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Slope mass movement processes susceptibility and risk assessment for the territory affected by the former Kakhovka Reservoir

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SUMMARY

The destruction of the Kakhovka Hydroelectric Power Plant (HPP) dam was such a catastrophic event that requires its analysis and risk assessment, identifying the most vulnerable areas and forecasting further hazardous processes development. The aim of this study is to analyse the consequences of the destruction of the Kakhovka HPP dam by improving the methodology for assessing risks and forecasting the development of slope processes within the area affected by the Kakhovka Reservoir. Based on the analysis of conditions and factors affecting the development of hazardous geological processes using the created inventory maps, the impact of tectonics and relief was determined, and a forecasting model of the development of slope mass movement processes within the studied area was provided. The analysis of the distribution of slope processes by distance from tectonic disturbances was also carried out. It was revealed that the areas of predicted slope mass movement processes extend beyond the previously mapped areas of slope processes manifestations. The obtained results will provide scientific and methodological support in recording and assessing the damage caused to the geological environment, as a result of russian armed aggression, as well as remediation measures and strategies for managing the affected territories.

Introduction

Risk assessment and forecasting of hazardous exogenous geological processes is an essential and relevant aspect of studying geological environment state, especially when it comes to the impact of hostilities and man-made catastrophic events resulted from it. Slope mass movement processes pose a threat to human health and life, cause destruction, including catastrophic disasters, and lead to economic losses. It is known that both natural and anthropogenic factors can trigger slope mass movement processes (ex., van Westen et al., 2008; Shekhunova et al., 2022; Pilatasig et al., 2025). In particular, emergencies, catastrophic events, and military actions can lead to a disturbance in the equilibrium of the components of geological environment and, as a result, to the intensification of hazardous geological processes. The destruction of the Kakhovka Hydroelectric Power Plant (HPP) dam (June 6, 2023) was such a catastrophic event that caused a significant change in the groundwater hydrodynamic parameters as well as the engineering and geological conditions of the territory, which requires their analysis and assessment, identifying the most vulnerable areas and forecasting further hazardous processes development. The aim of this work is to analyse the consequences of the destruction of the Kakhovka HPP dam by improving the methodology for assessing risks and forecasting the development of slope processes within the area affected by the Kakhovka Reservoir. It will provide scientific and methodological support in recording and assessing the damage caused to the geological environment, as a result of russian armed aggression, as well as remediation measures and strategies for managing with the affected territories, creation of information base for decision-making.

Materials and Methods

Analysis of the impact of slope processes predisposing factors and providing a forecasting model was carried out, using previously developed GIS system for landslide hazard modelling (opened to new data processing methods and algorithms) (Shekhunova et al., 2022). In accordance with the methodology for constructing a forecasting model of slope mass movement processes, the following data sets and models were generated:

- A GIS-integrated database of hazardous exogenous geological processes for the territory affected by the former Kakhovka Reservoir was compiled (Map…landslides, 2008; Map … karst process, 2008; National Report…, 2021; Shekhunova et al., 2025; State geological map…, 1975; State geological map …, 1976);
- The Digital Elevation Model (DEM) was obtained by processing high-resolution satellite data (maps based on Google Earth and Copernicus) and data from previously created topographic maps using GIS technologies (Figure 1).
- The Digital model of tectonic disturbances in the studied area (Tectonic map…, 2007).

Basing on this data analysis of factors affecting slope mass movement processes (landslides, erosion) was carried out.

Results & Discussion

Based on the analysis of factors affecting development of hazardous geological processes using the created inventory map, the degree of influence of tectonic disturbances and relief was determined, and a susceptibility map of slope mass movement processes (landslides, erosion) within the studied territory was provided (Figures 1, 2, 3).

Analysis of the impact of tectonic disturbances on slope mass movement. Based on the results of the analysis of the impact of fault tectonics as a factor affecting the development of exogenous processes, the histogram of the distribution of slope process data points depending on the distance from tectonic disturbances was obtained (Figure 2). For this purpose, the polygons of slope processes were divided into elementary sections represented by a regular grid of points (point theme) within the polygons.

Subsequently, the distribution of points by distance from the faults was determined. Considering that the distribution of polygons is described by an exponential function, it was concluded that there is an impact. The research area is a part of two main tectonic elements – the Ukrainian Crystalline Shield and the South Ukrainian Monocline, with a boundary between them extending sublatitudinally. The location of the faults is shown in the relief model (Figure 1). Basement rocks are represented by magmatic formations in the

northern part, while the southern part of the territory is characterized by the spread of sedimentary strata covering the basement of the East European Platform. Numerous disruptive faults of both the first and second orders were identified in each of these tectonic elements.

