Sveučilište u Zagrebu
RUDARSKO
GEOLOŠKO
NAFTNI FAKULTET

STUDIJA

Sveučilište u Zagrebu

Rudarsko-geološko-naftni fakultet

10000 ZAGREB, Pierottijeva 6

Interreg

Co-funded by the European Union

Italy – Croatia

CRESCO Adria

Naručitelj:	**Sveučilište u Rijeci** **Građevinski fakultet** **Radmile Matejčić 3, 51000 Rijeka**
Zadatak:	**Procjena podložnosti na klizanje Vinodolske općine M 1:5.000**
Projekt:	**Interreg Italy-Croatia 2021.-2027** **Programme CRESCO Adria – Climate RESilient COastal planning in Adriatic**
Broj izvještaja:	**IG0288-001/2025**
Voditeljica zadatka:	**doc. dr. sc. Sanja BERNAT GAZIBARA, mag. ing. geol.**
Dekan:	**izv. prof. dr. sc. Vladislav BRKIĆ**
Mjesto i datum:	**Zagreb, studeni 2025.**

NARUČITELJ:	**Sveučilište u Rijeci** **Građevinski fakultet** **HR-51000 Rijeka, Radmile Matejčić 3**
IZRAĐIVAČ:	**Sveučilište u Zagrebu** **Rudarsko-geološko-naftni fakultet** **HR-10000 Zagreb, Pierottijeva 6**
ZADATAK	**Procjena podložnosti na klizanje Vinodolske općine M 1:5.000**
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SURADNICI:	**prof. dr. sc. Snježana MIHALIĆ ARBANAS, dipl. ing. geol.** **izv. prof. dr. sc. Martin KRKAČ, dipl. ing. geol.** **dr. sc. Marko SINČIĆ, mag. ing. geol.** **Hrvoje LUKAČIĆ, mag. ing. geol., mag. ing. min.**
DEKAN:	izv. prof. dr. sc. Vladislav BRKIĆ

Sveučilište u Zagrebu
RUDARSKO
GEOLOŠKO
NAFTNI FAKULTET

DATUM:	**studeni 2025.**

REPUBLIKA HRVATSKA
TRGOVAČKI SUD U ZAGREBU

IZVADAK IZ SUDSKOG REGISTRA

SUBJEKT UPISA

MBS:
080159382

OIB:
99534693762

NAZIV:
1 SVEUČILIŠTE U ZAGREBU RUDARSKO-GEOLOŠKO-NAFTNI FAKULTET

1 SVEUČILIŠTE U ZAGREBU RGN-fakultet

SJEDIŠTE/ADRESA:
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PRAVNI OBLIK:
1 ustanova

DJELATNOSTI:

1	*	- visoko obrazovanje
1	*	- izdavanje knjiga
1	*	- izdavanje časopisa i periodičnih publikacija
1	*	- rušenje građevinskih objekata i zemljani radovi
1	*	- pokusno bušenje i sondiranje terena za gradnju
1	*	- izrada i upravljanje bazama podataka
1	*	- istraživanje i eksperimentalni razvoj u prirodnim, tehničkim i tehnološkim znanostima
1	*	- arhitektonske djelatnosti i inženjerstvo te s njima povezano tehničko savjetovanje
1	*	- tehničko ispitivanje i analiza
1	*	- djelatnost knjižnica i arhiva
2	*	- stručni poslovi zaštite okoliša
8	*	- hidrogeološka istraživanja i geofizička istraživanja
10	*	- vještačenje iz područja zaštite okoliša, procjene utjecaja na okoliš, geologije, mineralnih sirovina i rudarstva
10	*	- izrada dokumentacije o rezervama mineralnih sirovina i/ili dokumentacije o građi, obliku, veličini i obujmu geoloških struktura pogodnih za skladištenje ugljikovodika i trajno zbrinjavanje plinova
10	*	- izrada rudarskih projekata istraživanja i eksploatacije mineralnih sirovina

OSNIVAČI/ČLANOVI DRUŠTVA:

1 Sveučilište u Zagrebu, pod RUL: 1-910,

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REPUBLIKA HRVATSKA
TRGOVAČKI SUD U ZAGREBU

IZVADAK IZ SUDSKOG REGISTRA

SUBJEKT UPISA

OSNIVAČI/ČLANOVI DRUŠTVA:
Zagreb, Trg Maršala Tita 14
1 - osnivač

OSOBE OVLAŠTENE ZA ZASTUPANJE:

15 Vladislav Brkić, OIB: 41535238353
Zagreb, Veslačka ulica 23
15 - dekan
15 - zastupa samostalno i pojedinačno, od 01.10.2021. godine

PRAVNI ODNOSI:
Osnivački akt:
2 Dopunom Statuta Rudarsko-Geološkog-Naftnog fakulteta u Zagrebu od 17.12.1999. izmjenjen je članak 4 Statuta u pogledu djelatnosti.

Statut:
1 Odlukom dekana od 13. 02. 1997. godine donesen je Statut, a Odlukom Upravnog vijeća Sveučilišta broj 01/407-0697 od 30. 06. 1997. godine dana je suglasnost na Statut
3 Izmjenom i dopunom Statuta od 25.06.2001. godine izmijenjeni su članci 2., 7., 10., 11., 12., 13., 17., 37., 123., 130. Statuta.
5 Odlukom fakultetskog vijeća od 06.07.2005. godine izmijenjen Statut od 13.02.1997. godine te dopune istog, u cijelosti. Potpuni tekst Statuta od 06.07.2005. godine dostavljen u zbirku isprava.
6 Odlukom Senata Sveučilišta u Zagrebu od 14. prosinca 2006. godine izmijenjen je čl. 5 Statuta od 06. srpnja 2005. godine u pogledu znaka fakulteta. Pročišćeni tekst Statuta od 17. studenog 2006. godine dostavljen u zbirku isprava.
8 Odlukom Fakultetskog vijeća Rudarsko-geološko-naftnog fakulteta Sveučilišta u Zagrebu od 27. travnja 2012. izmijenjen je Statu Rudarsko-geološko-naftnog fakulteta Sveučilišta u Zagrebu od 17. studenog 2006. u pogledu djelatnosti. Potpuni tekst Statuta Rudarsko-geološko-naftnog fakulteta Sveučilišta u Zagrebu dostavljen sudu i uložen u zbirku isprava.
10 1. Fakultetsko vijeće donijelo je dana 24. svibnja 2016. godine Odluku kojom se usvoja novi STATUT Fakulteta i dodaje nova djelatnost, a Senat Sveučilišta u Zagrebu je dana 15. studenog 2016. godine donio Odluku kojom se daje suglasnost na STATUT.
2. Fakultetsko vijeće donijelo je dana 22. rujna 2017. godine Odluku o dopuni STATUTA kojom se mijenja čl. 4. na način da se dopunjuje u pogledu djelatnosti, a Senat Sveučilišta u Zagrebu je dana 17. listopada 2017. godine donio Odluku kojom se daje suglasnost na Odluku o dopuni STATUTA.
Pročišćeni tekst STATUTA od 22. rujna 2017. godine dostavljen sudu radi ulaganja u zbirku isprava.

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REPUBLIKA HRVATSKA – TRGOVAČKI SUD U ZAGREBU

REPUBLIKA HRVATSKA
TRGOVAČKI SUD U ZAGREBU

IZVADAK IZ SUDSKOG REGISTRA

SUBJEKT UPISA

PRAVNI ODNOSI:

Statut:

13 Fakultetsko vijeće SVEUČILIŠTA U ZAGREBU RUDARSKO-GEOLOŠKO-NAFTNOG FAKULTETA na 2. redovitoj sjednici u akad. god. 2019/2020., održanoj dana 21.11.2019. godine donijelo je odluku kojom se mijenja Statut u čl. 30. st. 8., toč. 4. Na Statutarnu odluku Senat je dao suglasnost 14.01.2020. godine.
Potpuni tekst Statuta od 30.01.2020. godine dostavljen je sudu u zbirku isprava.

