IDENTIFYING POTENTIAL LANDSLIDE AREAS BY EMPLOYING THE EROSION RELIEF INDEX AND METEOROLOGICAL CRITERIA IN UKRAINE

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Key-words: remote sensing data, digital elevation model, Erosion Relief Index, landslides, meteorological criteria, erosion.

Abstract. A method for determining landslide-prone areas based on remote sensing data and meteorological data is proposed for the Ukrainian territory. It was tested within different landscape sites of the country: the Ukrainian Carpathians, the Dniester river valley, the right-bank of Dnieper river within Kyiv and Kaniv, right side of the Dnieper-Donets Rift within Kharkiv, and the Black Sea Lowland within the Odessa city. The digital elevation model (DEM) data based on the topographic survey by Shuttle Radar Topography Mission (SRTM) as well as data from meteorological stations were used. The Erosion Relief Index (ER) method was obtained based on terrain morphology as reflected by the DEM. The index considers vertical and horizontal terrain dissection. The potential areas prone to erosion and landslide risks were identified by the ER index values. On the background of the Köppen climatic classification, the potential of rainfall events to cause the activation and intensification of landslides was analyzed by adopting threshold curves of meteorological criteria. The study argues that the use of the ER index in conjunction with meteorological data is an effective method to identify potential areas with erosion and landslide risks.

1. INTRODUCTION

Modern conditions are characterized by intensive engineering and economic land development. The global technogenic and natural processes lead to the activation of negative factors. These natural and anthropogenic factors intensify social and economic problems. Prevention is possible by rational use of natural resources and the introduction of measures. It will be possible to prevent occurrence of the new areas of natural disasters: mudflows, landslides *et al*. The main causes of such disasters are factors of hydrogeology and geomorphology.

Human safety, well-being and health depend on climate conditions. Climate determines complex of the weather and natural state. The modern climate situation leads to considerable environmental changes. The last decades showed the increase of catastrophic natural disasters worldwide. The most of the catastrophic natural disasters are related with hazardous exogenous variables: landslides, mudflows *et al*. The activities of exogenous variables are changed to more susceptible to the weather conditions.

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Climate change and global warming assign to safety of ecological environment. The global warming has expressed in physical characteristics of the atmosphere and lithosphere during the last ears of XXth century and within XXIth century. Increases of global average temperature of 1,4–5,8°C till the end of current century are projected (Suruchi *et al.*, 2021). The high temperatures destruct soil layers. During intensive sunshine, the soil drains, and become a dry crust. The drops of heavy rain are more heavily and stronger. Heavy rains destroy soils. In such cases, rains do not saturate soils with necessary water. The soil layer erodes and forms gullies. Gullies with time become deepen and induce strengthening erosion and destruction. So, considerable land areas become decommission. Such land areas are unusable in agronomy and construction (Belayneh *et al.*, 2020; Bastola *et al.*, 2018).

It is expected further increase of the water vapor, evaporation and precipitation size on the global level. On the regional level, increases and decreases of precipitation within different areas are predicted. The changes in dynamic intensity, frequency and variability of heavy, catastrophic rains are observed (Hosseinzadehtalaei *et al.*, 2020; Li *et al.*, 2019; Wasko and Sharma, 2017; Kundzewicz *et al.*, 2014). The increase of significant ecosystems dislocations in consequence of drought and freshet is expected. Heavy rainfalls will lead to freshets, floods, mudflows. The reduction of frosty days and cols waves is possible. In conditions of air temperature increasing, it will facilitate decline freezing of the soil in winter. It is observing acceleration in water infiltration of soils and increasing groundwater level. Floods and landslides will intensify and activate (Gariano and Guzzetti, 2016; Panek, 2019).

Attention must be paid to operational developments for detecting potential hazard areas especially areas with landslide activity. It is optional and effective to involve the remote sensing data. Such methods can detect areas with potential environmental problems. Based on remote sensing data is possible development prevention and operational observing of landslides.

Landslide hazard is a negative factor of ecological and technogenic safety of terrain on the regional and local level. Landslides lead to huge losses in nature, agriculture, economics and humans' life. The evolution of landslide is caused by many factors. The most significant factor is action of hydrometeorological processes during anthropogenic disorders of vegetation cover, surface and underground runoff. During the spring melting snow process and summer heavy rains the maximum of landslide activity is observed. The landslide studies must include characteristics of liquid and solid precipitation on the soil substance.

The landslides are a dangerous hazard. During landslide activity the huge soil masses can be displaced. The movements may cause damages to buildings, communications, and threaten human lives.

The natural origin of landslides is localized mainly within ravine-beam lands, river valley slopes, along the coasts, in the mountains, on the watersheds.

The aim of this study is to identify the potential areas with erosion and landslide risks within Ukraine as well as landslide intensification and triggering thresholds of unexpected climatological indicators, by employing data derived from remote sensing and meteorological stations.

This study is concentrated on addressing some unresolved tasks, such as: (a) generalized characterization of the impact of climatological indicators on landslides; (b) the identification of threshold values of unexpected meteorological factors, which determine the activation of landslide processes in Ukraine.

2. BACKGROUND

The erosion and landslides are widely distributed all around the world, with numerous cases reported especially in USA (Smith and Wegmann, 2018), China (Tang *et al.*, 2020; Zhang *et al.*, 2020), Indonesia (Nugraha *et al.*, 2015), Italia (Cencetti *et al.*, 2020), Pakistan (Khan *et al.*, 2019), Brazil (Mendonca and Silva, 2020) etc.

To study the natural and anthropogenic landslides by remote sensing data many sensor systems were developed: radiolocation, active and passive systems, radiometers, scatterometers (Zhao and Lu, 2018; Casagli *et al.*, 2016).

