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Landslide susceptibility analysis for the Kerch Peninsula using weights of evidence approach and GIS

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Abstract. Landslides are one of the most important problems on Kerch Peninsula. Rapidly increasing anthropogenic pressure, which has been particularly could be seen in recent years, leads to destabilization of slopes and significant economic and social damage. Nowdays, economic activities for the further development of Kerch Peninsula, urbanization and the construction of new infrastructure facilities may lead to destabilization of slopes and activation of landslides. Application of an integrated mathematical model, helped us to reflect the current state of Kerch Peninsula in the context of solving this problem. With the help of field research, we mapped a complex of landslide areas, which made it possible to identify the main types of them occurring here – earth and earthwork slips landslides, and in the coastal zone – landfalls and caving slides, total area of which reaches 87.5 km^2 (7.4% of the

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research area territory). We chose an optimal method under the given conditions – the weight of evidence. The approach presented in this paper allows us to classify the territory according to the degree of its susceptibility to landslides with rather high accuracy and analyze the existing situation in this area and analyze possible scenarios for its development. We zoned the territory of the Kerch peninsula into 3 classes – stable, unstable and unsusceptible according to the degree of landslide probable occurrences. The susceptibility analysis revealed that the factors causing the activation of landslides on the Kerch Peninsula are the slope steepness from 20 to 40 degrees, the anthropogenic impact, excessive salinity of the soil cover and the lithological composition of the terrain.

Introduction

Landslides are devastating phenomenon. Their environmental impact can occur after a considerable amount of time. In exceptional cases, the topographic effects caused by the convergence of soil masses can persist for many thousands of years. Active landslides can block water bodies with an excess of suspended solids. In rare cases, they can block rivers and streams, worsening the quality of water and the habitat of aquatic organisms. Landslides can destroy vegetation cover, destroying the habitat of the fauna, and also destroy fertile soils located in the area of their activity [*Nikolic,* 2015]. Also we can trace the relationship between the socio-economic and environmental aspects of landslides [*Krivoguz and Burtnik,* 2018]. The main reason of it is a need of high-quality environment for sustainable development of the territory. The socio-economic impact of landslides can be seen mainly in areas where their activity leads to destruction of forests or agricultural lands, where large amount of suspended solids gets into water bodies etc. [*Highland,* 2009; *Nawaz Khan,* 2001].

One of the most characteristic problems for the Kerch Peninsula has always been the landslides activity. We can see it in transformation of existing landscapes and ecosystems, that leads to serious economic and social damage. Being complex, landslides can significantly affect not only the functioning of the urbanized environment, but also lead to significant loss of life.

The study of landslides has both scientific (allows you to understand the evolution of relief) and practical importance [*Haque et al.,* 2016]. It is especially important in applied research (soil erosion control, surveys for construction structures on slopes etc.). Features of the formation of landslides are reflected primarily in morphology, i.e., external features of slopes: steepness, length, profile shape.

The main researches in this field includes I. Fomenko [*Fomenko and Zerkal,* 2017; *Shubina et al.,* 2017], A. Aydin and R. Eker [*Aydin, Eker,* 2016], S. Bilashco [*Sanda et al.,* 2016], M. Vahidni [*Vahidnia et al.,* 2009], B. Feizizadeh and T. Blaschke [*Feizizadeh and Blaschke,* 2014], S. Baban and K. Sant [*Baban and Sant,* 2005], I. Tazik [*Tazik et al.,* 2014], A. Coe and J. Godt [*Coe et al.,* 2004], B. Pradhan [*Lee et al.,* 2017], L. Ayalew and H. Yamagashi [*Ayalew et al.,* 2004], A. Akbari [*Akbari et al.,* 2014], F. Mancini and K. Ceppi [*Mancini et al.,* 2010], M. Ercanoglu [*Ercanoglu,* 2005], A. Ramos-Cañón and L. Prada-Sarmiento [*Ramos-Cañón et al.,* 2016], P. Atkinson and R. Massari [*Atkinson and Massari,* 1998] etc. in which they showed the possibilities of using various approaches to landslide susceptibility assessment according to the degree of resistance to landslides and the possibilities of their practical application.