14 Fakultetsko vijeće SVEUČILIŠTA U ZAGREBU RUDARSKO-GEOLOŠKO-NAFTNOG FAKULTETA na 8. redovitoj sjednici u akad. god. 2020./2021., održanoj dana 18.06.2021. godine donijelo je Odluku kojom se dopunjuje Statut u čl. 4. na način da se dopunjuje u pogledu djelatnosti. Na Statutarnu odluku Senat Sveučilišta u Zagrebu je dao suglasnost 13.07.2021. godine. STATUT (pročišćeni tekst) od 29.07.2021. godine dostavljen sudu radi ulaganja u zbirku isprava.

OSTALI PODACI:

1 Subjekt je bio upisan u trgovačkom sudu u Zagrebu pod registarskim brojem 1-2004

EVIDENCIJSKE DJELATNOSTI:

14 * - djelatnost snimanja iz zraka

Upise u glavnu knjigu proveli su:

RBU	Tt	Datum	Naziv suda
0001	Tt-97/3072-2	23.07.1997	Trgovački sud u Zagrebu
0002	Tt-00/5507-4	13.06.2001	Trgovački sud u Zagrebu
0003	Tt-01/5574-4	16.01.2002	Trgovački sud u Zagrebu
0004	Tt-05/8332-3	28.09.2005	Trgovački sud u Zagrebu
0005	Tt-05/9319-4	28.10.2005	Trgovački sud u Zagrebu
0006	Tt-07/303-4	19.01.2007	Trgovački sud u Zagrebu
0007	Tt-09/10758-2	02.10.2009	Trgovački sud u Zagrebu
0008	Tt-12/16175-8	16.01.2013	Trgovački sud u Zagrebu
0009	Tt-13/22640-2	11.10.2013	Trgovački sud u Zagrebu
0010	Tt-17/41384-2	13.11.2017	Trgovački sud u Zagrebu
0011	Tt-19/33114-4	05.11.2019	Trgovački sud u Zagrebu
0012	Tt-20/14383-2	30.06.2020	Trgovački sud u Zagrebu
0013	Tt-21/22110-2	11.05.2021	Trgovački sud u Zagrebu
0014	Tt-21/36912-2	19.08.2021	Trgovački sud u Zagrebu
0015	Tt-21/43629-2	04.10.2021	Trgovački sud u Zagrebu

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REPUBLIKA HRVATSKA
TRGOVAČKI SUD U ZAGREBU

IZVADAK IZ SUDSKOG REGISTRA

SUBJEKT UPISA

U Zagrebu, 19. srpnja 2022.

Ovlaštena osoba

REPUBLIKA HRVATSKA TRGOVAČKI SUD U ZAGREBU ZAGREB

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CONTENTS

1. INTRODUCTION

The landslide susceptibility assessment of the Municipality of Vinodol was prepared pursuant to the Contract (your reference number CLASS: 406-09/25-01/14, REF. NO.: 2170-1-40-01-00-25-6 of 31 March 2025) of the Client, the University of Rijeka, Faculty of Civil Engineering, by which the Client commissioned the Contractor, the University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, to provide the service of assessing the landslide susceptibility of the Municipality of Vinodol at a scale of 1:5,000. The main result of the landslide susceptibility assessment is the Landslide Susceptibility Map of the Municipality of Vinodol, scale 1:5,000.

Since landslides are a relatively broad term, as they include all phenomena (i.e. morphological forms) that arise from processes involving the movement of rock or soil (or both) down a slope (Cruden, 1991), it is important to note that this technical basis was prepared for landslides that occurred as a consequence of sliding and/or flow processes (for simplicity, only the term sliding is used hereinafter). This means that landslide phenomena caused by falling, toppling and lateral spreading processes were excluded from the analyses.

Landslides are most commonly the consequence of natural conditioning factors, which can be classified as geomorphological, geological and hydrological landslide-conditioning factors, as well as anthropogenic factors, and are most often triggered by causes such as intense precipitation or earthquakes. Sustainable spatial management at any level is difficult, and almost impossible, without knowledge of all types of geohazard processes and their spatial distribution in a given area, or without the systematic recording of phenomena resulting from their occurrence (Bell, 2003; Clague and Roberts, 2012). Landslide research and landslide hazard assessment fall within the domain of geosciences, and the final results are maps of existing landslides, i.e. landslide inventory maps, and predictive maps that provide information for a wide range of users, most commonly from the domain of local, regional and national administration. Predictive landslide maps imply the zoning of the study area into homogeneous spatial units classified with respect to landslide danger, i.e. the actual or potential degree of landslide susceptibility, hazard or risk (Van Westen et al., 2005). Predictive landslide hazard maps are the result of spatial analyses, but their preparation requires detailed and complete landslide inventories (Glade, 2001; van Westen et al., 2008).

Significant reductions in potential losses and damage (risk) can be achieved by combining landslide hazard mitigation measures through spatial planning and construction with measures and activities of the civil protection system. A practical and feasible guide for county and local self-government units involved in landslide hazard mitigation is provided by the Guidelines for the Application of Landslide Maps in the Republic of Croatia (Mihalić Arbanas et al., 2023), as they present data and information on landslides that are necessary for mitigating landslide hazard and risk, as well as ways of applying such data and information at regional and local levels that are appropriate for the Republic of Croatia.

2. NATURAL FEATURES OF THE STUDY AREA

The study area is the Municipality of Vinodol (153 km²), located in the north-western part of Adriatic Croatia (Figure 2.1). The area is predominantly rural and consists of more than 50 smaller settlements in the valley, mutually connected by a relatively dense road network. Elevation ranges from 20 to 1,426 m a.s.l., while terrain slopes are generally between 5 and 32°. The climate is maritime (Zaninović et al., 2008), with average annual precipitation between 300 and 700 mm.

The study area for which a landslide inventory was previously prepared within the CRESCO project (53 km²) is located in the western part of the Municipality (Figure 2.1), from the settlement of Križišće in the northwest to the town of Novi Vinodolski in the southeast, following a northwest-southeast direction. The landslide susceptibility analysis was conducted for the relevant 53 km² for which the landslide inventory was prepared, while the final landslide susceptibility map presents susceptibility zoning for the entire territory of the Municipality of Vinodol.