Synthetic-aperture radar (SAR) has wide coverage and high spatial resolution. The significant advantage is its independence of weather conditions and capability of day and night imaging. For landslide detection and exploration widely used are: European Remote Sensing Satellites (ERS-1, ERS-2) (Refice *et al.*, 2019; Hayati *et al.*, 2020), Envisat ASAR (Frangioni *et al.*, 2013), COSMO, SkyMED (Soldato *et al.*, 2019; Konishi and Suga, 2018), Terra SAR-X (Liu *et al.*, 2020; Zhao *et al.*, 2018), Sentinal-1 (Solari *et al.*, 2019; Mondini *et al.*, 2019). The main radiolocation sensing direction is measuring earth and water surface. Based on this data, digital elevation models are derived.

The optical remote sensing data are in use also for landslide research and monitoring. Optical methods are used for landslide inventory and mapping (Kyriou and Nikolakopoulos, 2020; Fang, 2020; Ramos-Bernal, 2018). The most useful optical systems for this purpose are considered Landsat (Hashim *et al.*, 2018; Cahalane *et al.*, 2019), SPOT (Khan *et al.*, 2019), ASTER (Ramos-Bernal *et al.*, 2018; Chang *et al.*, 2019), RapidEye (Kim and Kim, 2018; Cahalane *et al.*, 2019).

One of the most popular and useful method of erosion observing is digital elevation model (DEM). It identifies terrain changes. The LiDAR systems obtain long-term imaging. It is effective for quantitative assessment of landscape changes within large areas. The Terrestrial Laser Scanning (TLS) obtains three-dimensional relief changes with the high level of detail, that is effective for landslide researches (Li and Tomas, 2017; Pradhan, 2017). The digital elevation model from the Indian satellite IRS obtains stereophotogrammetric images. Such images are better to use for mapping and quantitative assessment of landscape erosion and landslide processes (Chen *et al.*, 2020; Chang *et al.*, 2019).

The textural features analysis method is used for landslide detection. It is based on difference in textures and features of objects on the satellite images. The method is used as additional and subsidiary in complex with other methods (Knevels *et al.*, 2019; Timchenko *et al.*, 2016). The method is used to detect the difference between the roughness and smooth of the surface. It is possible to determine the landslide bounds, stability and instability zones, zones with active and passive phases. Detecting the erosion with high-spectral and temporal remote sensing frequently based on the qualitative colored background method. Different color corrections, color combinations, color compositions, merging images are also effective to erosion signification (Fauzi *et al.*, 2015; Fernandez *et al.*, 2008). In this case the vegetation cover is good separated, forming the high contrast in vegetation and non-vegetation zones. The near infrared (NIR) band is widely used for vegetation separation. As the control data points are usually used the Normalized Difference Vegetation Index (NDVI) which is calculated based on remote sensing data (Lin *et al.*, 2005). Interpretation of space images include filtrating of polyline features, slope gradients, different object classification methodic.

Spectroscopic and 3D effect analyses permit to identify landslides by morphological features, such as borders, earthfall and accumulation zones, elevations. Complex long-term monitoring observations and momentary images enables to assess activity of landslides, displayed by pixel movement and changes. The pixel changes in subsequence satellite images shows the intensity, dynamics and trends of the process.

Since the erosion is worldwide spread, many scientists develop monitoring and research methods. One of the methods is the detection of the dynamics of landslides (Gatter *et al.*, 2018), observing the impacts of landslide on the social-economic systems (Perera, 2018), ecosystems and environment (Nicolic, 2014). Quantitative evaluation of landslide susceptibility using multiple regression methods and principal component analysis is used for landslides estimation. Physically-based modelling illustrates the physical processes of landslide formation and rainfall impacts. The combination of field surveys and remote sensing techniques is widely applied due to multifactorial consideration of landslide processing. The modelling methods are effective, because they are based on quantitative and different features consideration: slope angle, curvature of the slopes, soil features, precipitation conditions etc. The landslide monitoring must be improved for later prevention of negative societal consequences. The detection of erosion processes and of their impact on the environment allow to proceed with modeling of vulnerability risks on natural disasters and hydrogeological risks (Kostyuchenko, 2015; Kostyuchenko *et al.*, 2016).

The observation and study of denudation processes is a significant task in Ukraine as well. Based on Landsat 5/TM remote data a modeling of the land degradation risk assessment was performed within the Oleshky Sand dunes during two periods: 1983–1991 and 1991–2010, while considering vegetation cover changes and soil erosion dynamics (Popov *et al.*, 2012). It was ground different aspects of remote sensing data application as a component of landscape monitoring conditions using geoinformation systems (GIS) (Lai and Tsai, 2019; Mersha and Meten, 2018). Besides it was considered the main approaches of assessment erosion within wide areas based on remote sensing data, determined dangerous of erosion process manifestation using GIS, based on spatial geoinformation erosion modeling of soil losses, develop approaches for water soil erosion modeling, identified measures, diagnostic parameters, quantitative and qualitative assessment of soil degradation, using integral assessment of relief identified erosion risks (Svetlitchnyi, 2009; Svetlitchnyi, 2018).

The tendency of ecological hazard increasing with intensity of precipitation (heavy rains) was estimated by Ukrainian and world scientists (Lyalko *et al.*, 2018; Dourte *et al.*, 2015).

3. CHARACTERISTICS OF THE STUDY AREA

The Ukraine is situated on the southwest part of East European Plain. Ukrainian Carpathians are located in the western part and the Crimean Mountains in the southern part of Ukraine. Within the Ukraine there are mountains, uplands and lowlands, plains. Such physiographic conditions vary due to climate changing from perhumid on the west part to arid on the south of the country. The climate is favorable for human life and activity. However, location features, evolution of atmospheric processes establish conditions for adverse meteorological phenomena formation, which increase during XXI century.

Therefore, the Ukraine is characterized by wide diversity of natural, climatic and geological conditions. It determines formation of different exogenous geomorphological processes. Some of them have a negative influence on the human lives and activities. This category includes erosion, landslides, anthropogenic and other processes. Beside natural exogenous processes defined anthropogenic processes that are widespread on the east of the Ukraine. It's spreading caused by development of mineral deposits.