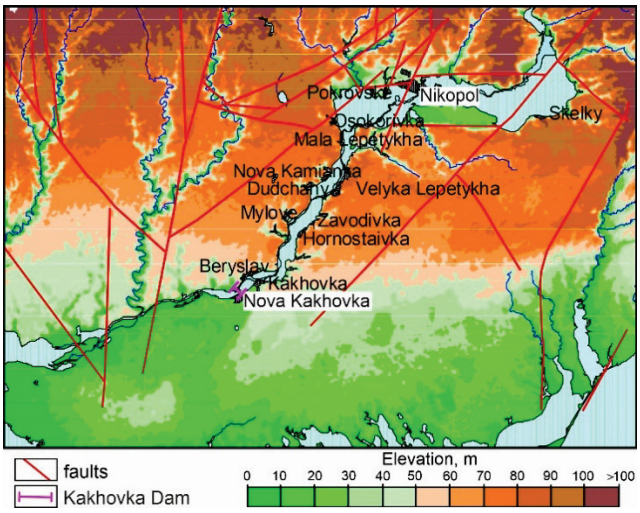

Figure 1 *Digital Elevation Model for the territory affected by the former Kakhovka Reservoir*

In this study we have not yet classified faults by rank, but it has been established that the largest number of unstable slope areas are located at distance of up to 2 km from fault zones of the first and second order, and their influence decreases with increasing distance from the fault zones.

Analysis of the impact of relief on the development of slope processes. The study was carried out using DEM generated from satellite data (Figure 1). The relief in the northern right-bank part of the territory is more dissected than in the southern part. Within the region, there are significant areas of closed depressions – pods. On the left bank, in the estuary of the Dnipro River, there is a developed dune relief with height difference of several metres. The surface is characterised by heights of 150–160 m in the north and 2–3 m in the south. The lowered areas are related to the sea coast and the Dnipro River delta, where the absolute marks range from no more than 1.5–4m. The territory has fairly high Seismicity rating of 5–6. In general, the studied area is characterised by a high degree of erosion.

According to previously published results on hydrogeological conditions changes preliminary assessment after the explosion of the Kakhovka HPP dam (Liuta, Sanina, 2023; Shekhunova et al., 2023), the draining of the Kakhovka Reservoir resulted in a change in the water regime of the territory (level, flow direction and discharge), and the subsequent change in the erosion base is expected to lead to increased rock erosion and gully formation in the adjacent area. Erosion processes, that have a significant impact on slope formation, combined with other exogenous processes, may trigger the activation of slope mass movement processes widespread within the territory affected by the former Kakhovka Reservoir.

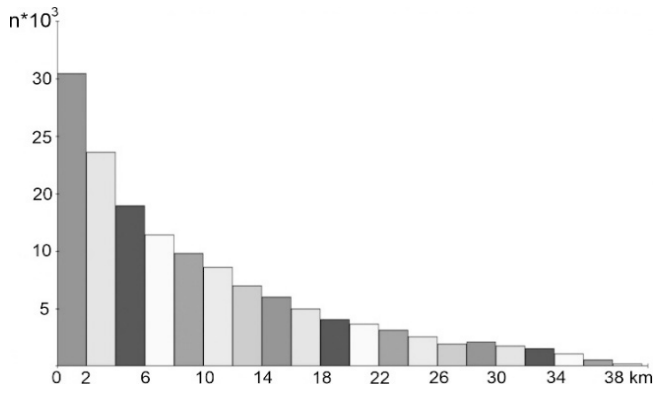

Figure 2 *Distribution of slope processes depending on the distance from tectonic disturbances (along the y-axis, the number of slope processes manifestations is shown in n*10³)*

While ravines can occur even at zero slope angles, at least minimal slope angles are required for landslide mass movement down the slope. Therefore, natural conditions and trigger factors are responsible for the realisation of slope mass movement scenarios.

Slope mass movement susceptibility assessment. A map of slope angles was produced to model forecast areas prone to slope processes. The map shows the areas where slope processes are localised. The risk of landslides increases with increasing slope angles (Figure 3). The areas of predicted slope mass movement processes extend beyond the previously mapped areas of slope processes (in particular, inventory maps published by Shekhunova et al., 2025).

Landslides are observed mainly on the slopes of river valleys. Depending on the sliding surface, there are four types of landslides: in Neopleistocene loess or in rocks that have previously undergone landslide

formation processes; in red-brown Pliocene clays; in the upper layer of Meotian clays; in deep horizons of Meotian clays. Deformations of first two types are landslide (flow-type) associated with overmoistening of rocks, that occurred along river banks. On the left bank, landslides mainly develop on the slopes of ravines. On the banks of rivers in the area affected by the former Kakhovka Reservoir, there are numerous small and medium-sized landslides covering an area of up to several tens of thousands of square metres. They are forming in Meotian, Sarmatian, red-brown clays, as well as in loess-like loams.