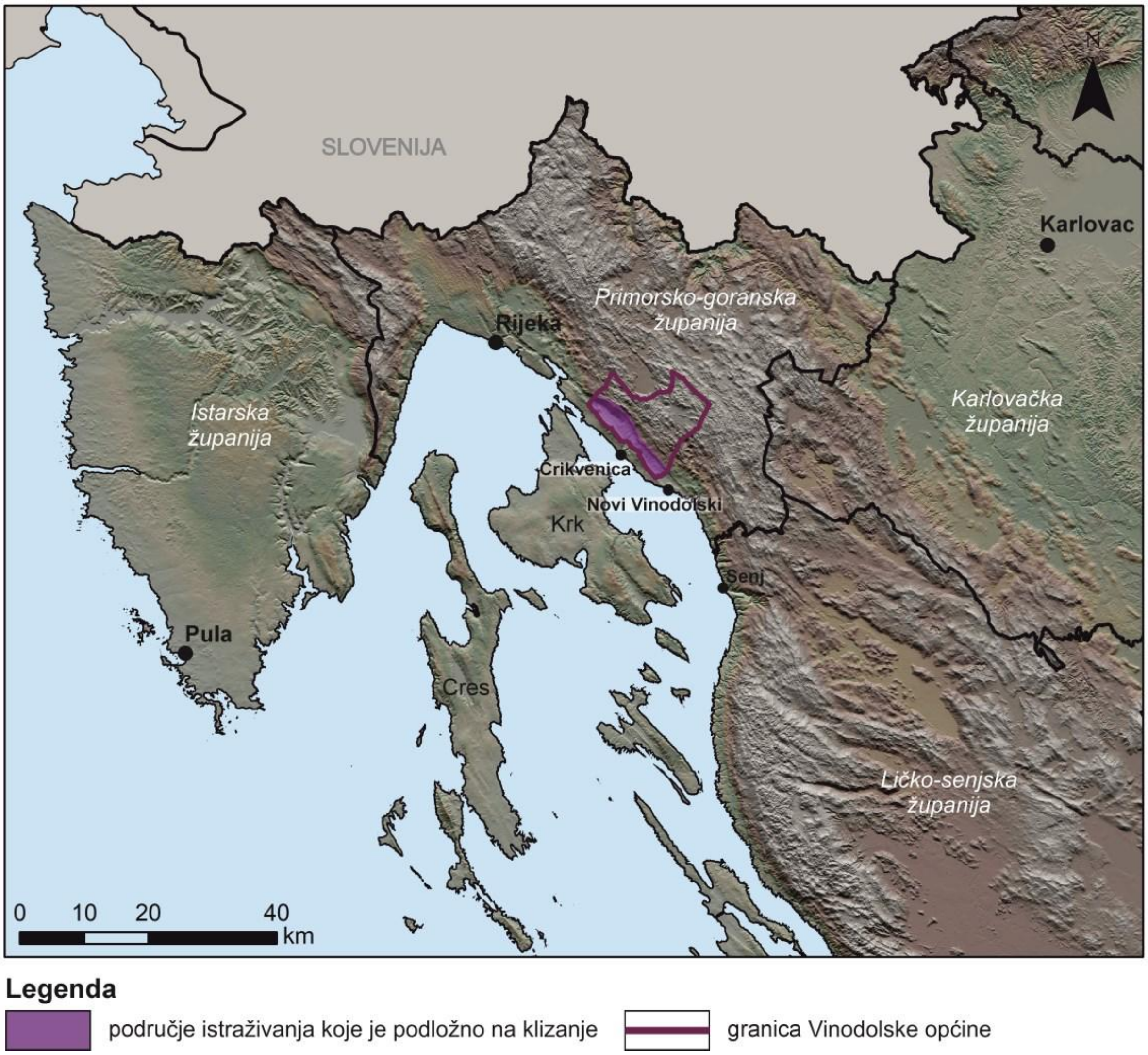

Figure 2.1 Study area shown on the digital terrain model.

The geological structure of the Vinodol Valley is shown on an excerpt from the Crikvenica sheet (Šušnjar et al., 1970) of the Basic Geological Map (OGK) at a scale of 1:100,000 (Figure 2.2). According to the explanatory notes to the OGK for the Crikvenica sheet (Grimani et al., 1973), the oldest deposits in the area of the Municipality of Vinodol belong to the Middle Jurassic epoch, and the youngest to the Quaternary period. Sliding and flow processes are associated with Paleogene flysch deposits in the Vinodol Valley, which occupy about 25 km² within the study area. The remaining part of the study area (128 km²) is composed of carbonate deposits of Middle Jurassic to Paleogene age, where sliding and flow processes are not possible.

The basic geological structure of the Vinodol Valley can be described as a synclinal structure, composed of carbonate rock mass located in the limbs of the syncline and Paleogene flysch deposits located in the core. Flysch deposits, or Eocene clastics, consist of marl, sandstone and limestone (calcarenite and biocalcarenite), and locally of breccia and conglomerate, which often alternate vertically and laterally (Grimani et al., 1973). Given that, in the Vinodol Valley area, flysch outcrops with a characteristic vertical alternation of clastic sequences deposited by turbidity currents are actually rare, it is more appropriate to refer to these clastic Eocene deposits as flysch or flysch-like deposits (Blašković, 1999). The thickness of the flysch deposits is about 320 m (Grimani et al., 1973).

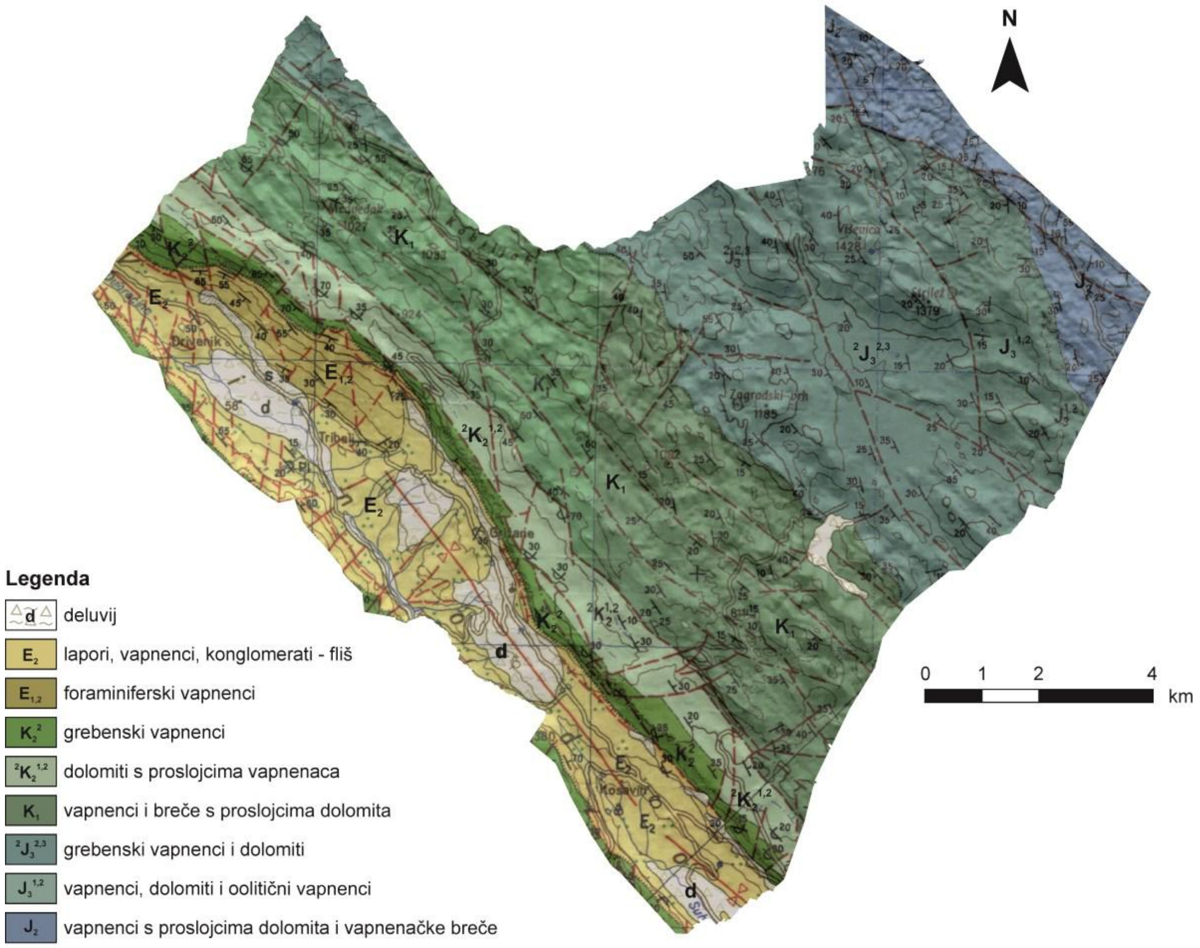

Figure 2.2 Geological structure of the Vinodol Valley according to an excerpt from the Basic Geological Map (OGK), scale 1:100,000, Crikvenica sheet (Šušnjar et al., 1970).

As part of the doctoral dissertation by Đomlija (2018), a map of geomorphological units was prepared for the Vinodol Valley area, and it was also used for the purposes of the landslide susceptibility assessment. The procedure for delineating cartographic units was carried out on the basis of detailed visual interpretation of the high-resolution DTM. A total of 11 geomorphological units were identified in the Vinodol Valley area: (i) carbonate plateau; (ii) carbonate slope; (iii) carbonate escarpment; (iv) slopes in breccia; (v) younger colluvial belt; (vi) older colluvial belt; (vii) proluvial belt; (viii) denudation slope; (ix) denudation depression; (x) accumulation footslope; (xi) alluvial plain. The spatial distribution of geomorphological units in the central part of the Vinodol Valley is shown in Figure 2.3.