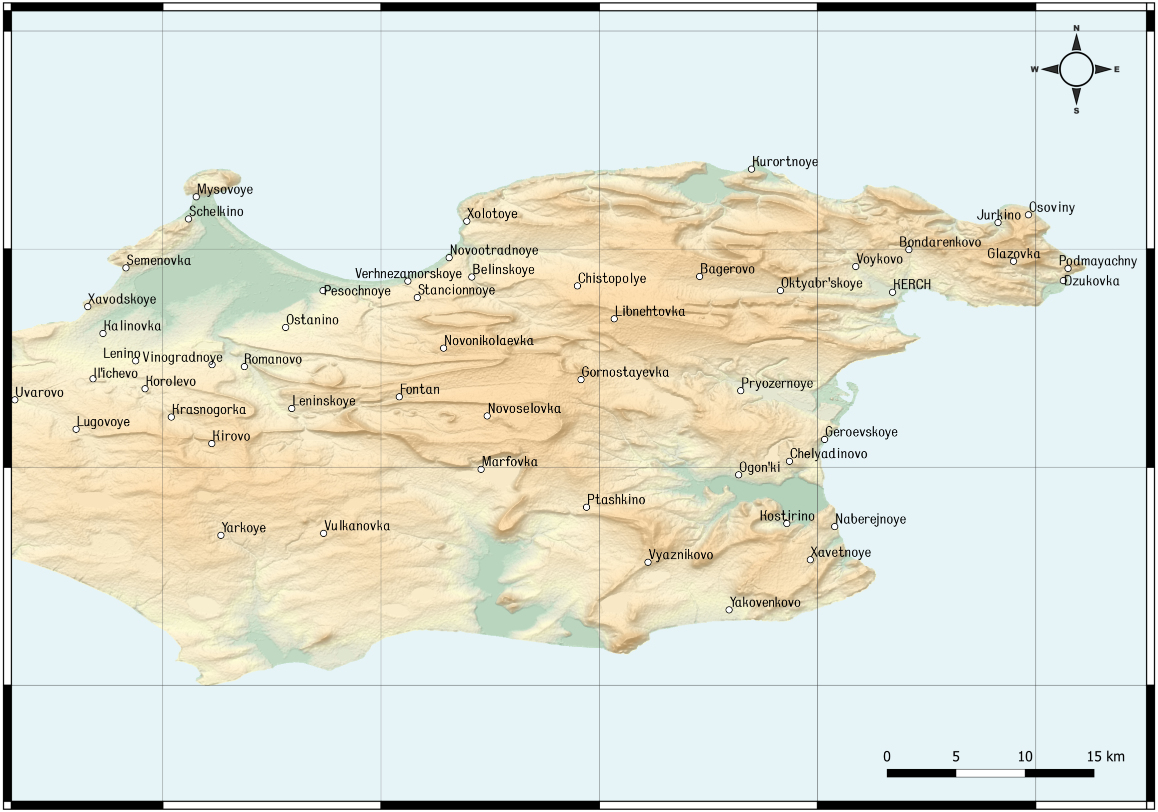

Figure 1. Map of the Kerch Peninsula.

Study Area

The Kerch Peninsula is located in the eastern part of the Crimean Peninsula from which it is separated by the Akmonai Isthmus and is washed by the Black Sea and Sea of Azov, as well as the Kerch Strait (Figure 1). The largest distance from east to west, from the Akmonai Isthmus to the waters of the Kerch Strait, is about 90 km, and from south to north – up to 54 km. The total area of the peninsula is approximately 3000 km^2 [*Krivoguz and Burtnik,* 2018].

Relief of the peninsula can be described as the steppe hills that can be divided into 2 parts – a gentle southern and western part and hilly northern and eastern. Geologically, the Kerch Peninsula belongs to the Kerch-Taman folding, where prevails only sedimentary rocks, the thickness of which reaches more than 5 km [*Krivoguz and Bespalova,* 2017; *Matishov et al.,* 2016].

Kerch Peninsula is a seismically active zone, seismic level of which is largely similar to the mountain systems of the Caucasus and the Crimean Mountains. Basically, a high level of seismic activity is observed in deformations of young geological formations, areas of mud volcanoes presence and movements of the Earth's surface [*Dzeboev and Krasnoperov,* 2018; *Torgoev et* *al.,* 2013]. But according to recent studies, it is in a stage of seismic lull at this time [*Korzhenevsky et al.,* 2017].

The climate of Kerch peninsula can be described as dry, moderately hot, continental type. The average annual air temperature is 11°C. The average temperature of the warmest month – July is 26°C, the coldest (February) -4° C. Winters are mild, but with rare short-term temperature drops. The absolute minimum is about 25–27°C below zero. In summer, the air temperature can reach 35–40°C. The average annual rainfall here is 459 mm. Their highest level occurs in the winter months and early spring. The spatial distribution of precipitation is approximately the same throughout. There is a slight tendency to decrease from east to west. Most atmospheric precipitation falls in the area of the Kerch (about 436 mm per year) [*Krivoguz and Bespalova,* 2018].

