Landslide25_15

Monitoring hydrogeological impact on landscape integrity within Kyiv-Pechersk Lavra

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SUMMARY

A comprehensive analysis of the observations made during archaeological explorations within the protected zone of the Kyiv-Pechersk Lavra was carried out to assess the stability of the current state of the landscape. Results were obtained for the calculation of the Normalized Difference Moisture Index (NDMI), indicating significant oversaturation of near-surface soil layers and geological materials. Areas of slope deformation were identified, coinciding with disruptions in water supply routes, drainage systems, and thermal networks. These processes negatively affect the preservation of the cultural layer and archaeological heritage. Geoinformation systems and remote sensing methods were used to visualize the results. A digital model of the current terrain was generated, and spatial-elevation correlation of emergency zones with utility infrastructure was performed. The most vulnerable to dynamic shifts are the areas around the Dormition Cathedral, the Church of the Savior at Berestove, and other structures within the Lavra ravine.

The conducted research enables real-time monitoring of the most active zones of soil moisture stress and supports timely decision-making for preventive measures.

Introduction

The modern landscape within the Kyiv-Pechersk Lavra reserve has been shaped by both natural and anthropogenic factors. Archaeological research has revealed several types of layered fill soils, indicating ongoing redevelopment and reorganization of the monastery territory across different stages of its evolution (Taranenko, 2021). Among adverse geological processes, the most widespread are hidden waterlogging processes. These are likely caused by the accumulation of surface runoff in local terrain depressions, followed by infiltration into the bulk soil strata.

The existing drainage system and clinker pavement prevent evaporation of excess moisture from the surface layer. Regular monitoring of groundwater levels has been conducted for an extended period within the territory of the Kyiv-Pechersk reserve. Observation wells are located in the Upper Lavra, its slopes, and the Lower Lavra. Since 2006, periodic measurements in wells have been carried out in the area of the Near Caves (Cherevko, 2017).

The aim of this study is to identify areas of intensified soil oversaturation caused by groundwater recharge and leaks from utility systems in zones with the highest slope loading.

Method and/or Theory. In addition to field investigations, remote sensing methods were applied, including graphical construction of a digital elevation model adjusted to the current Earth's surface elevations.

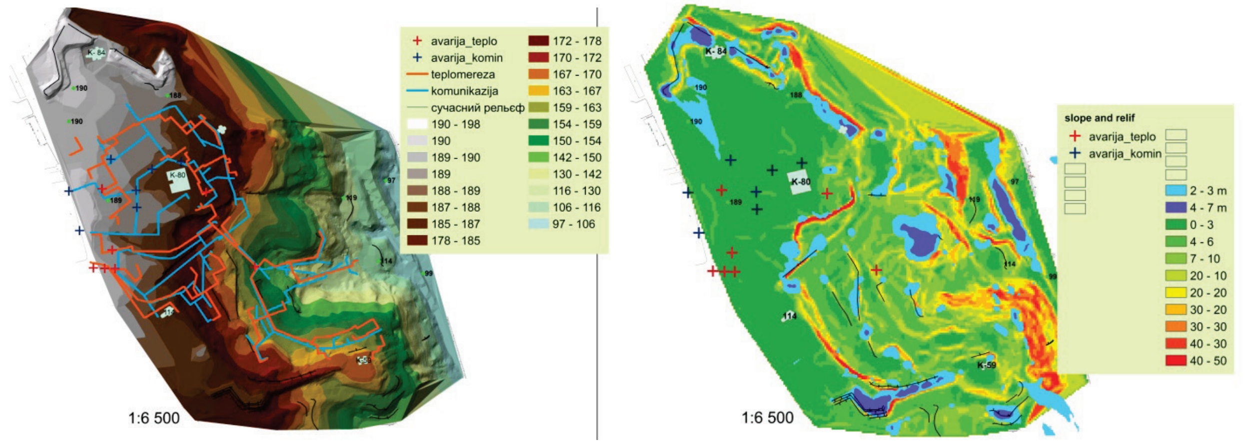
Results. Long-term monitoring has shown that the main disturbances to the natural hydrogeological regime are caused by the accumulation of surface runoff and leakages from water-bearing utility systems, particularly from the surrounding urban development. Repeated leakages from infrastructure have led to localized rises in groundwater levels. These waters discharged as springs in the Near Caves Garden, flooded building basements, and caused structural deformations of heritage monuments. A branched system of engineering networks has been installed within the reserve, including water supply lines, heating pipelines, sewer systems, and both deep and shallow drainage systems (Arhypenko, 2018).

During the study, the layout of utility and heating networks was overlaid on the digital elevation model of the reserve. This enabled determination and visualization of their elevation positioning. Critical zones of leaks in heating and utility systems were separately identified and compared with the current surface slope map. It was established that all leak zones are located within the Upper Lavra plateau at elevations of 188–189 m (Fig. 1(a)).