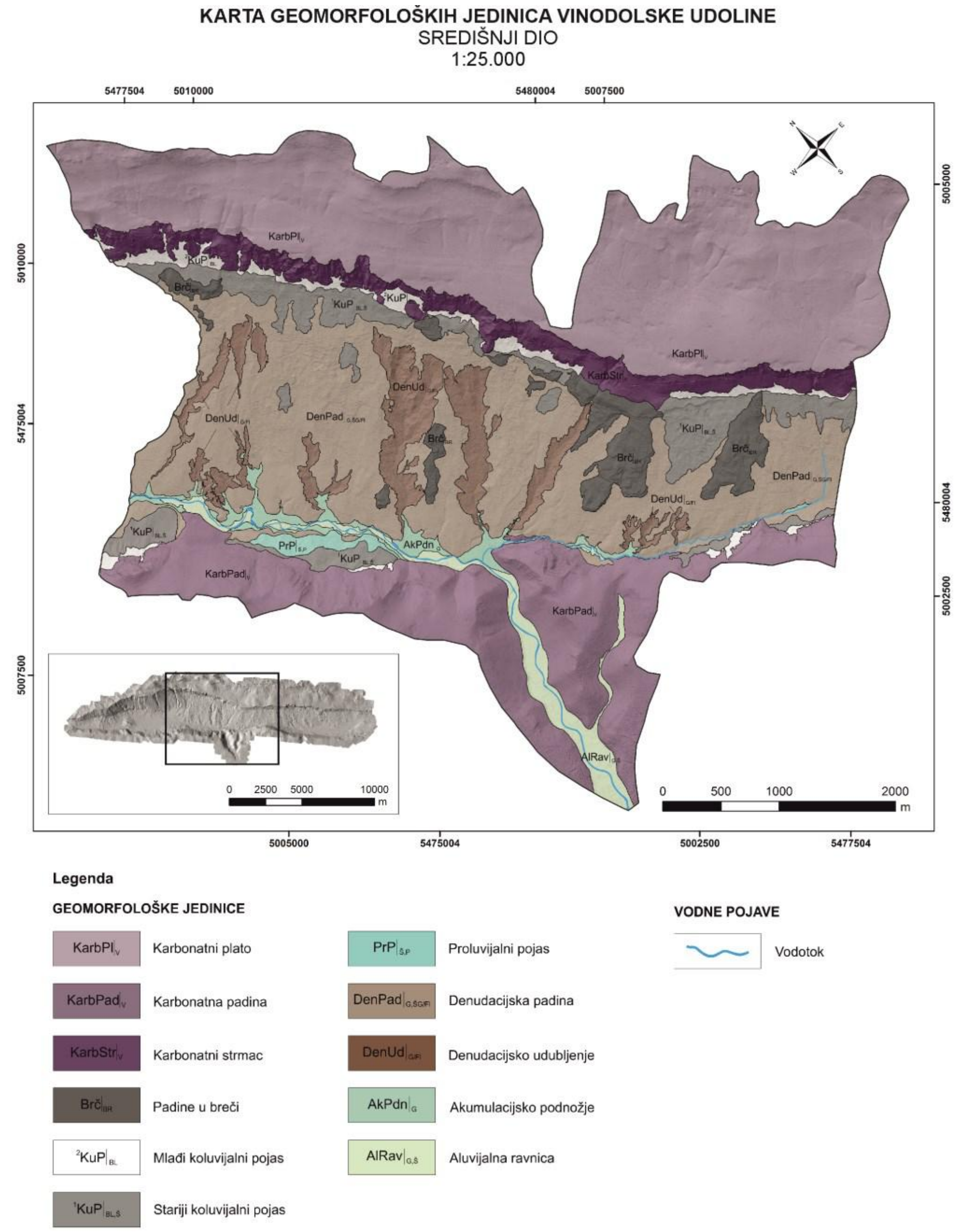

Figure 2.3 Spatial position of geomorphological units in the central part of the Vinodol Valley (Đomlija, 2018).

3. EXISTING LANDSLIDE SUSCEPTIBILITY MAPS

To date, two landslide susceptibility maps have been prepared for the Vinodol Valley area within the following studies or research:

(i) the doctoral dissertation "Susceptibility of the Dubračina River catchment to surficial geodynamic processes" (Toševski, 2018);

(ii) the project "Applied landslide research for the development of risk mitigation and prevention measures (PRI-MJER), K.K.05.1.1.02.0020" (Bernat Gazibara et al., 2023).

Within the doctoral dissertation "Susceptibility of the Dubračina River catchment to surficial geodynamic processes" (Toševski, 2018), the first landslide susceptibility map was prepared for part of the Municipality of Vinodol. The landslide susceptibility assessment was conducted using the information value method and the frequency ratio method. The landslide susceptibility analysis was based on a landslide inventory in which a total of 88 landslides were recorded, of which 52 landslides were identified and mapped by visual interpretation of the LiDAR DTM, and 36 landslides by field mapping.

In addition to the landslide inventory, the following landslide-conditioning factors were used as input data: land cover, dispersivity of the ground surface, lithology, slope angle, mean annual precipitation, slope aspect, distance from a dispersive sample, distance from springs, distance from roads, distance from faults, distance from watercourses, clay content, silt content, sand content and gravel content in the cover deposits.

Statistical modelling of landslide susceptibility produced a total of four landslide susceptibility maps, shown in Figure 3.1.

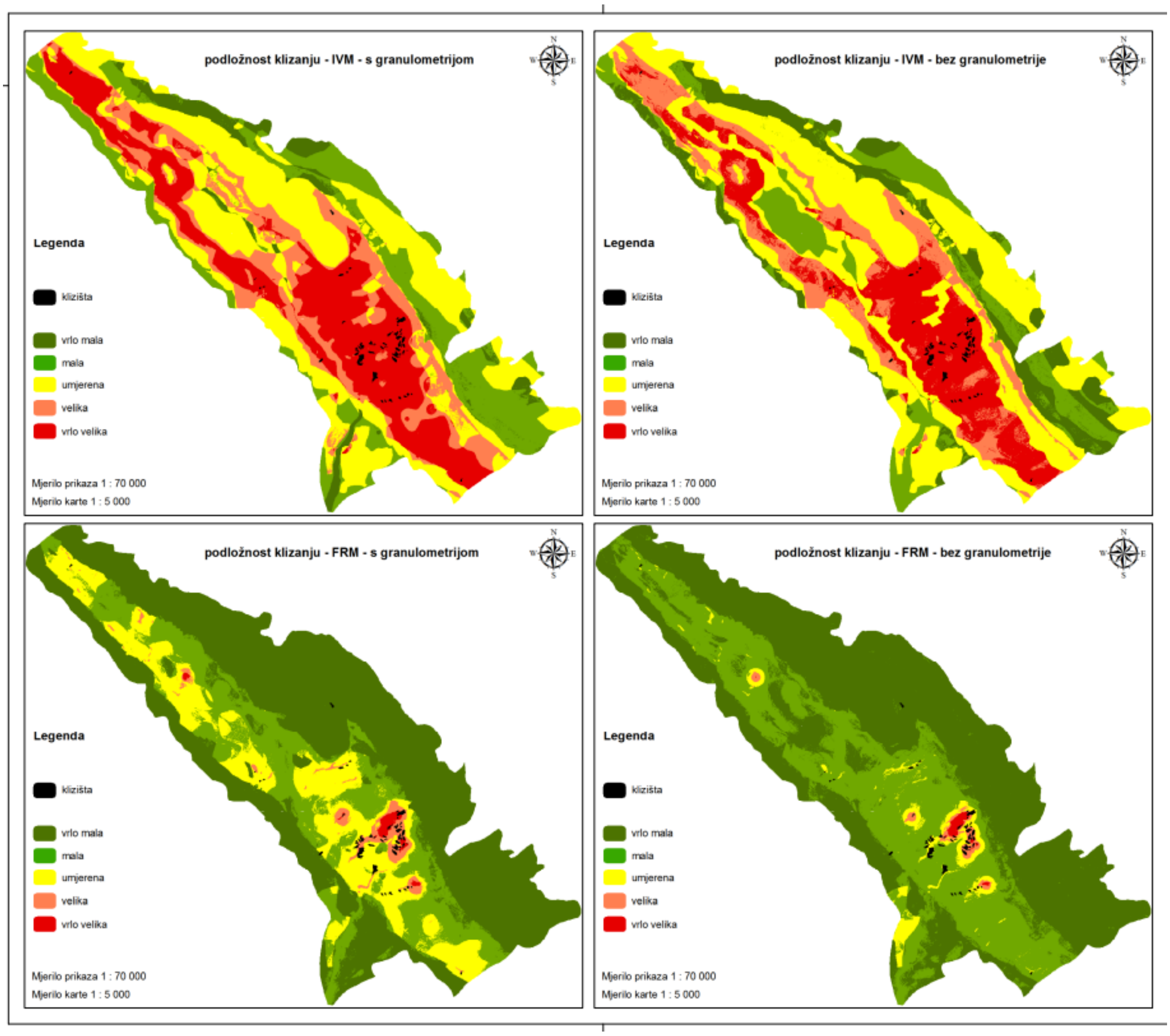

Figure 3.1 Landslide susceptibility maps prepared within the doctoral dissertation by Toševski (2018).