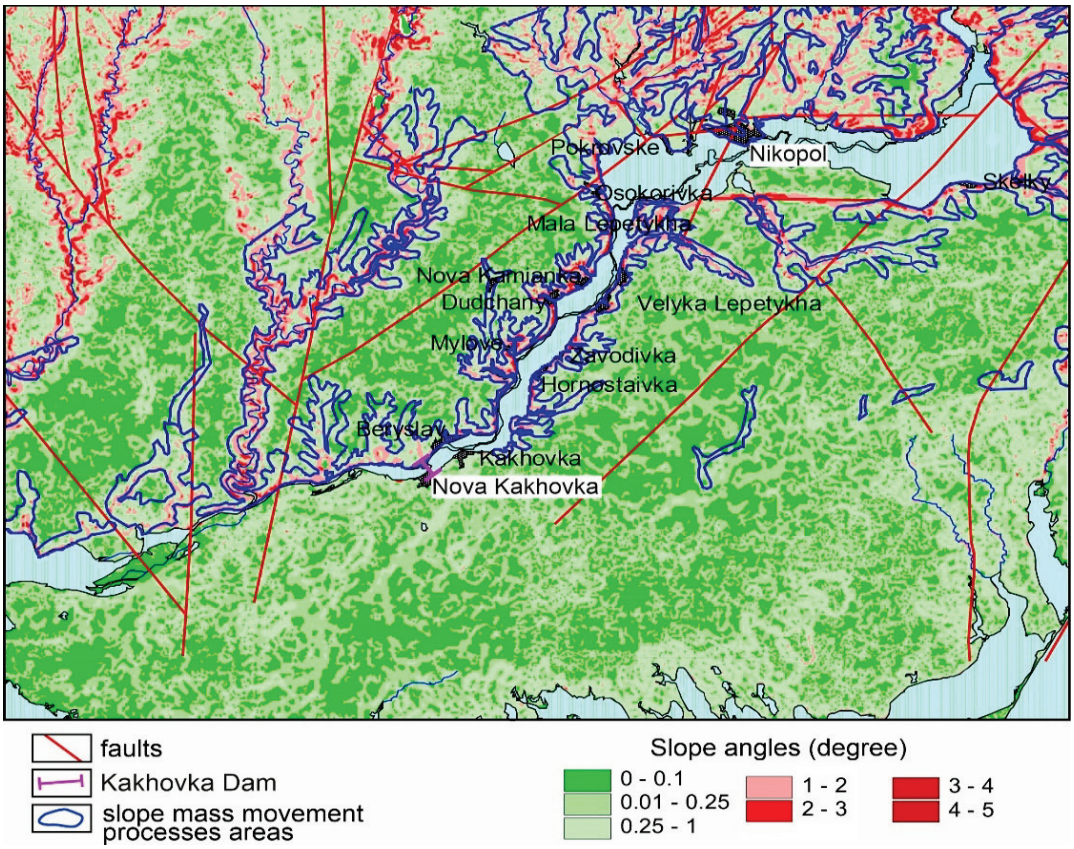

Figure 3 *A slope mass movement susceptibility map for the territory affected by the former Kakhovka Reservoir*

According to the obtained results, the forecast areas of slope processes development are the edges of gullies and ravines, mainly on the right banks of rivers and the former Kakhovka Reservoir banks.
Analysis of the influence of relief and slope angles, tectonic disturbances on the manifestation of slope mass movement have been carried out. Relief and slope angles are, as a rule, a natural predisposing condition for the development of slope processes. Tectonic disturbances with zones of fracturing that diminish with distance from the main fault trace improve conditions for atmospheric precipitation infiltration and contribute to moistening of the landslide body, reduction in the friction coefficient on the sliding surface, etc.
Thus, the models obtained can be used as an informative basis for decision-making and strategy development for remediation of the territory and economic development of the region.

Conclusions

Based on the analysis of conditions and factors affecting the development of hazardous geological processes using the created inventory maps, the impact of tectonics and relief was determined, and a forecasting model of the development of slope mass movement processes within the studied area was provided. The analysis

of the distribution of slope processes by distance from tectonic disturbances was also carried out. All of them indicate the influence of disturbances on their development and a decrease in this influence with distance from the faults. It was revealed that the areas of predicted slope mass movement processes extend beyond the previously mapped areas of slope processes manifestations.

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