The condition of monuments in the Upper Lavra is primarily affected by leaks from water utility systems, which actively alter the physico-mechanical properties of the soil cover. Loess-like loams are especially hazardous for sinkhole development. A genetic link between the emergency situation of the pressurized water main and subsidence of loess-like loams was also demonstrated. Suffosion processes (washing out of fine soil particles by groundwater) occur, resulting in the formation of sinkholes and subsidence. Their locations correspond to areas with surface slopes of 4^0–6° (Fig. 1(b)) (Nesterovskyi et. al., 2023)

A damaged section of the heating network was also identified in the Lower Lavra area at elevations of 150–159 m. This area is located on loess plateau slopes within the Lavra Ravine valley, which belongs to the first above-floodplain terrace of the Dnipro (Tustanovska, 2024). It includes an aquifer overlain by brown and variegated clays. Moisture content of the variegated clays is controlled by groundwater level and unauthorized leaks. A 2021 heating network failure caused significant swelling of clay material and disrupted the natural equilibrium of upper soil layers. These changes triggered active landslide processes in the Lavra Ravine.

Among the negative geological processes and phenomena within the reserve, hidden waterlogging has developed most extensively. This is caused by significant accumulation of surface runoff, which infiltrates into the thickness of cultural layers. Due to the lack of free evaporation caused by continuous clinker paving, persistent overmoistening of near-surface soil occurs (Taranenko et. al., 2019).



a) b)

Figure 1. Layout of utility and heating networks and locations of failures over the past five years

Soil moisture content and drought monitoring over the past five years were determined using the Normalized Difference Moisture Index (NDMI). The NDMI scale ranges from –1 to +1. Negative values approaching –1 correspond to bare soil (red color). Values close to zero (from –0.2 to +0.4) reflect soil water stress (from yellow to light blue). High positive +1 values correspond to dense vegetation cover without overmoistening (blue color) (fig. 2).

To calculate the normalized moisture index, satellite images from the spring period (early April) were used. At this time, in the absence of vegetation cover, the indicators provide more accurate values. Data obtained over the past five years showed that the highest soil overmoistening values are recorded on the plateau within the damaged areas. Each year, the area of such zones increases. In 2025, such an area was identified around the Dormition Cathedral.

It is likely that soil overmoistening is caused not only by spring atmospheric precipitation and water leakage from utility networks, but also by a high groundwater level. The highest groundwater levels within the Upper Lavra were recorded at absolute elevations of 178–181 m. In recent years, prolonged rises in levels were recorded in wells located closest to Lavrska Street, where city water pipelines are located. The fluctuation in level reached up to 1.7 m (Arhypenko, 2018).

In the Lower Lavra area, groundwater levels fluctuate seasonally: the highest values are observed each spring, and the lowest — in winter. The annual amplitude of fluctuations ranges from 0.4 to 1.5 m. On the slopes of the Lavra Ravine, groundwater lies at depths from 0.9 to 3.2 m below the surface, with absolute elevations of 150–160 m. The thickness of the aquifer is 1–5 m, with a fluctuation amplitude of 1.2–3.4 m. In the upper part of the area, the aquifer is permanent, while in the lower part it is temporary: it forms on the clay surface during snowmelt and prolonged rainfall and is retained for 6–8 months (Arhypenko, 2018).

A high NDMI index in the range of –0.1 to +0.1 was detected in the Lavra Ravine and its upper part, which nearly reaches the foundation of the Dormition Cathedral (fig. 2). The ravine bed corresponds hypsometrically to the aquifer level and serves as a sensitive indicator of soil moisture changes. NDMI values for 2025, despite a dry spring, indicate increased surface moisture within this ravine. Likely causes of this phenomenon include a combination of factors, such as outdated utilities, emergency conditions in heating and water networks, shallow groundwater levels, and the physical properties of the loess-like loam layer.

Five-year soil moisture monitoring showed that overmoistened areas vary in size but remain stable within their geographical locations.