Surface waters here are represented by low-water rivers and beams, which is caused by an insignificant level of precipitation. Autumn-winter floods are mild, sometimes occur in December–January. The intensity of floods increases due to a decrease in leakage losses due to soil salinity in summer and their freezing in winter. The average intensity of water levels rising in rivers in the spring is 0.1 … 0.2 m/day, the maximum is 0.5 m/day, which are most often observed in the spring (March–April), or at the beginning of summer (June). In some cases, they were recorded in July–August [*Matishov et al.,* 2016].

The main soil types on Kerch Peninsula are southern solonetzic chernozems, dark chestnut soils, solonetzes. The relief, lithological structure, and hydrological conditions of the area determine the complex nature of the soil cover. Geographically, soils of the peninsula can be divided into two physico-geographical areas – southwest and northeast. The southwestern region is characterized by the dominance of soils formed on dense saline heavy clay. On the west of the region there are dark chestnut soils, southern chernozems and solonetzes soils. The lowlands are characterized by the occurrence of a complex of hydromorphic solonetzes and chestnut-meadow deep saline soils. On the other hand, the northeastern region is more drained, unlike the southwest. The main cause of this is a stronger differentiation of absolute heights. As a result, the soils of the amorphous types are very widespread here [*Korzhenevsky et al.,* 2017].

Vegetation of the Kerch peninsula has mainly Mediterranean type. It mainly represented by such families as *Asteaceae, Poaceae*, *Fabaceae, Brassicaceae*, *Lamiacae, Caryophyllaceae*, *Apiaceae, Rosaceae, Boraginaceae, Chenopodiaceae* and others. According to Kvitnitskaya, about 71% from all of the vegetation have a tap-root system type. Other 29% of species have the fibrous-root system type. Classifying by depth, we can divide all of the vegetation into 3 big groups: 45% of all species have a deep root system, 30% of species have a medium root system and 24% of species have a short root system [*Krivoguz and Burtnik,* 2018].

Economic activity on the Kerch Peninsula is mainly focused on the agricultural sector, which employs about a third part of the population. The main crops grown here are wheat, barley and peas. The largest enterprises in this area are "Vostok" and "Zolotoy Kolos". In addition to the agricultural-industrial complex, there is several gas-producing enterprises, which are located in the East Kazantip and North Bulganak. Separately, it is worth considering the economic activities of the city of Kerch. The main sectors of the economy that have developed here are shipbuilding, ship repairing, fishing and fish resources processing [*Matishov et al.,* 2016].