Combined manifestation of different exogenous processes leads to increase of unusable land areas. The intensification of exogenous processes including landslides as a result of global and regional warming is observed. A comprehensive study of these both problems and their interdependence is an interesting aspect.

4. DATA AND METHODOLOGY

This study is based on the complexion of methods, include the national and world experience. The methodological workflow is reflected in the Figure 1. The statistical data of the ground meteorological stations within Ukraine were used. For geological observations the cartographic data were applied. The remote sensing data, such as digital elevation model (DEM) with 30m resolution form the Shuttle (SRTM) were used for landslide assessment. The field measurements include the data from 60 ground-based meteorological instrumental stations, verified by Central Geophysical Observatory of Ukraine named after Boris Sreznevsky. Field meteorological surveys include quantity of monthly precipitations from 1900 to 2018: rainfall events (30 mm precipitation in 12 hours); heavy rainfall events (precipitation 50 mm and more in 12 hours); long-term rainfall events (precipitation 100 mm and more).

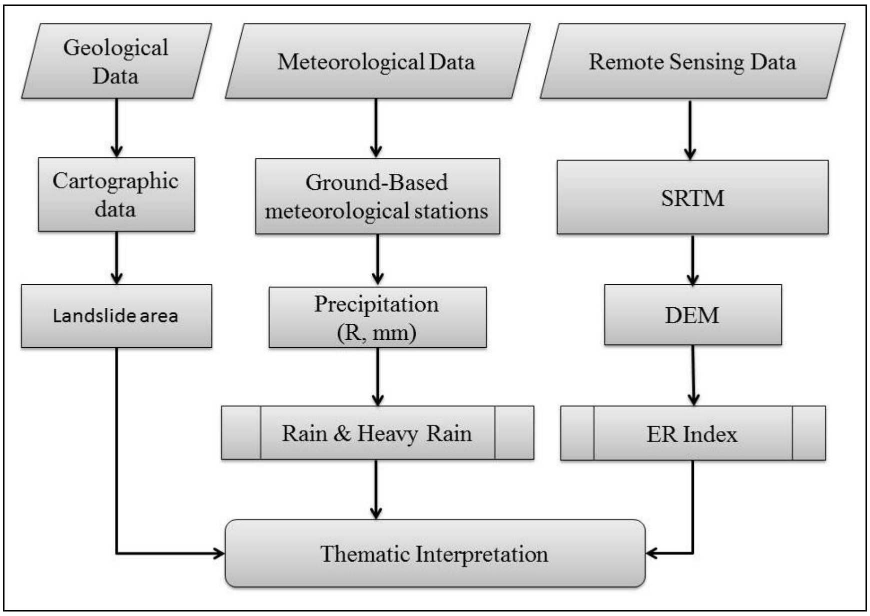


Fig. 1 – The scheme for the assessmant of landslide-prone areas in Ukraine.

For determining threshold values of climatological factors the next algorithm was put in practice: 1) the analysis of a multiannual precipitation data carried out for diagnostic estimation of the precipitation distribution changing in Ukraine; 2) the compilation of the structured dataset on precipitation which can lead to the landslides intensification. The intensity of each heavy rainfall event was estimated; 3) the threshold values were obtained in accordance to the Guzzetti approach (Guzzetti *et al.*, 2007) which describe the landslides activation in Ukraine; 4) rainfall events which can provoke the landslides were determined by exceeding the actual rainfall average intensity over the threshold proposed by Guzzetti *et al.*, 2007.

The intensity of relief dissection was derived through the Erosion Relief Index (ER) used as a methodological tool to assess potential landslide areas. ER Index were developed and tested in Ukrainian Carpatians (Lyalko *et al.*, 2018) and Dnieper River Vally withib Kyiv region (Lyalko *et al.*, 2017). The intensity of erosion dissection (Q) is estimated by equation 1:

$$Q = \frac{\Delta H * L}{P^2} \qquad (1)$$

where, $\Delta H / P$ is the vertical amplitude (vertical dissection) of relief, ΔH is the difference between the highest and lowest points in a particular area within moving window (relative relief), *P* is the area of moving window, L / P is the interfluvial amplitude (horizontal dissection), *L* is the total length of river in the moving window.

In this study, it has been suggested to use the length of contour lines in the moving window instead of total length of the river. In this way, the equation for intensity of erosion dissection of the area (Erosion Relief Index) takes the following form:

$$ER = \frac{\Delta H * (N * l)}{P^2} \qquad (2)$$

where, $(N * l) / P$ is the interfluvial amplitude (horizontal dissection), *N* is the number of contour line pixels in the moving window, *l* – length of the pixel.

Based on the digital elevation model from the reusable spacecraft Shuttle was obtained for Ukraine. The spatial resolution of 30 m was too low for this purpose. Therefore, the ERDAS Imagine software product was used for processing digital elevation model data with the *Bilinear Interpolation* procedure. According to this procedure, the changing in the heights between nearest pixels was assumed as linear with 30 m change degree.

To estimate the vertical dissection of the relief the *Spatial Modeler* module within ERDAS Imagine was used to implement the following equation:

$$\frac{\Delta H}{P} = (H_{\max} - H_{\min}) / P \tag{3}$$

where, H_{min} and H_{max} are the minimum and maximum elevation values in the moving window.

Using the *Interpreter* module from ERDAS Imagine, the contour lines for all Ukraine territory were obtained with 5m horizontal interval for estimation of the relief dissection.

The next step was focused on estimating the horizontal dissection of relief within the moving window according to the equation:

$$(N * l) / P \tag{4}$$

Thus, using the ERDAS Imagine software the intensity of erosion dissection (ER) was estimated with equation 2.

The erosion relief index (ER) was estimated from the DEM. The values of ER index depend on the latitudes. To compare different areas, the values of ER were scaled according to the following equation:

$$ER_{new} = 100 * (\frac{ER - ER_{\min}}{ER_{\max} - ER_{\min}}) \tag{5}$$

where, ER is the current value, ER_{min} and ER_{max} are the minimal and maximal value of ER index within the study area.