Within the project "Applied landslide research for the development of risk mitigation and prevention measures (LandSlidePlan), ESF KK.05.1.1.02.0020", a landslide susceptibility zoning map was prepared for part of the Municipality of Vinodol at a scale of 1:5,000 (Figure 3.2). It covers the central part of the Vinodol Valley, including parts of the settlements of Grižane-Belgrad, Tribalj and Bribir. Spatial probability zones provide information on where landslides may occur, i.e. where sliding and flow processes may be activated. Landslide susceptibility zoning was carried out using the random forest statistical method, based on a series of cartographic data on the study area, i.e. data on landslide-conditioning factors: slope angle, slope aspect, terrain curvature, engineering-geological conditions, terrain wetness, land use and distance from roads.

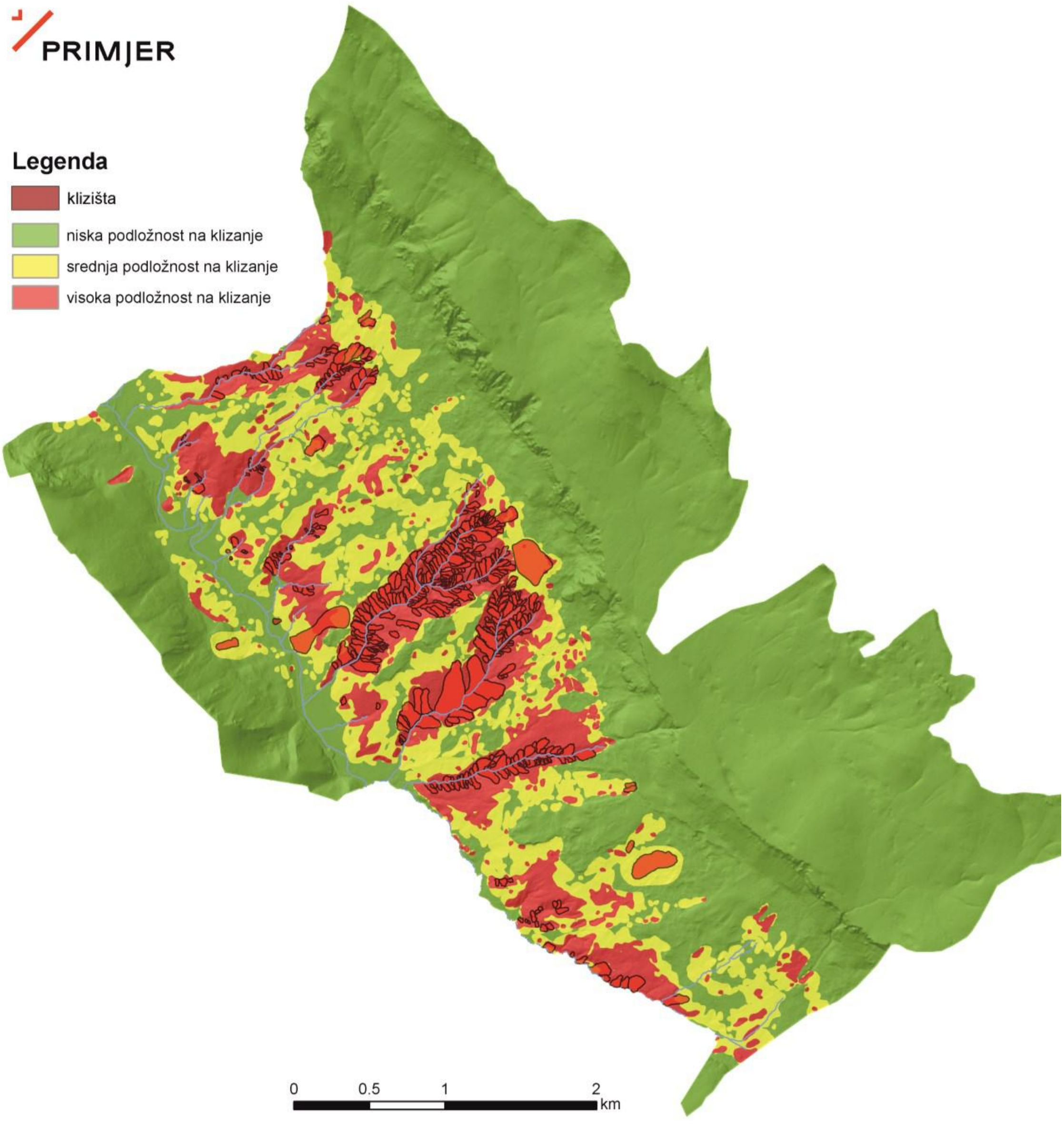

Figure 3.2 Landslide susceptibility zoning map of part of the Municipality of Vinodol, original scale 1:5,000 (Bernat Gazibara et al., 2023).

4. INPUT DATA AND METHODOLOGY OF LANDSLIDE SUSCEPTIBILITY ASSESSMENT M 1:5,000

Predictive landslide maps imply the zoning of the study area into homogeneous spatial units classified with respect to landslide danger, i.e. the actual or potential degree of landslide susceptibility, hazard or risk (Van Westen et al., 2005). The first qualitative methods of landslide hazard assessment were developed in the early 1970s, and the best-known examples are Brabb et al. (1972) and Kienholz (1978). Quantitative zoning methods were developed in the late 1980s, and most intensively during the 1990s (Brand, 1988; Wong and Ho, 1998). Landslide susceptibility can be defined as the spatial probability of landsliding (the occurrence or reactivation of a landslide phenomenon) under predefined landslide-conditioning factors (Guzzetti et al., 1999). The main assumptions in landslide susceptibility zoning are (Varnes and IAEG, 1984; Hutchinson, 1995, as cited in Aleotti and Chowdhury, 1999): (a) landslides will be activated in the future due to the same geological, geomorphological, hydrogeological and climatic factors as in the past; (b) the occurrence of landslides is conditioned by landslide-conditioning factors that can be identified and classified; (c) the degree of susceptibility can be assessed using various qualitative and quantitative methods; and (d) all types of slope instability can be identified and classified. Susceptibility maps do not provide information on the size of activated landslides or the temporal probability of landslide occurrence, i.e. “when” and “how often” landslides will be activated (Guzzetti et al., 2005).

The selection of a method for assessing landslide susceptibility depends on the scale and purpose of the final map, as well as on the availability of data on landslides and landslide-conditioning factors in the study area. Heuristic, statistical and deterministic methods are applied for landslide susceptibility assessment. Statistical methods for landslide susceptibility assessment are most commonly used for areas ranging from 10 to 10,000 km², i.e. for large-scale maps (1:5,000 to 1:25,000), and the result is a quantitative assessment of spatial probability for application at the local level. Input data for landslide susceptibility analysis using statistical models are the landslide inventory, which represents the dependent variable, and landslide-conditioning factors, i.e. landslide factor maps, which represent the independent variables. The main assumptions of quantitative statistical methods are that landslides throughout the entire study area occur within the same combinations of factor maps and that the same types of landslides are conditioned by the same landslide factors (Corominas et al., 2013).

The phases of landslide susceptibility zoning are: (i) preparation of a landslide inventory map; (ii) preparation of maps of the most relevant landslide-conditioning factors; (iii) analysis of landslide-conditioning factors/terrain conditions for different landslide types and determination of the relative influence of landslide factors on landslide occurrence; (iv) assessment of the weights of individual landslide factors and formulation of criteria for the landslide susceptibility model; (v) assessment of the training and prediction accuracy of the model; and (vi) landslide susceptibility zoning.

Furthermore, insufficient knowledge of the study area, i.e. a lack of knowledge about different landslide types and processes in the study area, affects the selection of relevant landslide factors and the final assessment of landslide susceptibility. The quality of the resulting landslide susceptibility map primarily depends on the quality of the input data, i.e. on the spatial resolution and accuracy of the factor maps and on the completeness and accuracy of the landslide inventory map (Ardizzone et al., 2007). In the present landslide susceptibility assessment, the input data consist of a detailed landslide inventory obtained by interpreting morphometric maps derived from the LiDAR DTM recorded in 2021/2022, and of landslide-conditioning factors derived from spatial data of high resolution and spatial accuracy.