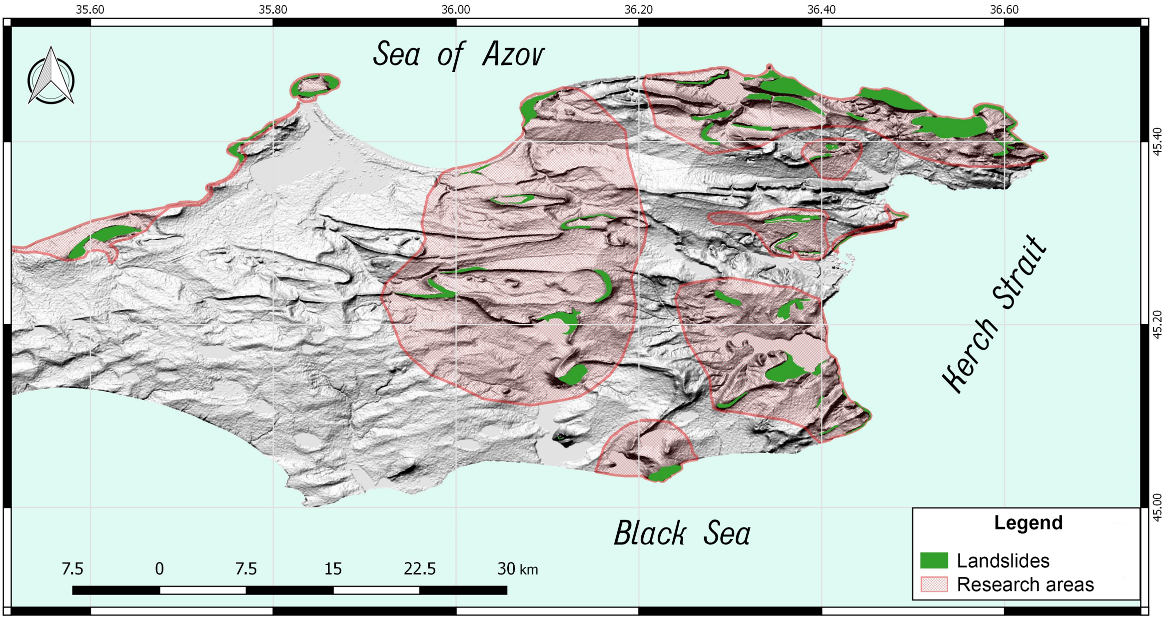

Figure 2. Map of the research areas and landslide locations.

Materials and Methods

Studying and mapping of the landslides in Kerch Peninsula took place through field trips in research areas, which are represented in Figure 2.

Total estimated area, covered by our research is 1181 m^2 or more than a third part of the peninsula's territory. We've investigated both coastal and settlements territories, steppe part of the peninsula, as well as protected areas.

The results of field studies are presented in Figure 2. We mapped 64 objects, identified as landslides. Total area of mapped landslides was 87.5 km^2 or 7% of the investigated area [*Krivoguz and Bespalova,* 2017].

According to morphological and morphometric studies, main types of landslides on Kerch Peninsula according to Varnes classification system [*Cruden and Varnes,* 1996; *Hungr et al.,* 2014] are: in the central part of the peninsula and in areas of the Tavrida highway – rotational earth slumps and earth slides. In coastal zone of the peninsula – earth and rock falls, locally – earth slides [*Krivoguz and Bespalova,* 2017; *Matishov et al.,* 2016; *Peshkov,* 2015].

Currently, there are a several numbers of different methods for landslide susceptibility assessment. These methods are based on the spatial-statistical approach, which involves the using and analyzing of data obtained as a result of observations of various aspects that affect landslide process, their subsequent processing, and analysis using geographic information systems.

By defining a landslide susceptibility, S. van Westen [*van Westen,* 1997; *van Westen et al.,* 2008] understood the quantitative or qualitative assessment of types, volumes, or territories and the spatial distribution of landslides that exist or may appear in the study area [*Ismail-Zadeh,* 2016; *Nikolov et al.,* 2015].

Landslide susceptibility of the territory should be understood as the state of area in which a combination of factors that directly or indirectly affect the territory does not lead to activity of existing or forming new landslides.

The susceptibility of landslide can be mathematically described as the sum of the contribution of factors influencing it (weighting factors). Thus, the contribution of factors that have a positive effect and actually lead to landslide activity will be in the range from 0 to ∞, while the contribution of factors that have a restraining effect on landslides will be in the range from $-\infty$ to 0. The boundary, in which there is a transition from an unstable state to a stable one and vice versa, we can assume as 0.

Obtained numerical results of landslide susceptibility index can be interpreted as follows:

- < -2 – susceptible territories, that characterized by strong stability. Set of factors, that affecting landslides is minimal or their level prevails over the factor's level that lead to instability.
- $-2 - 2$ – unstable or transitional territories. They are characterized by an ambiguous level of stability, which is expressed in overlapping the level of exposure of some factors to others. Even with a slight change in the level of impact of at least one of these factors, a transition of the state of the territory is possible both in the direction of resistance to landslides, and vice versa.
- > 2 – unsusceptible territories. Level of factors, that affecting landslides is maximum or the level of influence of factors contributing to the slope instability prevails over the level of factors contributing to its stability.

The spatial analysis of landslide susceptibility lies in fact that when we analyzing the factors for a given number of grid cells $N\{D\}$, containing the event D

and the total number of grid cells $N\{T\}$, the prior probability is expressed by the (1)

$$P\{D\} = \frac{N\{D\}}{N\{T\}} \tag{1}$$

Assuming that a binary predictor of influencing factor B occupies $N\{B\}$ grid cells, and if a certain number of known landslides are within the cells of this factor, then the probability of occurrence, given the possibility of the presence of a predictor factor and the absence of an influencing factor, can be expressed by the (2) and (3).

$$P\{D|B\} = \frac{P\{D \cap B\}}{P\{B\}} = P\{D\}\frac{P\{B|D\}}{P\{B\}} \tag{2}$$

$$P\{D|\bar{B}\} = \frac{P\{D \cap \bar{B}\}}{P\{\bar{B}\}} = P\{D\}\frac{P\{\bar{B}|D\}}{P\{\bar{B}\}} \tag{3}$$

The posterior probability determines the presence or absence of a factor and is denoted by $P\{D|B\}$ and $P\{D|B^{-}\}$, respectively. $P\{D|B\}$ and $P\{D|B^{-}\}$ denote the posterior probabilities of finding the grid cells of factor B in the grid cells of event D.