This allows comparing areas in different physiographic regions. Without scale normalization by equation 5, it is hard to observe the local erosion features of different areas, including plains (Lyalko *et al.*, 2017; Lyalko *et al.*, 2018).

5. RESULTS AND DISCUSSIONS

Monitoring and modeling studies shown the significant impact of climate change on stability of natural and engineering slopes of activating landslides. The mechanisms and intensity of such processes in space and time, as well as the frequency of landslides during climate changing are unclear (Kovrov *et al.*, 2018).

Multiannual values of weather define the concept of climate as a characteristic of natural conditions of an area. Due to the general circulation of atmosphere, the climatic fluctuations spread through the planet. The physical aspects of global climate changes have been studied for a long time. Currently, the greenhouse effect, created by greenhouse gases is considered as main impact on climate (Hertzberg *et al.*, 2017).

The unstable climatic conditions are manifested in Ukraine. In order to complete analysis of the modern exogenous processes, in particular landslides, the diagnostic assessment of the modern climate of Ukraine were done in this study. The warming, which has no analogues in duration and intensity began from 1989 in Ukraine (Elistratova and Apostolov, 2018; Lyalko, 2015).

Table 1

Deviation of air temperature (ΔT, °C) from the climatic norm of 1981–2010 in Ukraine from 2001 to 2017

Years	**Months**												**Average (ΔT, °C)**
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	
2001–2017	0,1	0,3	1,2	1,0	0,7	0,9	1,5	1,2	1,0	0,1	1,5	0,5	0,8

Table 1 shows the deviation of air temperature from the climatic norm within 1981–2010 in Ukraine. The total air temperature deviation for 17 years in the XXI century is 0.8. Annual observations demonstrated that the average of annual temperature is increasing (Lyalko *et al.*, 2020).

Particularities of climate in Ukraine depend on the global climate system, as well as from the general circulation processes which take place in the European area. Ambiguous causes of climate change in Ukraine are characterized by precipitation distribution. The formation and fall of precipitation in Ukraine is a consequence of macrocirculary processes that determine heat and moisture changes in the atmosphere. The essence of these processes consists in transferring heat and moisture over a considerable distance from the Atlantic Ocean and the Mediterranean Sea. Under the influence of cyclones, the large-scale vertical air movements develop that lead to the precipitation (Martazinova, 2019). The average amount of annual precipitation in Ukraine has not changed significantly, but it was observed its distribution by months. Precipitation fluctuations relative to the norm persist, although there is a tendency to precipitations decreasing. During the decades 1981–1990, 1991–2000, 2001–2010, 2011–2020 the decrease in precipitation fluctuations is observed, which indicates a slight weakening of precipitation processes. Despite this, the humidification becomes more stable (Lyalko *et al.*, 2015).

The map of average annual of precipitation (R) in Ukraine for the period 1900–2018 is created on the bases of meteorological data from the Central Geophysical Observatory of Ukraine named after Boris Sreznevsky and presented in Fig. 2. The largest values of average annual precipitation occur in the northern, western and northwestern parts of the territory.

The main feature in the precipitation characteristic is the increase expectations of heavy rainfalls. Due to both the global and regional (Ukraine) warming, the frequency and intensity of heavy rainfalls are increasing. It is the main cause of the rapid landslide processes. The natural phenomena, including precipitation, snowmelt, temperature changes as well as anthropogenic activity are the dominant factors for slope instability. In the long run, the climate changes will affect the slopes stability at different temporal and spatial scales. Therefore, it is expedient to study the influence of meteorological factors (especially heavy rains) on landslide occurence in Ukraine.

Exogenous processes develop the modern relief of Ukraine and depend on neotectonic vertical movements. Ukraine territory is affected by neotectonic uplifts for a long time. Neotectonic structures of Ukraine represent a system of closely related elements of the relief in the modern deposits. Neotectonic vertical movements imprinted the elevations of relief, slopes, form of slopes where the exogenous processes take place.

Thus, the diversity of natural, climatic, geological and geomorphological conditions in Ukraine contributes to the formation and development of different exogenous processes. In particular, erosion in Ukraine has a high dynamic and destructive ability.

Analysis of long-term monitoring of exogenous processes (EGP) in Ukraine shows the fundamental changes of slopes during technological development. It is manifested in the disbalance of the upper zone of geological environment by unfavorable constructions. Industrial-urban agglomerations, degradation and soil subsidence processes are constantly increasing. The soil weakening increases the tendency of landslides intensifies. The number and frequency of its activation over time are increasing (Kovrov *et al.*, 2018; Kovrov *et al.*, 2020).