4.1 Landslide inventory

Visual identification and mapping of landslides in the Municipality of Vinodol was carried out by interpreting morphometric maps derived from the LiDAR DTM recorded in 2021/2022 by the author P. Jagodnik (2025). The morphometric maps used during the visual identification of landslides were three maps derived from the LiDAR DTM recorded in 2021/2022, namely the hillshade maps with illumination azimuth/altitude of 315°/45° and 45°/45°, the slope map and the contour map with 2 m contour interval.

The landslide inventory was prepared for part of the study area of the Municipality of Vinodol covering 53 km², where conditions exist for the occurrence of sliding and flow processes. In the remaining part of the study area, geomorphological and geological conditions for the occurrence of landslides do not exist. The landslide inventory consists of a total of 843 identified and detailed mapped landslides, whose spatial distribution in the Municipality of Vinodol is shown in Figure 3.1.

Most landslides, i.e. 631 phenomena, are located in the central part of the study area in which landslides were mapped (53 km²), where landslides are mainly developed along numerous gullies (Đomlija et al., 2019; Jagodnik et al., 2020). A total of 170 landslides are located in the southeastern part of the study area, while only 42 landslides were recorded in the northwestern part of the study area. Landslides cover a total area of 2 km², i.e. 1.3% of the Municipality of Vinodol. Landslide size ranges from 48 m² to 120,000 m², while the average landslide size is 2,377 m²; however, 75% of landslides are smaller than or equal to 773 m².

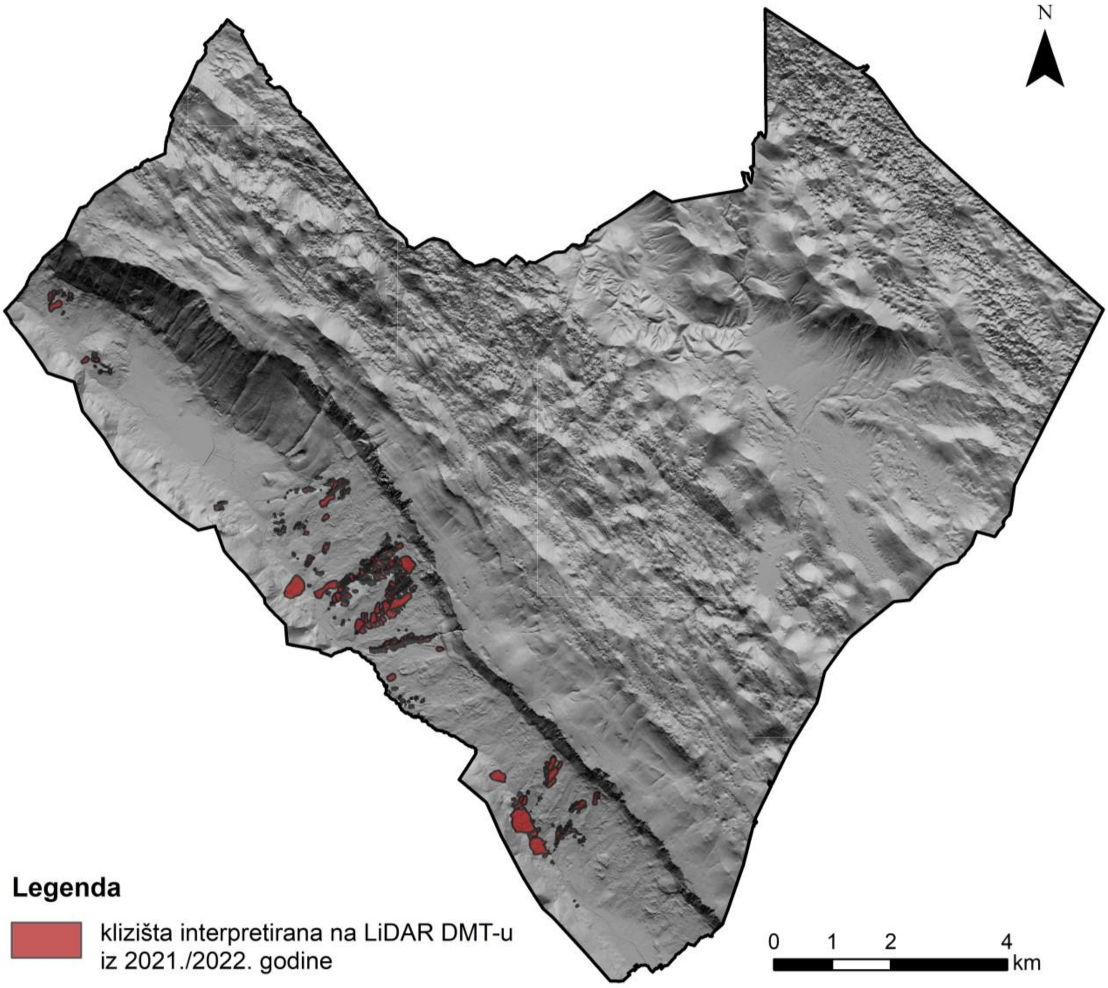

Figure 3.1 Landslide inventory map of the Municipality of Vinodol according to Jagodnik (2025), obtained by interpretation of a LiDAR DTM with a resolution of 1 m.

4.2 Landslide-conditioning factors

The landslide susceptibility zoning map of the Municipality of Vinodol at a scale of 1:5,000 was prepared using a machine-learning method based on prior knowledge of existing landslide locations and all landslide-conditioning factors that can result in the occurrence of landslides. In the landslide susceptibility analysis, only sliding and flow processes were considered, while other movement mechanisms, such as falling, toppling and lateral spreading, were not analysed and are not the subject of this study. The reason is that each individual movement mechanism is caused by different conditioning factors and must therefore be analysed separately.

Landslides in the Municipality of Vinodol (152.9 km²) occur as a direct or immediate consequence of landslide triggers (precipitation, earthquakes, anthropogenic processes) in locations where certain landslide-conditioning factors exist (geological structure, geomorphological characteristics, physical processes and anthropogenic influence). The analysis of landslide-conditioning factors in the pilot area was conducted through spatial analyses of derived maps that show geomorphological, geological, hydrological and anthropogenic landslide-conditioning factors. All cartographic input data were derived from: (1) a digital terrain model with a resolution of 5 x 5 m derived from a point cloud obtained by airborne laser scanning in 2021/2022; (2) the engineering-geological unit map at a scale of 1:25,000 (Đomlija, 2018); (3) the digital orthophoto from 2021 and 2022; (4) the topographic map at a scale of 1:25,000 (TK25); (5) the Croatian Basic Map at a scale of 1:5,000 (HOK); (6) the point cloud (class 6) obtained by airborne laser scanning in 2021/2022; (7) the OpenStreetMap database (URL-1, 2022).

All analysed landslide-conditioning factors are listed in Table 3.1. Initially, 17 conditioning-factor maps were analysed, which can be divided into four groups: (1) geomorphological landslide-conditioning factors - conditioning-factor maps prepared from the digital terrain model with a resolution of 5 x 5 m; (2) geological landslide-conditioning factors - conditioning-factor maps prepared on the basis of the engineering-geological unit map at a scale of 1:25,000 (Đomlija, 2018); (3) hydrological landslide-conditioning factors - conditioning-factor maps prepared from the digital terrain model with a resolution of 5 x 5 m, the topographic map at a scale of 1:25,000 and the Croatian Basic Map at a scale of 1:5,000; and (4) anthropogenic landslide-conditioning factors - conditioning-factor maps prepared on the basis of the digital orthophoto from 2021 and 2022, the OpenStreetMap database (URL-1, 2022) and the LiDAR point cloud (class 6). All 17 conditioning-factor maps were subjected to a pairwise correlation statistical test and a test of the influence of individual factor maps (landslide-conditioning factors). In this way, some factor maps that are mutually dependent, as well as maps that have no influence on the final susceptibility map, were excluded from the analysis. After analysing all landslide-conditioning factors, a total of 10 maps remained, on the basis of which the landslide susceptibility zoning map of the Municipality of Vinodol at a scale of 1:5,000 was prepared. Of the geomorphological landslide-conditioning factors, the slope angle map, slope aspect map and terrain curvature map were used. Of the geological landslide-conditioning factors, the engineering-geological unit map and the map of distance from the boundaries of engineering-geological units were used. Hydrogeological influences were analysed through the effects of the slope exposure index map, the integrated wetness index and the distance from the drainage network. Anthropogenic landslide-conditioning factors were analysed through the effects of land use and distance from roads.