Weights for binary factors are determined by (4) and (5):

$$W^{+} = \log_{e} \frac{P\{B|D\}}{P\{B|\bar{D}\}} \tag{4}$$

$$W^{-} = \log_{e} \frac{P\{\bar{B}|D\}}{P\{\bar{B}|\bar{D}\}} \tag{5}$$

where W^{+} and W^{-} are the weights of the absence or presence of factors affecting landslides, respectively.

Weights are also used to find the contrast index (C) which determines the measure of correlation between the factor change and the landslide, which is expressed by (6).

$$C = W^{+} - W^{-} \tag{6}$$

The final result of the analysis using weights of evidence method is the calculation of the landslide susceptibility index (LSI), which is determined by (7).

$$\mathrm{LSI} = \exp(\Sigma W^{+} + \ln(O_f)) \tag{7}$$

where O_f – weight coefficients of landslide presence in the study area.

Results and Discussion

Landslide susceptibility index was calculated by using next factors: morphometric (slope, mass balance index, stream power index), vegetation cover, seismic activity, precipitation, lithology, soil types, surface waters and anthropogenic activity (Figure 3).

Result of the factor's analysis for their contribution to landslide susceptibility is presented in Table 1.

Thus, by ranking the destabilizing classes include: slope angles are more than 40°(2.6015), slope angles are from 20 to 40°(1.3992), distance to the road network is less than 500 m (1.2098), presence of solonetzic soils (1.1382), the lithological composition is presented by clays, sands, loams (1.0834).

The influence of the slope angles is due to physical reasons, which include an increase in the gravity effect with an increasing of them. In general, based on calculations, the Kerch Peninsula is characterized by landslides on slopes more than 15°.

Distance to roads is an important factor, largely reflecting anthropogenic activity. So, according to calculations, the most significant class is the distance no more than 500 m from the road network to landslides. First of all, existing roads are sources of noise and vibration, which increase the instability of slopes. From the other hand, roads construction produced with slope stabilization measures, that usually prevents landslide occurring. An important role is also played by the glut of the slopes with technical facilities, the cutting of them when laying new transport routes, etc.

The influence of solonetzes soils is caused both by the presence of readily leachable gypsum rocks and readily salts, which leads to erosion and loss of stability, as well as clay lower horizons, which leeds to the active sliding of ground masses down the slope with sufficient moisture [*Korzhenevsky et al.,* 2017]. This can occur both from groundwater activities and from extremely high levels of precipitation, which is rare for this region.

Speaking about lithology, clays, sands and loams are most spread types of unstable slopes areas. This can be caused both by the presence of clays, which, with sufficient moisture, can lead to the sliding of soil masses, and due to the presence of conglomerates, which are partially composed of easily leachable rocks, which can lead to erosion and a decrease slope stability [*Gvishiani et al.,* 2018; *Rybkina and Rostovtseva,* 2017].

Stabilizing classes include: dense vegetation (-7.3520), grasslands (-2.8805), lithological composition is represented by sands, clays, loams, siltstones (-2.574), slope angles are 5–7°, 7–10° and 3–5°(-1.8468, -1.9051 and -1.8468, respectively), primitive sandy soils (-1.4877).

The main reason for such high levels of resistance in areas with dense vegetation is the natural ability of trees to restrain soil from sliding with their root system [*Pande et al.,* 2002; *Tibaldi et al.,* 1995]. The most common tree species here are *Robinia pseudoacacia L.*, *Platanus orientalis L., Populus alba L., Elaeagnus commutata Bernh. Ex Rydb.,* etc. Mostly all of these trees have a deep root system of about 10–15 meters, capable of penetrating deep horizons of the slopes and strengthening it. An exception is an *Elaeagnus commutata*, whose root system is located near the surface, but has a sufficiently large density.

Grass cover also has a strong effect on slope stability. It allows to strengthen the upper parts of the slopes, not allowing them to slide down. In this case, the danger is often caused by fires, destroying significant parts of the grass cover, due to the typical temperatures in the summer.

As a result of the calculations, we obtained the distribution of LSI on the Kerch Peninsula, presented in Figure 4. The accuracy of the analysis was 81% [*Krivoguz,* 2019].