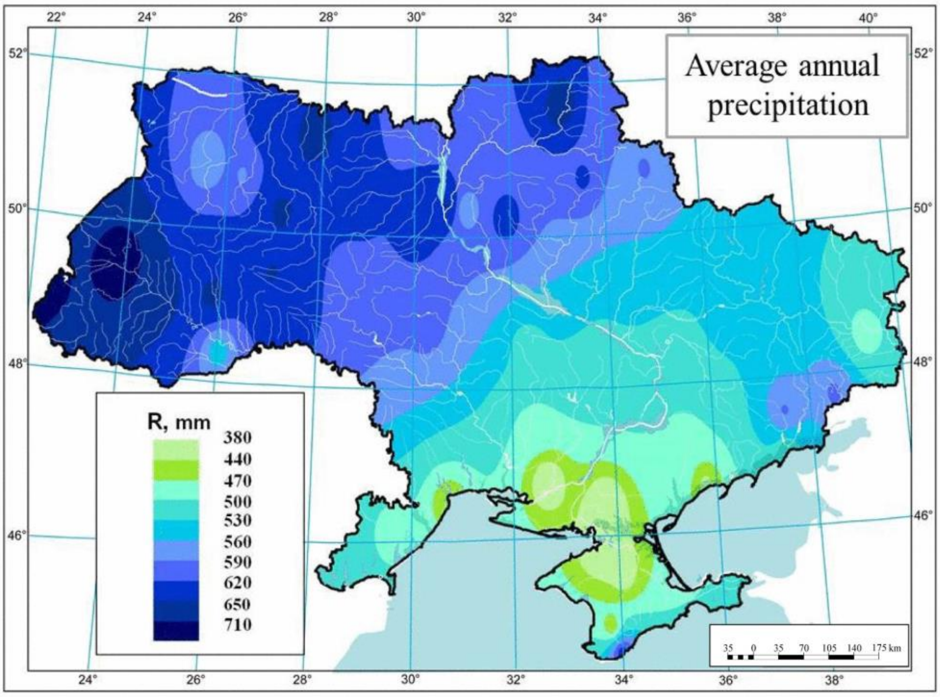


Fig. 2 – Map of the disturbtion of average annual precipitation (R) in Ukraine for the 1900–2018 period.

The majority of landslide processes appear on the slopes and in the coastal areas, which are composed of unstable rocks subject to deformation. On the river valley slopes these processes develop with the deepening of valleys during tectonic uplift movements. When the potential energy of relief increases the unilateral displacement of watercourses takes place imprinting an asymmetry to river valleys. The landslide development in mountain areas occurs due to the significant elevation and steepness of the slopes, when the thick layer of weathered rocks and intensive dissection of the terrain take place.

The largest areas of landslides in Ukraine are observed on the Black and Azov Sea coasts, within the basin the Seversky Donets River (Donetsk region), the right bank of the Dnieper River and its right part tributaries. For the climatic and geographical conditions of Ukraine, the intensification of landslides will remain at a high level due to the growth of anthropogenic impacts on the environment and global climate change (Kovrov *et al.*, 2018). The precipitations can act as a trigger factor in this case.

According to the State Geology Department data (Information yearbook, 2017), the map of landslide distribution in Ukraine was compiled for the year 2016 (Fig. 3).

Figure 3 illustrates the landslide distribution within the Ukraine in 2016. The background color shows the area of landslides in sq. km and the areas with active landslides. The columns of different colors and sizes show the number of slides for each administrative region (oblast in Ukrainian). The most developed landslide areas are in the mountain regions – the Crimean Mountains and the Carpathians. Also, active landslide areas are along the banks of the Dnieper and the Dniester rivers, and in the eastern part of territory due to anthropogenic pressure.

To study the connection between precipitation and exogenous processes (landslides, debris flows, gullies), areas located in different climatic conditions of Ukraine were selected (Fig. 4).

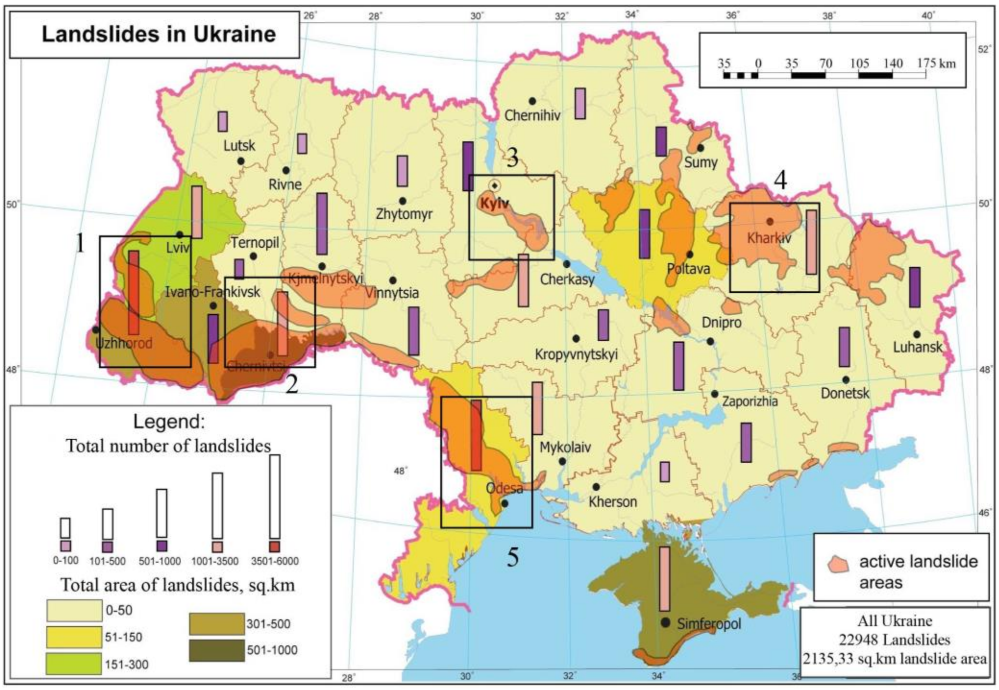


Fig. 3 – The map of landslides within the Ukraine for the year 2016.