Table 3.1 Landslide-conditioning factors analysed for the purpose of preparing the landslide susceptibility map for the area of the City of Zagreb.

No.	Group of landslide-conditioning factors	Source	Landslide-conditioning maps	Landslide factor map
1	geomorphological landslide-conditioning factors	LiDAR DTM 5 m (DGU, 2023)	1. elevation	NO
			2. slope angle	YES
			3. slope aspect	YES
			4. terrain curvature	YES
			5. terrain roughness	NO
			6. terrain dissection	NO
			7. landform map	NO
2	geological landslide-conditioning factors	Engineering-geological unit map M 1:25,000 (Đomlija, 2018)	8. engineering-geological units	YES
			9. distance from engineering-geological boundaries	YES
3	hydrological landslide-conditioning factors	LiDAR DTM 5 m (DGU, 2023) Topographic map M 1:25,000 (Geoportal, 2025) Croatian Basic Map M 1:5,000 (Geoportal, 2025)	10. slope exposure index	YES
			11. integrated wetness index	YES
			12. distance from drainage network	YES
			13. distance from watercourses	NO
			14. distance from permanent watercourses	NO
4	anthropogenic landslide-conditioning factors	DOF, digital orthophoto (Geoportal, 2023) LiDAR point cloud (DGU, 2023) OpenStreetMap (URL-1, 2022)	15. land use	YES
			16. distance from roads	YES
			17. distance from buildings	NO

5. METHODOLOGY OF LANDSLIDE SUSCEPTIBILITY ASSESSMENT AT A SCALE OF 1:5,000

The landslide susceptibility analysis of the Municipality of Vinodol was conducted using a machine-learning method, i.e. the influences of individual landslide-conditioning factors on slope instability were statistically defined. The spatial analysis of landslide causes (factors) was conducted in MatLAB and ArcGIS 10.8 software. The result of the conducted spatial analysis is the landslide susceptibility zoning map of the Municipality of Vinodol at a scale of 1:5,000. The susceptibility analysis conducted for this study represents an improvement of the susceptibility analysis carried out for the previous Landslide Susceptibility Zoning Map of part of the Municipality of Vinodol M 1:5,000, prepared within the PRI-MJER project (Mihalić Arbanas et al., 2023; Bernat Gazibara et al., 2023), in that new LiDAR data from 2021/2022 were analysed, which enabled the collection of more recent landslide data for the entire area of the Municipality of Vinodol (153 km²).

In the present study, a method called logistic regression, LR, was applied. Logistic regression was formalized by Cox (1958) for use in binary classification. Logistic regression belongs to the group of machine-learning methods (statistical methods) and is a reliable method (Merghadi et al., 2020) that is today most commonly used in landslide susceptibility assessments (Reichenbach et al., 2018). It has been applied in numerous studies (e.g. Hemasinghe et al., 2018; Bornaetxea et al., 2018), and its practical use is also possible through the LAND-SUITE software package (Rossi et al., 2022). Unlike linear regression, which predicts continuous values, logistic regression transforms the linear combination of input variables using the logistic function. The logistic function constrains the output, expressed as probability, to a range from 0 to 1, enabling a quantitative assessment of landslide susceptibility. Logistic regression relates landslides (the dependent variable) to a set of factor maps (independent variables) that influence their occurrence by means of a fitting function that estimates the contribution of each variable factor. For preparing the Landslide Susceptibility Map of the Municipality of Vinodol M 1:5,000, logistic regression was used in the MATLAB software interface, namely through the Statistics and Machine Learning Toolbox.

The cartographic unit used for the landslide susceptibility analysis of the study area consisted of regular 5 x 5 m cells. Landslide factor maps were derived as continuous rasters; in the case of distance maps, they were derived in such a way that they represent distance from a line or polygon in increments of 5 m. The accuracy of the landslide susceptibility model was assessed using a success rate curve, and model verification was performed using a prediction rate curve (Chung and Fabbri, 1999, 2003). Success and prediction rate curves (Figure 3.3) are graphical representations of the relationship between the cumulative percentage of the pilot area (on the x-axis) and the cumulative percentage of landslide area (on the y-axis). As the success or prediction curve approaches the upper-left corner, the accuracy or verification of the model increases (Figure 3.3). The measure used to determine classifier efficiency is the area under the success curve; if the area under the curve (AUC) equals 1, corresponding to an accuracy of 100%, the classifier is ideal. If the AUC is 0.5, corresponding to an accuracy of 50%, the classifier is random.

Model reliability was determined based on random sampling of landslides 10 times and calculation of AUCT (AUC values for landslides on which the model was trained) and AUCV (AUC values for landslides on which the model was verified) values for determining accuracy and verification. A model with a high level of reliability is characterized by low oscillations in AUCT and AUCV values across 10 different samples. High oscillations in AUCT and AUCV values characterize a model with a low level of reliability.

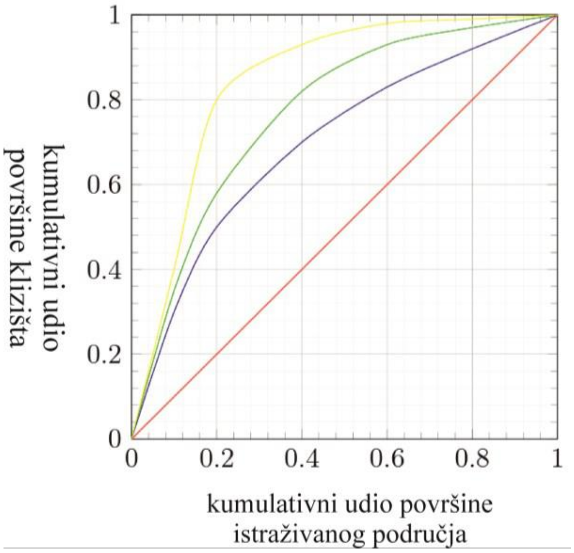

Figure 3.3 Success rate curve (or prediction rate curve) for different classifiers.

The resulting susceptibility model has spatial probability values for landslide occurrence ranging from 0 to 1 and is classified into three zones: (i) the low landslide susceptibility zone, with a probability range from 0 to 0.25; (ii) the moderate landslide susceptibility zone, with a probability range from 0.25 to 0.55; and (iii) the high landslide susceptibility zone, with a probability range from 0.55 to 1. The final landslide susceptibility zoning map was generalized and averaged using the focal statistics tool in ArcGIS 10.8 in such a way that the spatial accuracy of the landslide susceptibility map remained unchanged.

6. LANDSLIDE SUSCEPTIBILITY ASSESSMENT OF THE MUNICIPALITY OF VINODOL M 1:5,000

The landslide susceptibility model was obtained using the logistic regression method based on a landslide inventory containing a total of 843 landslides and 10 landslide factor maps, namely the slope angle map, slope aspect map, terrain curvature map, engineering-geological unit map, distance from the boundaries of engineering-geological units, slope exposure index, integrated wetness index, distance from the drainage network, land use and distance from roads. During susceptibility modelling, 10 different scenarios were prepared. For each scenario, 50% of the landslides from the inventory were randomly selected and used to prepare the landslide susceptibility models, while the remaining 50% of landslides in the inventory were used for model verification. For all 10 scenarios, the accuracy of the landslide susceptibility model was AUCT = 89.28-93.05%, while model verification showed AUCV values from 87.09% to 91.27%. The accuracy of the final landslide susceptibility model with respect to all landslides in the landslide inventory was AUCT100 = 90.34%. The final landslide susceptibility zoning map was classified into three zones with respect to the probability of landslide occurrence, namely the low landslide susceptibility zone with values ranging from 0 to 0.25, the moderate landslide susceptibility zone with probability values from 0.25 to 0.55, and the high landslide susceptibility zone, represented by probabilities greater than 0.55. The final landslide susceptibility zoning map of the Municipality of Vinodol M 1:5,000 is shown in Figure 4.1 and Appendix 1.