Generally, all unsusceptible (with lowest LSI values) territories located in the northern part of the peninsula and occupied about 7% of total area. Also, in these areas situated a large number of transport roads, so a new route "Tavrida" will unload the existing Kerch–Simferopol highway.

By land use types, territory of the Kerch Peninsula can be divided into 7 categories (Figure 5): cities and settlements territories, agricultural lands, industrial lands, scrapyard areas, grassland areas with steppe vegetation, quarry areas and recreational territories.

Levels of territorial exposure to landslides by land use types is presented in Table 2.

It can be seen, that the greatest impact from the landslides can be exerted on the steppe and recreational territories. The level of territories unsusceptible to landslides here exceeds 30%. While the landslides formation is not so critical for the steppe territories, but for recreational areas it led to significant threat, expressed both in the reduction of available areas for people's recreation, and also in loss of human lives.

The insignificant level of unsusceptible areas on agricultural territories is mainly due to the relatively flat surface for choosing a farming area, that reduces the

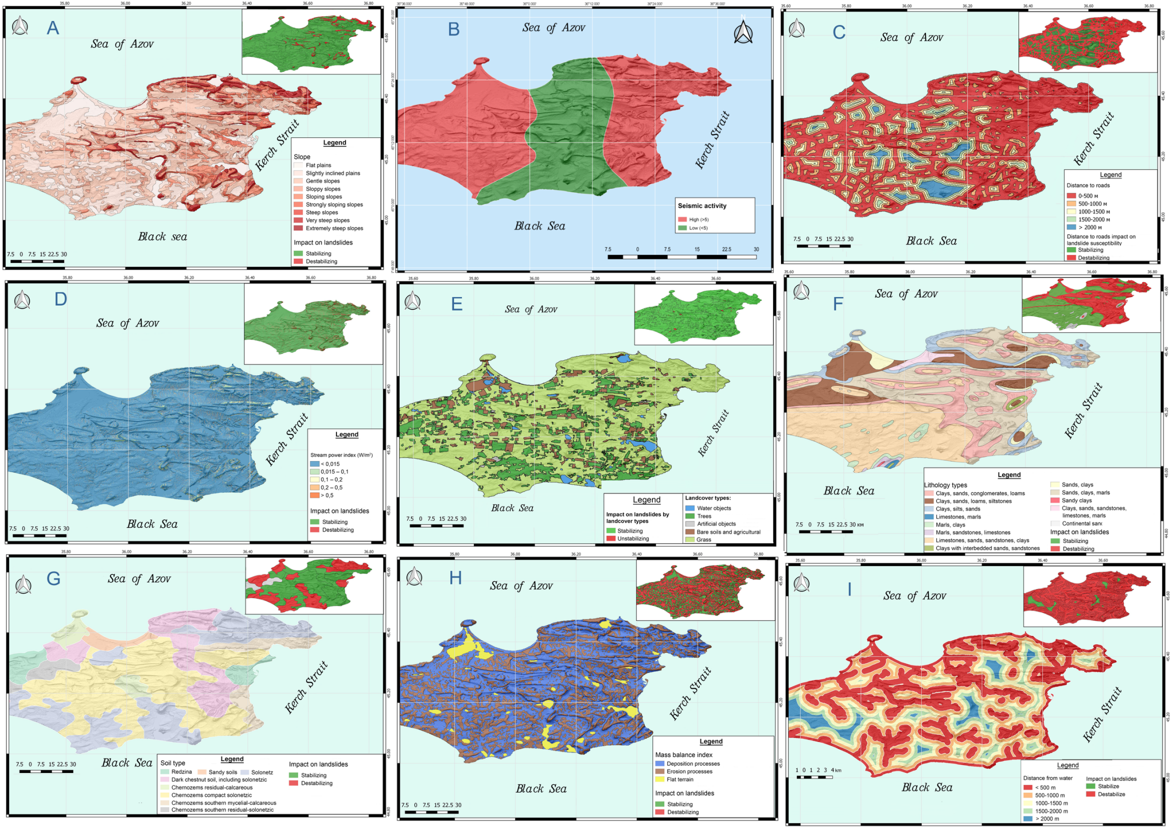

Figure 3. Factors for calculation landslide susceptibility index.
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Table 1. Result of the Factor's Analysis for Their Contribution to Landslide Susceptibility