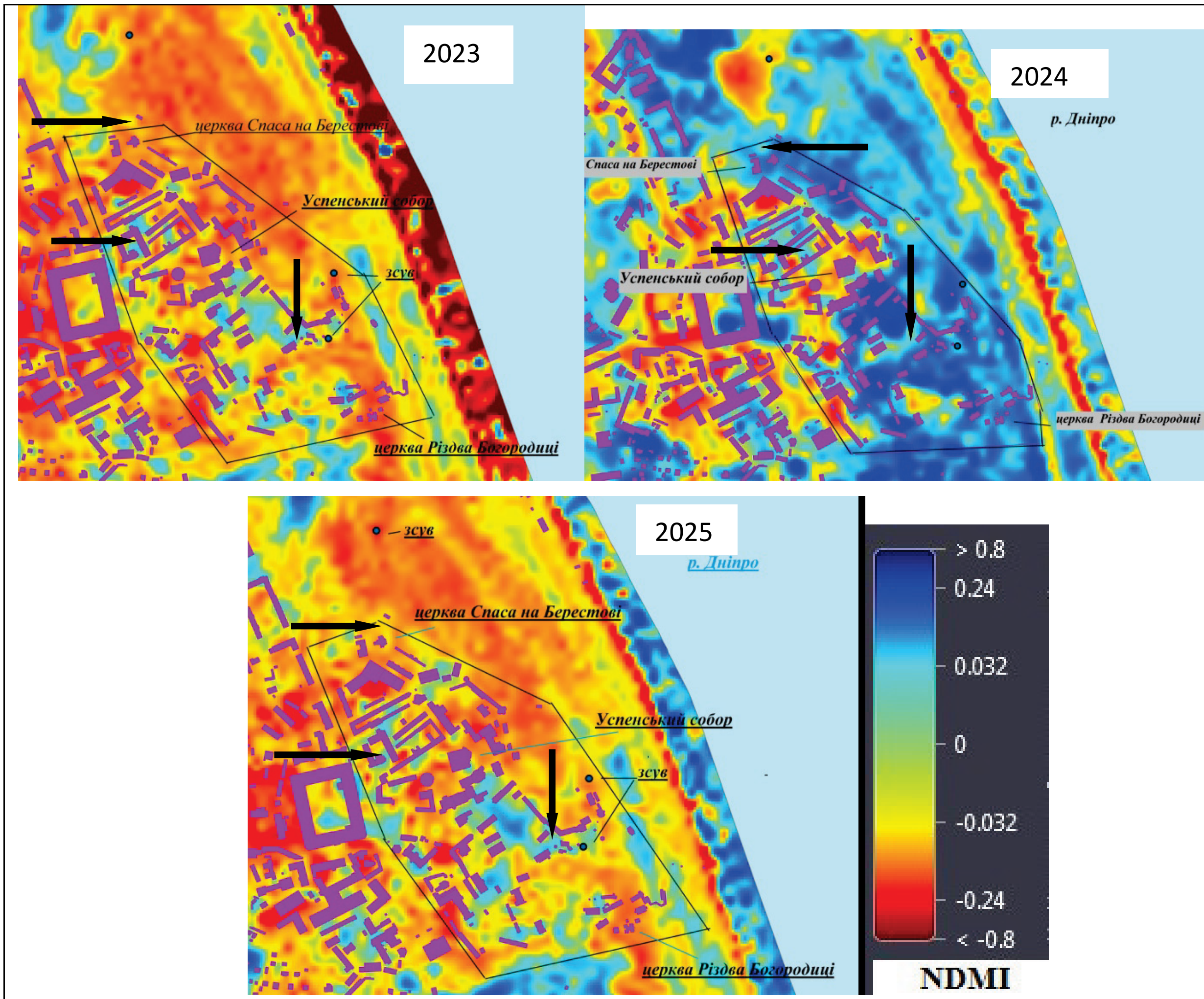


Figure 2. Monitoring soil water stress within the Reserve (using NDMI index)

According to index calculations, soil stress is also recorded in the areas of the Near and Far Caves. Constant surface moisture in these zones is associated with groundwater levels and the geological characteristics of the formations that make up the slopes of the Reserve. The groundwater is characterized by a chemical composition dominated by bicarbonates, sulfates, calcium, and magnesium, with moderate total hardness and mineralization (1.1–1.3 g/l). This composition of groundwater contributes to the accelerated weathering of rocks and the removal of material.

The most intense suffosion processes are recorded on the Upper Lavra plateau, as the mechanical removal of material by groundwater is further complicated by utility water discharged on the steep slopes of the Reserve and in the Lavra Ravine.

Within the area of the Church of the Saviour at Berestove, attention should be paid to the ravine in the Park of Eternal Glory, whose upper part approaches the hill where the church is located from the north, and which is bounded on the east by the steep slopes of the Dnipro valley. The slopes in this area experience constant water stress, which is clearly visible in satellite imagery analyzed using the NDMI index (–0.032) and in mapping of active landslides.

Conclusions A comprehensive analysis of the observations made during archaeological explorations within the protected area of the Kyiv-Pechersk Lavra was carried out to assess the stability of the current state of the landscape. Overlaying utility networks onto the digital terrain model made it possible to visualize the elevation alignment of the networks in relation to hazardous zones, including areas marked with infrastructure failures. Accidents that occurred on the plateau correlate with newly formed local depressions in the terrain, where surface slope ranges from 4° to 6°.

Monitoring of the Reserve's slopes enabled tracking of soil moisture stress over the past five years using the NDMI index. The integrated analysis considered only one spring month, groundwater levels, the layout of utility networks, and damaged areas with technogenic water leakage.

Based on NDMI data, the most vulnerable zones with persistent soil moisture were identified: on the Upper Lavra plateau — near the Dormition Cathedral and the Church of the Saviour at Berestove; in the Lower Lavra — within the Lavra Ravine and the cave areas.

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