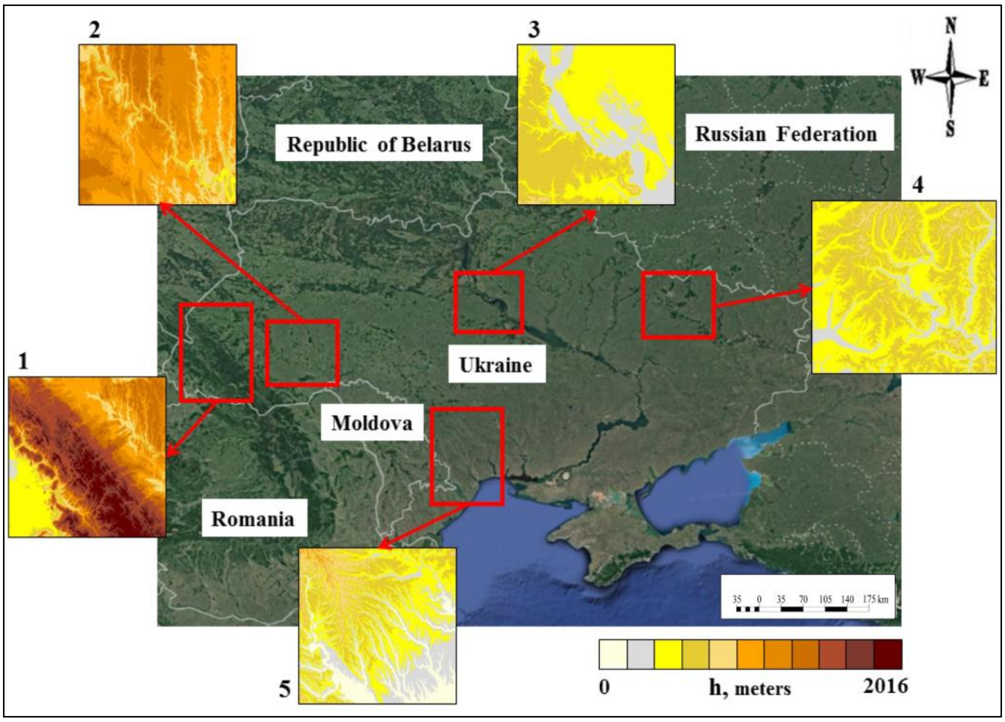
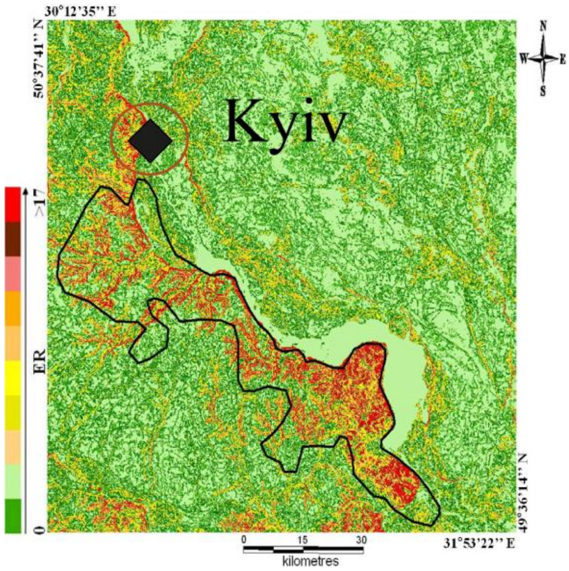


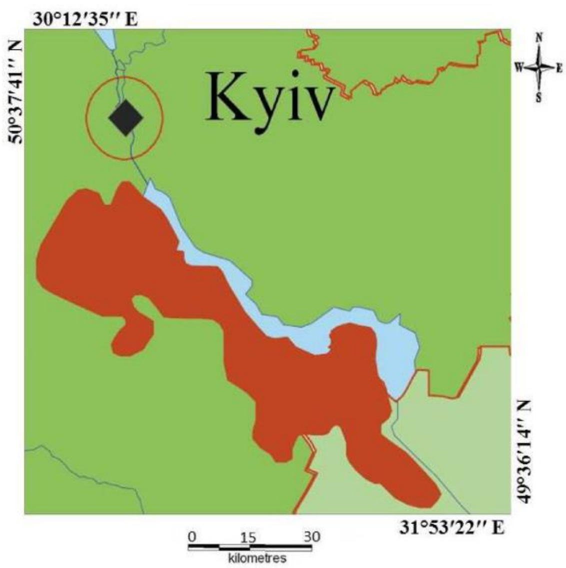
Fig. 4 – Location of the test sites with elevation imaging: 1) Ukrainian Carpathians; 2) Dniester River Valley; 3) the right bank of Dnieper River near Kyiv and Kaniv; 4) the right side of the Dnieper-Donetsk Depression near Kharkiv; 5) Black Sea Lowland near Odessa.

To assess the caabilities of the proposed method, the observations were done within several regions of Ukraine, which are in terms neotectonic activity and the level of terrain dissection. The Ukrainian Carpathians were selected as high elevation area. The territory between the Dniester River Valley and the right bank of Dnieper River between Kyiv and Kaniv was studied as a plain area. These two areas are located in the zone of active vertical neotectonic uplifts with a significant amplitude. A territory with weak neotectonic movements and weak erosion dissection is located around the Kharkiv city within the right bank of Dnieper-Donetsk Depression. The area of Black Sea Lowland near Odessa city is characterized ny neotectonic subsidence with intense erosion.

According to the proposed method, the disturibution of the intensity of Erosion Relief Index values for the right bank of the Dnieper River between Kiev and Kaniv is presented in Figure 5a. The color gradation from red to light green demonstrates the level of erosion dissection in the area according to the ER index shown in Table 2. Detailed gradation of of ER Index is eluminated in previous studies (Lyalko *et al.*, 2017; Lyalko *et al.*, 2018). To identified by ER index landslide area confirmation the fragment of the landslide distribution map according to the data from State Geological Department is presented in the Figure 5b (Information yearbook, 2017).



a



b

Fig. 5 – a) The relief dissection by Erosion Relief Index for the right bank of the Dnieper River between Kyiv and Kaniv area, according to processed DEM data; b) the fragment of landslide disribution map based on the data from information yearbook of dangerous exogenous geological processes activation in Ukraine according to EGP monitoring (Information yearbook, 2017).

Table 2

The values of ER index

Index values	**Color gradation**	**Danger level**
<2	Light to dark green	No danger
2–7	Mustard and yellow	Light
7–10	Light orange	Significant
10–13	Dark orange	Strong
13–17	Dark pink	Very strong
>17	Dark brown and red	Catastrophic

The results analysis showed that maximum values of the ER index are confined to the sloping surfaces. These relief elements are naturally affected by erosion. They are complicated by ravines and gullies of different ages and origins and require special erosion safety actions. There is a clear relationship between the vertical dissection and density of the ravines. This reflects the specificity of the area affected by linear water erosion. Besides, the morphometric parameters are of significant importance – *e.g*. slope angle, slope shape, slope length etc. By using the ER index it is possible to identify potentially threatened erosion areas. The index values obtained in this study can be used for other areas where the digital elevation model is obtained. According to the ER index, areas with very high potential of landslide activity are observed for the right bank of the Dnieper River between Kyiv and Kaniv. These areas will very likely respond to extreme meteorological values.