Class	Class name	Susceptibility value	Area, km^2
Slope	$< 1°$	−0.3763	226.7391
	1–3°	−1.4695	187.3897
	3–5°	−1.8468	289.7629
	5–7°	−1.9051	622.3431
	7–10°	−1.4254	250.6452
	10–15°	−0.8919	570.7517
	15–20°	0.0512	266.0778
	20–40°	1.3992	330.3291
	$> 40°$	2.6015	107.7023
NDVI	Water objects	−0.7891	54.0486
	Artificial objects	0.7392	818.003025
	Bare soils	−0.1989	1717.42905
	Grassland	−2.8805	300.803625
	Dense vegetation, trees	−7.3520	29.33505
Seismic activity	Low (< 5)	−1.0139	1650
	High (> 5)	1.0139	1350
Mass balance index	Deposition processes	0.2547	1440
	Flat terrain	−0.6271	150
	Erosion processes	−0.1619	1350
Stream power index	< 0.015	−0.8193	2747.033
	0.015–0.1	0.9364	80.81874
	0.1–0.2	0.6642	28.52946
	0.2–0.5	0.4991	14.62019
	> 0.5	0.4032	17.09549
Distance to water	0–500 m	0.3518	736.3948
	500–1000 m	0.0592	629.636
	1000–1500 m	0.0191	525.7279
	1500–2000 m	0.0118	409.4954
	> 2000 m	−0.6196	617.5648

Table 1. Continued.

Class	Class name	Susceptibility value	Area, km^2
Lithology	Limestones, marls	–	5.09
	Clays, silts, sands	0.9469	202.26
	Limestones, sands, sandstones, clays	−0.9652	908.17
	Sands, clays, marls	0.3485	660.95
	Clays, sands, sandstones, limestones, marls	−0.8421	33.59
	Clays, sands, conglomerates, loams	1.0834	438
	Clays, sands, loams, siltstones	−2.574	448.79
	Sands, clays (N_2k)	–	31.15
	Sands, clays (N_2p)	0.1809	32.38
	Continental sands	0.8135	18.43
	Clays with interbedded sands, sandstones	–	1.38
	Sandy clays	–	1.32
	Marls, sandstones, limestones	–	11.84
	Marls, clays	–	46.55
Distance to roads	< 500 m	1.2098	1878.894
	500–1000 m	−0.9881	597.784
	1000–1500 m	−0.6483	252.9791
	1500–2000 m	−0.0535	109.1504
	> 2000 m	−1.3394	91.36397
Soil types	Chernozems southern mycelial-calcareous	−0.2302	173.42
	Chernozems southern residual-solonetzic	–	154.38
	Chernozems compact solonetzic	−0.924	1108.86
	Chernozems residual-calcareous	0.8543	129.06
	Dark chestnut soil, including solonetz	−0.6601	546.26
	Solonetz	1.1382	790.85
	Redzina	0.3958	180.17
	Sandy soils	−1.4877	71.38

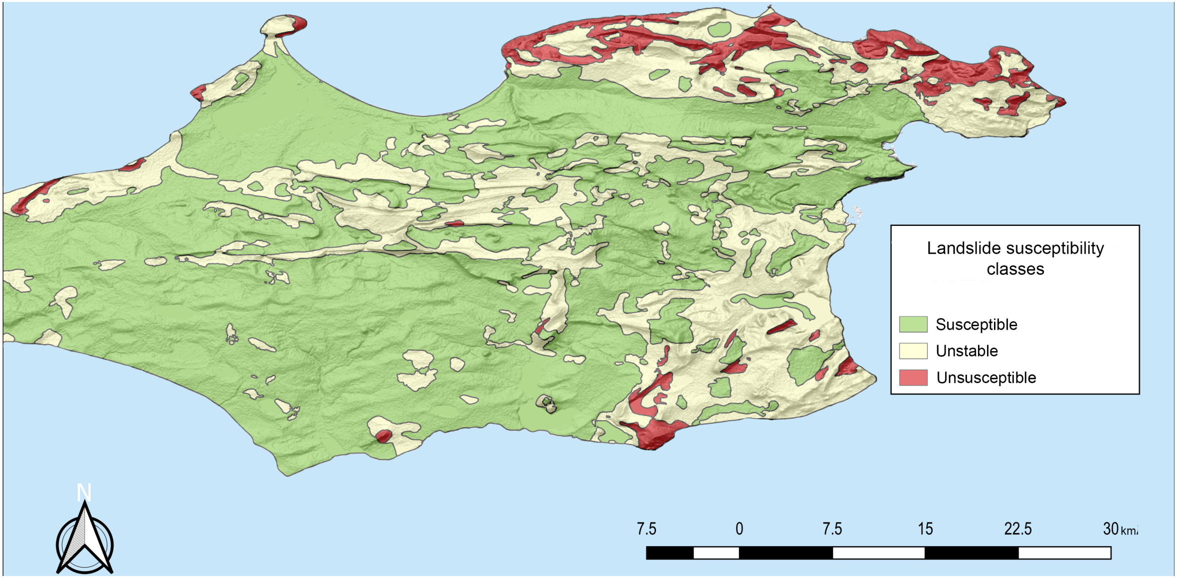

Figure 4. Landslide susceptibility assessment map.