The distribution of the area shares of landslide susceptibility zones and the number of mapped landslides by zone is shown in Table 4.1. With respect to the stated landslide susceptibility zoning classification, the low landslide susceptibility zone covers an area of 136.6 km², or 89.3% of the area of the Municipality of Vinodol, and only 1.1% of the total number of mapped landslides in the inventory is located in this zone. The moderate landslide susceptibility zone has an area of 7.9 km², or 5.2% of the area of the Municipality of Vinodol, and contains 4.9% of landslides from the total number of landslides in the inventory, while the area of the high landslide susceptibility zones is 8.4 km², or 5.5% of the area of the Municipality of Vinodol, and contains 94.1% of all landslides in the inventory.

Table 4.1 Distribution of the area shares of landslide susceptibility zones and the number of mapped landslides by zone on the final landslide susceptibility zoning map of the Municipality of Vinodol M 1:5,000.

landslide susceptibility zone	**susceptibility zone area (km²)**	**susceptibility zone share (%)**	**number of mapped landslides**	**share of mapped landslides (%)**
low landslide susceptibility	136.6	89.3	9	1.1
moderate landslide susceptibility	7.9	5.2	41	4.9
high landslide susceptibility	8.4	5.5	793	94.1
total:	**152.9**	**100.0**	**843**	**100.0**

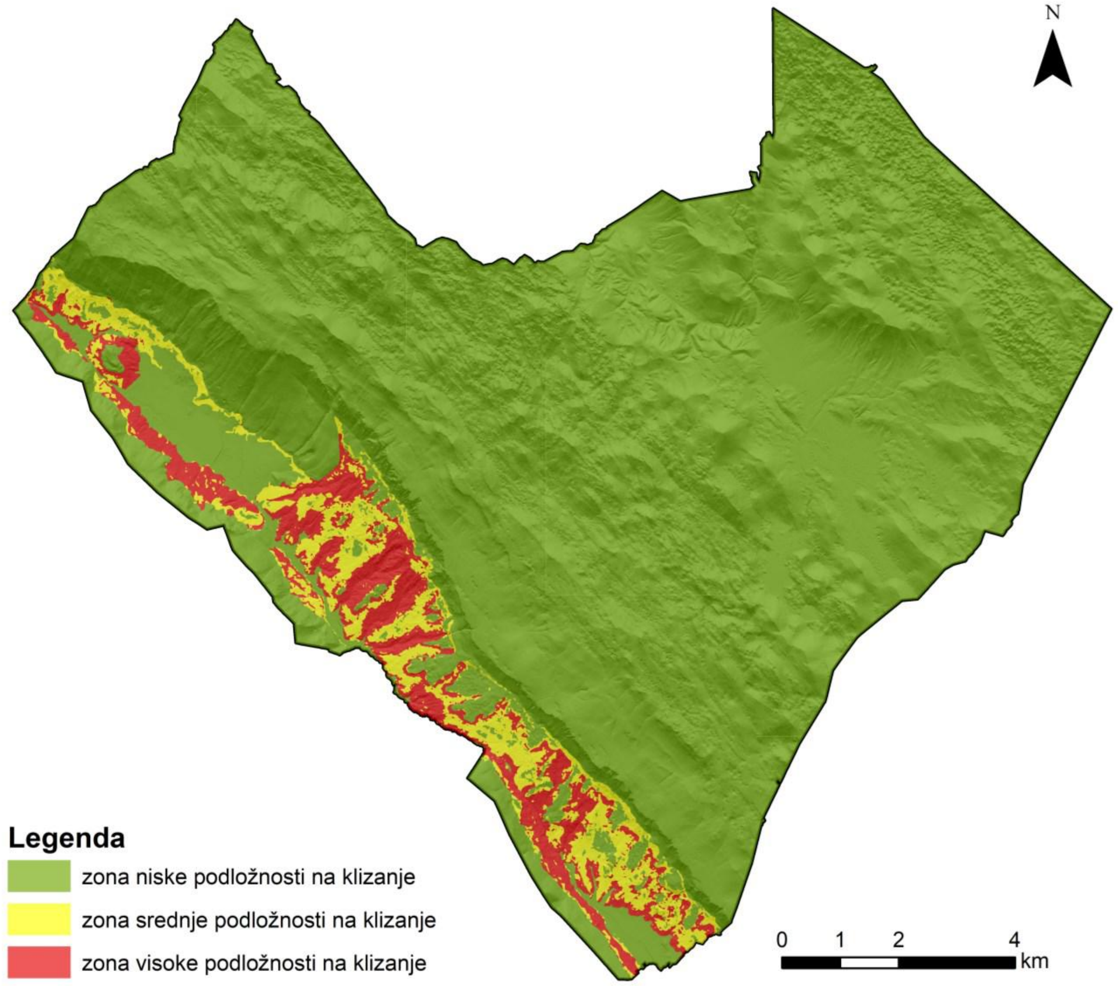

Figure 4.1 Final landslide susceptibility map of the Municipality of Vinodol, obtained by zoning the susceptibility model into three zones: low landslide susceptibility, moderate landslide susceptibility, high landslide susceptibility.

7. CONCLUDING REMARKS AND RECOMMENDATIONS

The landslide susceptibility map of the Municipality of Vinodol was prepared on the basis of a detailed landslide inventory developed through interpretation of the LiDAR DTM at a large scale and factor maps of landslide-conditioning factors with high resolution and spatial accuracy, using the logistic regression machine-learning method. The landslide-conditioning factors on the basis of which the landslide susceptibility model was derived are slope angle, slope aspect, terrain curvature, engineering-geological units, distance from the boundaries of engineering-geological units, slope exposure index, integrated wetness index, distance from the drainage network, land use and distance from roads. The landslide inventory (Jagodnik, 2025) applied in landslide susceptibility modelling includes landslide phenomena whose occurrence is associated with linear erosion processes (gullying) as the prevailing geomorphological factor influencing slope movements in the study area. It follows from the above that the prepared landslide susceptibility map identifies zones of low, moderate and high spatial probability of landslide occurrence caused by linear erosion, i.e. associated with gullies in the study area.

The final landslide susceptibility zoning map shows three landslide susceptibility zones: the low landslide susceptibility zone covers an area of 136.6 km², or 89.3% of the area of the Municipality of Vinodol, and only 1.1% of landslides from the total number of mapped landslides in the inventory is located in this zone; the moderate landslide susceptibility zone has an area of 7.9 km², or 5.2% of the area of the Municipality of Vinodol, and contains 4.9% of landslides from the total number of landslides in the inventory; the high landslide susceptibility zone covers 8.4 km², or 5.5% of the area of the Municipality of Vinodol, and contains 94.1% of all landslides in the inventory.

Large-scale landslide susceptibility zoning maps (1:5,000) prepared for towns and municipalities show zones for which conditions of use and construction conditions can be prescribed through the implementing provisions of spatial plans. They are recommended for use in the preparation or amendment/supplementation of the spatial development plan of a town or municipality and of the urban development plan, for decision-making on land use and designation, as well as on special conditions/regimes for construction and other interventions in space. In addition to spatial planners and associates involved in the preparation of spatial plans, information and data on landslides and landslide susceptibility zones are also intended for designers and other engineers involved in construction (engineering geologists or geotechnical engineers) as preliminary information on geohazards necessary for defining the scope of investigations for specific planned interventions, whether preliminary or detailed investigations required for design.

Landslide susceptibility zoning maps at a scale of 1:5,000 are also intended for determining zones in which landslide hazard mitigation measures need to be implemented, both for recorded landslides and for the potential hazard of new landslides. It is recommended to use the prepared landslide susceptibility map together with data on existing landslides, i.e. with the landslide inventory map at a scale of 1:2,000. Moderate and high landslide susceptibility zones should be treated as areas for which the spatial plan needs to prescribe special use regimes, i.e. construction conditions. Interpretation of landslide susceptibility zones in combination with data on recorded landslides from the landslide inventory map is necessary for decision-making on where it is optimal to route linear infrastructure facilities in relation to existing and potential landslide hazard, where to plan construction areas and individual interventions outside construction areas, and what types of structures to plan within a particular construction area.

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