The total number of landslides in Ukraine does not change, but the number of active landslides depends on the precipitation. The threshold values of climatological indicators, more precisely of precipitations (R), were estimated in order to distinguish areas with high moisture and potential landslide hazard. The landslide activation depends on the amount of precipitation, its seasonal distribution, precipitation regime, temperature changes in annual and multiannual terms.

To determine potential landslide hazard areas, the quantity of precipitation changes for the 1976–2018 period were estimated, based on data from the meteorological stations located on the right bank of the Dnieper River between Kyiv and Kaniv. Changes in the amount of precipitation by seasons for the period 1976–2018, corresponding to the right bank of the Dnieper River between Kyiv and Kaniv are illustrated in Figure 6.

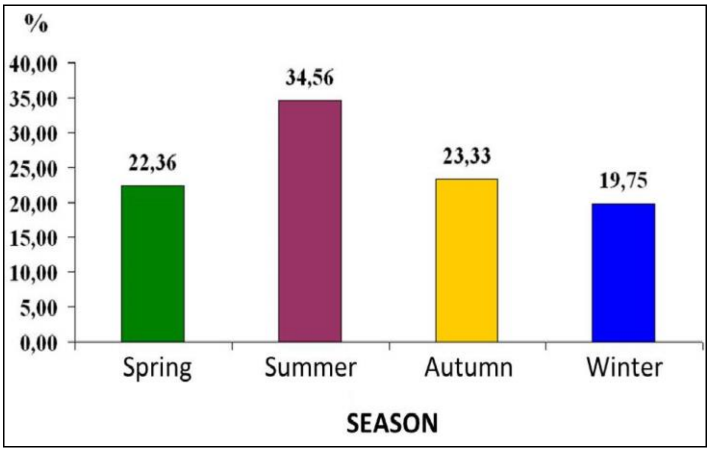


Fig. 6 – The precipitation quantity changes by seasons on the right bank of Dnieper River between Kyiv and Kaniv for the 1976–2018 period.

The average monthly precipitation for the 1976–2018 period was analyzed. For the period studied the excess of precipitations (wet years) was registered in 20 years.

In Table 3, the percentage of monthly precipitation average in comparison to the norm (1981–2010) for the 2001–2015 period was obtained for the right bank of the Dnieper River between Kyiv and Kaniv. According to Table 3, the average percentage of precipitation excess relative to the norm is 2.155 %.

Exceeding the norm 1,5–2 times provides oversaturation of soil with moisture and leads to the intensification of landslides (Matsuyama *et al.*, 2021; Brocca *et al.*, 2012). To identify the threshold values of meteorological factors, a structured dataset of precipitation (heavy rainfall events – HRE and rainfall events RE) was compiled for all tested sites. The dataset includes information about the station names, time and date, duration and intensity of atmospheric phenomena. As an example, the part of the constructed database is shown in Table 4. The database includes 113 rainfall events that triggered the intensification of landslides in the studied area.

Table 3

Percentage of monthly precipitation average from norm (1981–2010) during the 2001–2015 period for the right bank of the Dnieper River between Kyiv and Kaniv

Months / Years	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
2001	**118**	**114**	**239**	**120**	93	**197**	79	44	**107**	51	**146**	69
2002	56	92	52	75	**182**	**139**	63	**142**	**190**	**170**	92	27
2003	**137**	50	79	67	51	35	88	**120**	74	**300**	58	80
2004	**182**	**148**	72	54	**108**	27	**160**	**203**	**117**	68	**114**	50
2005	**132**	**163**	94	**129**	91	**123**	48	**172**	19	**149**	89	**182**
2006	43	**101**	**189**	89	**170**	**145**	67	**118**	**115**	**103**	58	26
2007	**137**	**137**	53	27	88	75	**103**	**124**	68	50	**164**	65
2008	89	37	**105**	**181**	79	52	**110**	48	**221**	36	90	**157**
2009	93	**156**	**138**	4	70	67	98	25	31	**129**	64	**195**
2010	**154**	**195**	65	60	**109**	50	**112**	42	82	78	**138**	**153**
2011	78	72	23	48	65	**162**	**189**	**101**	29	**153**	8	95
2012	**156**	89	89	**154**	55	85	74	**175**	69	**137**	80	**246**
2013	**176**	**168**	**278**	71	**112**	90	41	96	**264**	29	96	38
2014	**101**	28	52	96	**276**	76	96	76	57	55	32	75
2015	**134**	78	**176**	50	**135**	81	57	11	68	66	**127**	61

Table 4

Example of the structure of the constructed precipitation database, corresponding to the right bank of the Dnieper River between Kyiv and Kaniv

№	Station	Year	Precipitations	Date	Duration (time)	Intensity (mm/hour)
1	Teteriv	1998	HRE	17–17.07	1:00:00	30,00
2	Teteriv	1999	HRE	20–20.06	1:00:00	35,00
3	Teteriv	2001	HRE	04–04.07	1:00:00	41,00
4	Teteriv	2010	HRE	06–06.07	0:45:00	41,33
5	Teteriv	2013	HRE	28–28.06	0:57:00	31,58
6	Baryshivka	1977	HRE	10–10.07	1:00:00	34,00
7	Baryshivka	1988	HRE	25–25.06	1:04:00	45,94
8	Baryshivka	2011	HRE	16–16.08	0:44:00	45,00
9	Kyiv	1983	HRE	02–03.05	2:24:00	37,92
10	Boryspil	1977	HRE	28–28.06	0:48:00	38,75
…	…	…	…	…	…	…

The next step was dedicated to the detection of threshold values of meteorological factors that are causing landslide activation within the studied climatic zone. To select threshold values, a number of publications describing areas with the similar climatic conditions (Guzetti *et al.*, 2007). Determination of precipitation thresholds that can lead to the landslide activation processes at the selected test sites (Fig. 4) was carried out in accordance to the threshold formula (Guzetti *et al.*, 2007), which includes the Ukraine territory:

$$I_{П}=30{,}53D^{-0{,}57} \qquad (6)$$

where, D is the rainfall duration, in hours; $I_{П}$ is the average rainfall intensity, mm/h.