Table 2. Levels of Territorial Exposure to Landslides by Land use Types

Land use type	Area					
	Susceptible		Unstable		Unsusceptible	
	km^2	%	km^2	%	km^2	%
Industrial lands	51.1	65	21.4	30	2.9	5
Grassland areas, mainly with steppe vegetation	2.3	10	13.8	55	8.2	35
Cities and settlements territories	58.2	70	22.6	25	3.7	5
Quarry areas	2.8	35	4	50	1.3	15
Recreational territories	0.008	20	0.03	50	0.02	30
Agricultural lands	429.8	62	232.9	33	24.4	5
Scrapyard areas	0.3	73	0.1	22	0.02	5

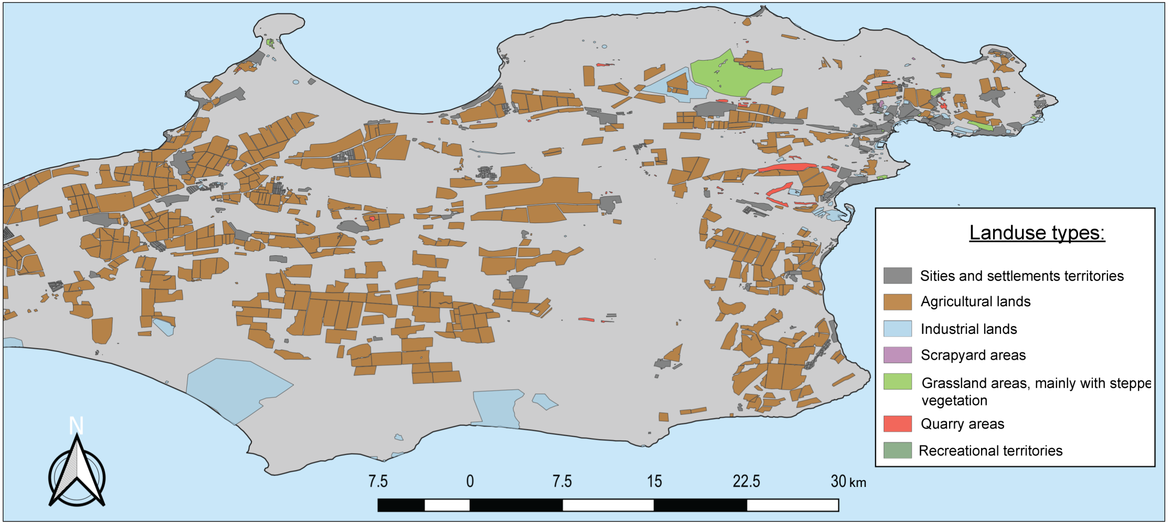

Figure 5. Types of land use on Kerch Peninsula.

risk of landslides.

In connection with the ongoing urbanization processes and the building a new infrastructure associated with the construction of the “Crimean bridge”, a special role should be given to land use planning in this region.

Since high anthropogenic activities can significantly aggravate the current situation related to landslides, strategic planning of at least the main aspects of land use is necessary.

Conclusions

1. Factors leading to landslides on Kerch Peninsula are slope angles from 20°to 40°, anthropogenic impact, excessive salinity of the soil cover and the lithological composition of the area.
2. The role of the most common factor of their formation – atmospheric precipitation is almost minimal. This is mainly due to the climatic features of the peninsula and its geographical location. Therefore, we can assume that due to the low amount of precipitation falling here, this factor in this case can be neglected.

3. Based on comprehensive field studies and modelling research, it was found that on the Kerch Peninsula there is a significant number of territories occupied by landslides, the area of which reaches 87.5 km^2 (7.4% of the field research area).

4. In the modern period, vigorous economic activity for the further development of the Kerch Peninsula, urbanization and the construction of new infrastructure facilities, can lead to destabilization of unsusceptible territories and leads to landslides forming.

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