 1:2000

[a] PPGZ—Spatial Plan of the City of Zagreb (county level)
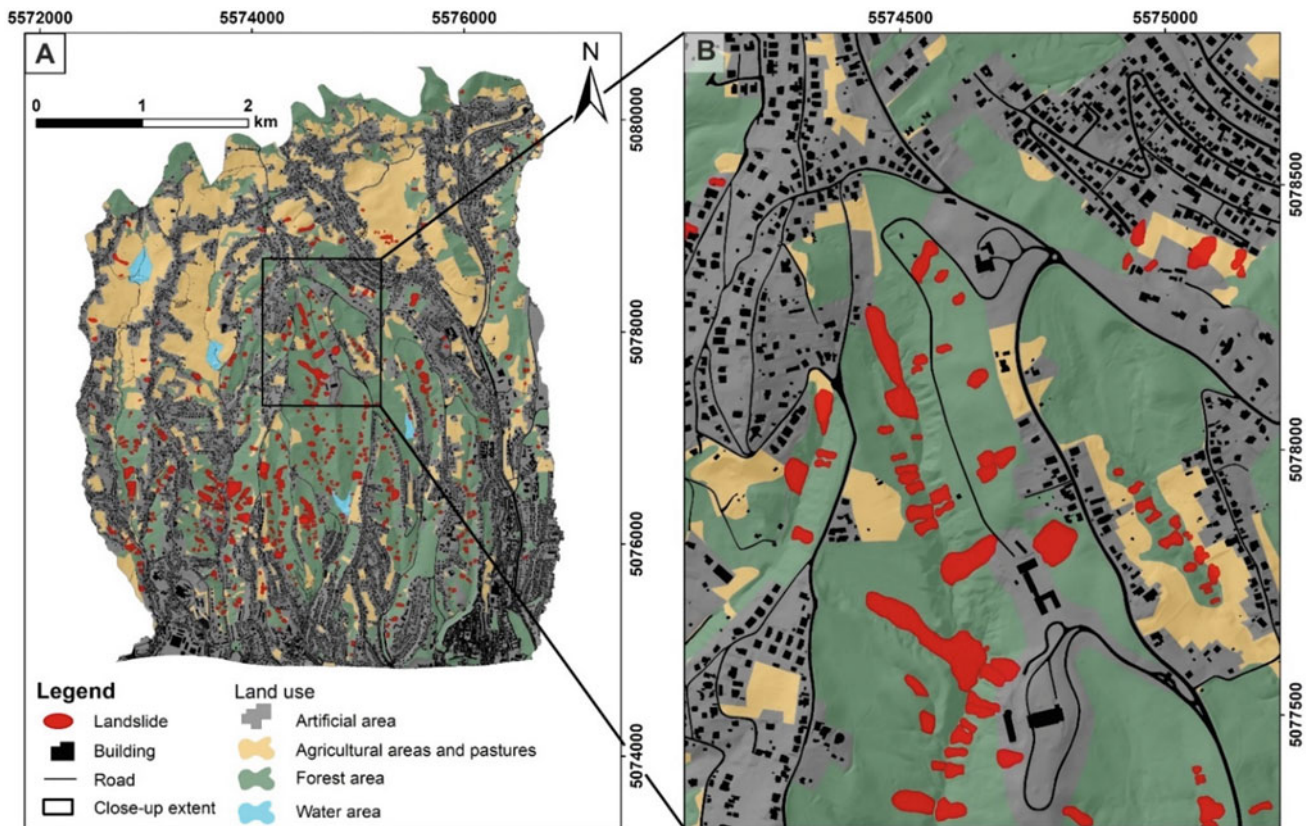
Fig. 10 Detailed landslide inventory map (21 km^2) overlapped with land use categories from the Spatial Plan of the City of Zagreb (modified from Bernat Gazibara et al. 2019a)
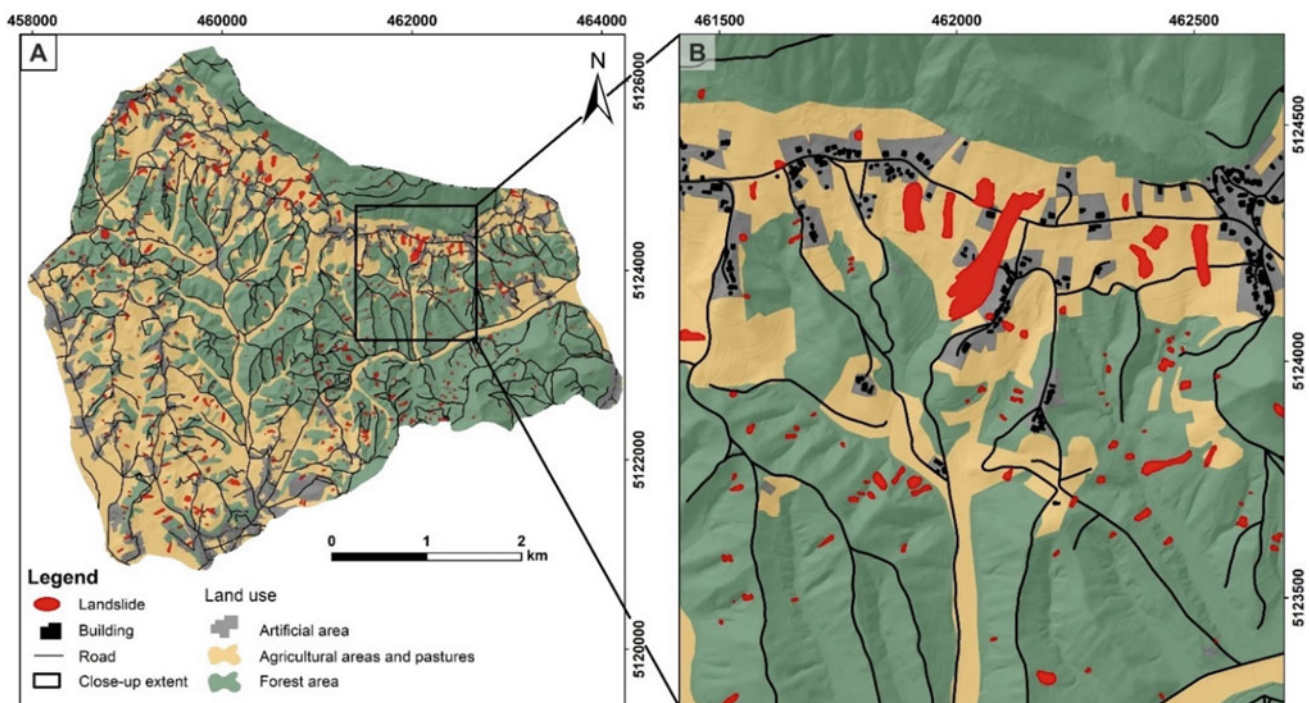
Fig. 11 Detailed landslide inventory map (20.22 km^2) overlapped with land use categories from the Spatial Plan of the Lepoglava City and Bednja Municipality (modified from Sinčić et al. 2022)