The threshold equation (6) was used for climatic class D according to the W. Köppen classification. This classification shows the diagnostic assessment of the climate type and is based on the temperature and precipitation characteristics. According to this classification, Ukraine makes part of the Dfb zone – temperate-continental climate, which is characterized by equable humidity, with pronounced seasonal differentiations (Beck *et al.*, 2018; Britannica, 2021).

In Figure 7, the map of ER index and threshold rainfall diagrams for the studied test sites within Ukraine are presented. The diagrams in Figure 7 demonstrate the location points (rainfall events) 1) for the Ukrainian Carpathians, where 718 rainfall events at 10 weather stations were observed; 2) for the Dniester River Valley – 372 rainfall events at 13 stations; 3) for the right bank of the Dnieper River between Kyiv and Kaniv – 113 rainfall events at 13 stations; 4) for the right side of the Dnieper-Donetsk Depression near Kharkiv – 59 events at 10 stations; 5) for Black Sea Lowland near Odessa – 97 rainfall events at 10 stations. In the diagrams (Fig. 7), the threshold curves estimated by equation (6) are illustrated for each tested site. The rainfall events points located near and above the threshold curves are expected to cause landslide intensification. They vary by intensity within the different areas of Ukraine. Their variation is a function of the neotectonic movements, the landscape and climatic conditions, anthropogenic impacts, and climate change.

6. FUTURE RESEARCH DIRECTIONS

Future research and monitoring envisage the use of the Sentinel-1 remote sensing data available for free. Considering that landslide processes lead to changes of the terrain surface, the interferometry method permits to assess the landscape changes and landslides detection.

Taking into consideration that global climate change is a long-term process, further monitoring and analysis of exogenous processes (changes is temperature, wind and water regime) will be necessary in the future.

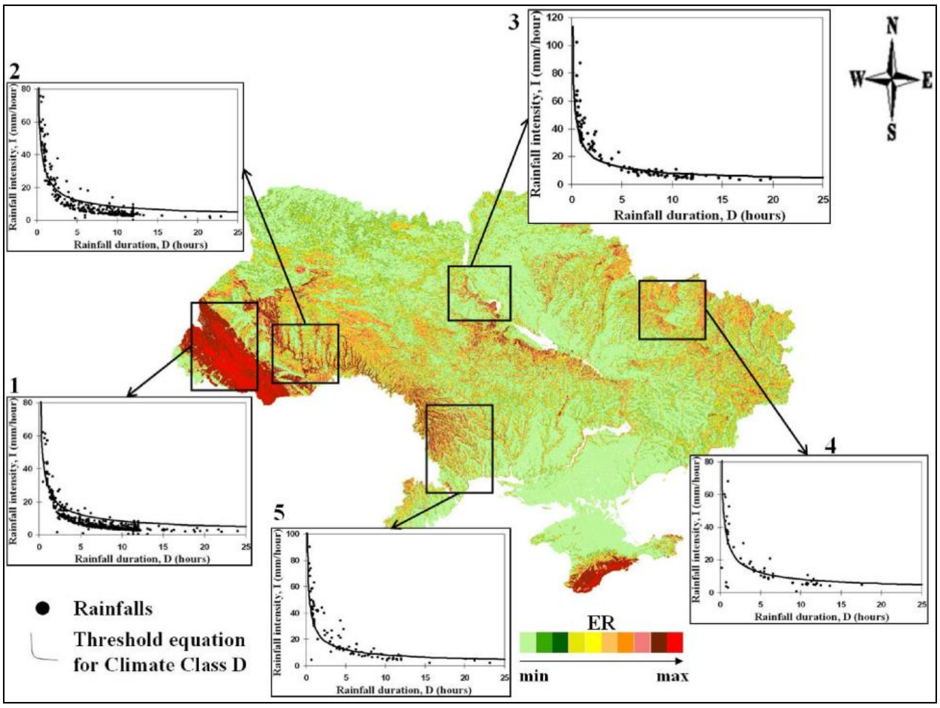


Fig. 7. – The ER index map of the Ukrainian territory and rainfall thresholds for the causing landslide intensification in: 1) the Ukrainian Carpathians; 2) the Dniester River Valley; 3) the right bank of Dnieper River near Kyiv and Kaniv; 4) the right side of the Dnieper-Donetsk Depression near Kharkiv; 5) Black Sea Lowland near Odessa.

7. CONCLUSIONS

The proposed method, based on combination of erosion relief index (ER) and threshold values of meteorological data (heavy rainfall events) allows for the identification of territories with potential erosion processes (landslides, gullies etc.).

In Ukraine, terrains with potential for the occurrence of erosion-type processes can quickly become as active erosion zones. The speed of activation depends on natural loading in conditions when the monthly precipitation average exceed the monthly norm in 1.5–2 times. The intensity of erosion increases with quick water accumulation, increasing of groundwater level. Saturation and waterlogging of soils occurs during rainfalls of high intensity within the long time period. To reduce the negative factors is necessary to implement large-scale geological surveys. It would be a good base for development of effective economic measures which can minimize the geoecological risks. The study performed shows an effective involvement of remote sensing data for prediction of erosion risks within the entire territory of the country. It could serve as a base for operative administrative solutions for relevant government services and governing specialization authorities.

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