5 Final Remarks

Advances in aerial laser scanning technology (ALS LiDAR) have made possible to produce high-resolution bare-earth digital terrain models that are the best source of data for mapping landslide phenomena and for deriving a range of morphological causal factors for landslide susceptibility analysis. Since the primary purpose of landslide maps presenting landslide inventory and landslide susceptibility is often land use management and control measures for sliding, it can be concluded that new technological possibilities enable obtaining data and information on landslides that we have always needed.

New and emerging techniques based on airborne LiDAR remote sensing technology, facilitate the production of landslide maps, reducing the time and resources required for their compilation and systematic update. At the same time, they enable the detection and mapping of small and shallow landslides overgrown, and often hidden by vegetation. These maps are sufficiently detailed to support mitigation actions at the local level. Moreover, the quality and completeness of the landslide maps will enhance the reliability of the estimates obtained from the inventories. The question then becomes one of identifying the most effective of the various mitigation approaches and obtaining funding to apply the best mitigation measures. Examples of detailed and complete landslide inventories compiled for three pilot areas in Croatia proved that they can be used for all 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.

The levels of zonation define scales of susceptibility maps. It is recommended that the map scales should be in accordance with scales and types of spatial planning maps. Landslide susceptibility zonation at the large scale that needs to enable planning of urban development at the local level, is shown on the example map from the Zagreb City pilot area. Landslides from the complete inventory were used for the statistical susceptibility analysis method, as well as morphometric maps derived from LiDAR DTM, which contributed to the reliability of the map. For the needs of landslide susceptibility zonation required by state or federal governments, for regional land use planning or disaster management planning, medium or small scale maps obtained by assessment from lower quality but widely available data are sufficient. We have presented the susceptibility maps obtained by the heuristic assessment that are of satisfactory reliability for defining obligations where a more detailed susceptibility mapping is needed, whether the users are spatial planners developing low-level spatial/urban plans or land developers, those developing major infrastructure such as highways and railways or managing recreational areas.

It will be appropriate to carry out landslide susceptibility zonation in small scale as a first stage in the multi-stage development of landslide susceptibility zonation for planning purposes. Multiscale mapping will allow better control of the process and may reduce the costs of the zoning by limiting the more detailed zoning only to areas where it is necessary. Data and information needed by officials and planners to reduce landslide risk and losses provided from the landslide susceptibility maps and assessments require the development and implementation of a plan for mapping and assessing landslide and other ground failure hazards, from nationwide susceptibility maps to landslide inventories at the local level. The use of standards and guidelines for landslide hazard maps and assessments will provide advice in planning the landslide zonation study and applying the outcomes to land use planning. Moreover, improved documentation and more active communication among different stakeholders would, however, contribute to more effective landslide management.

Preventive actions and measures can and are frequently taken to reduce accidents and their consequences. Data and information from landslide inventory and susceptibility maps could be also used for some of generic measures, and these are most often non-physical such as legislation and education at the national, regional, or local level. International directives and agreements, such as the Sendai Framework for Disaster Risk Reduction 2015–2030 (UN 2015), exert an influence on the development of national strategies and legislation. Landslide maps are tools that are necessary for identification and visualization of disaster risk factors and scenarios, including emerging disaster risks, in the medium and long term. In this way they can also contribute to the following: to increase research for regional, national, and local application; support action by local communities and authorities; and support the interface between policy and science for decision-making.

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