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Groundwater in the cities of Europe

Impact of hydrogeological factors on geotechnical conditions of the Kyiv-Pechersk Lavra Monastery complex: lessons from three decades of monitoring

Impatto del dissesto idrogeologico sullo stato geotecnico del complesso del Monastero delle Grotte di Kiev: indicazioni ottenute da tre decadi di monitoraggio

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Supplementary file - *File supplementare*

Section 1. Schemes of the engineering infrastructure

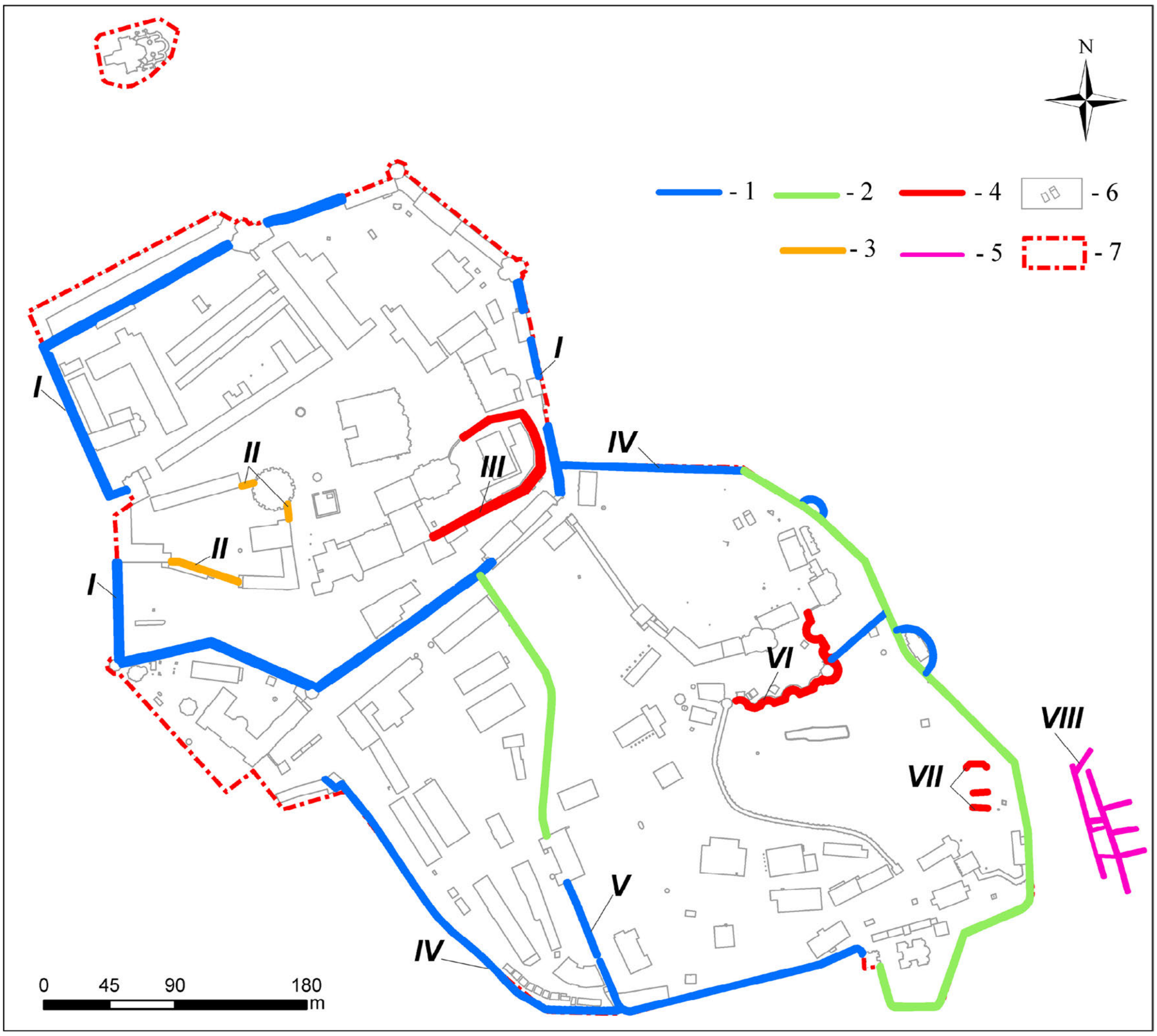

Fig. S1 - Retaining walls, protective and defensive structures of the Upper and Lower Lavra. Legend: 1 - defensive fences, 2 - combined structures (retaining and defensive), 3 - enclosing structures, 4 - retaining walls, 5 - combined structures (drainage and retention), 6 - buildings, 7 –boundary of Lavra, I — defensive fences of the Upper Lavra, II —wall with a gate near the Great Lavra Bell Tower, III — retaining wall of the observation terrace, IV — defensive walls of the Near and Far Caves, V — retaining wall 3-rd line, VI — retaining wall of de Bosquet, VII —cascade of retaining walls on the right side of the Lavra Ravine, VIII - complex structure designed by Peter Sukhtelen.

Fig. S1 - Muri di contenimento e strutture protettive e difensive nell'area del monastero delle Grotte di Kiev. Legenda: 1 – recinzione difensiva, 2 – strutture combinate (contenimento e difensive), 3 – strutture di chiusura, 4 – muri di contenimento, 5 – strutture combinate (drenaggio e contenimento), 6 – edifici, 7 – estensione del complesso, I – recinzione difensiva della parte alta del complesso, II – muro vicino all'ingresso della Torre campanaria della Lavra, III – muro di contenimento vicino alla terrazza panoramica, IV – muro difensivo vicino alle gallerie "Near Caves" e "Far Caves", V – muro di contenimento "terza linea", VI – muro di contenimento di de Bosquet, VII – serie di muri di contenimento sul lato destro della gola Lavrsky, VIII – struttura complessa progettata da Peter Sukhtelen.

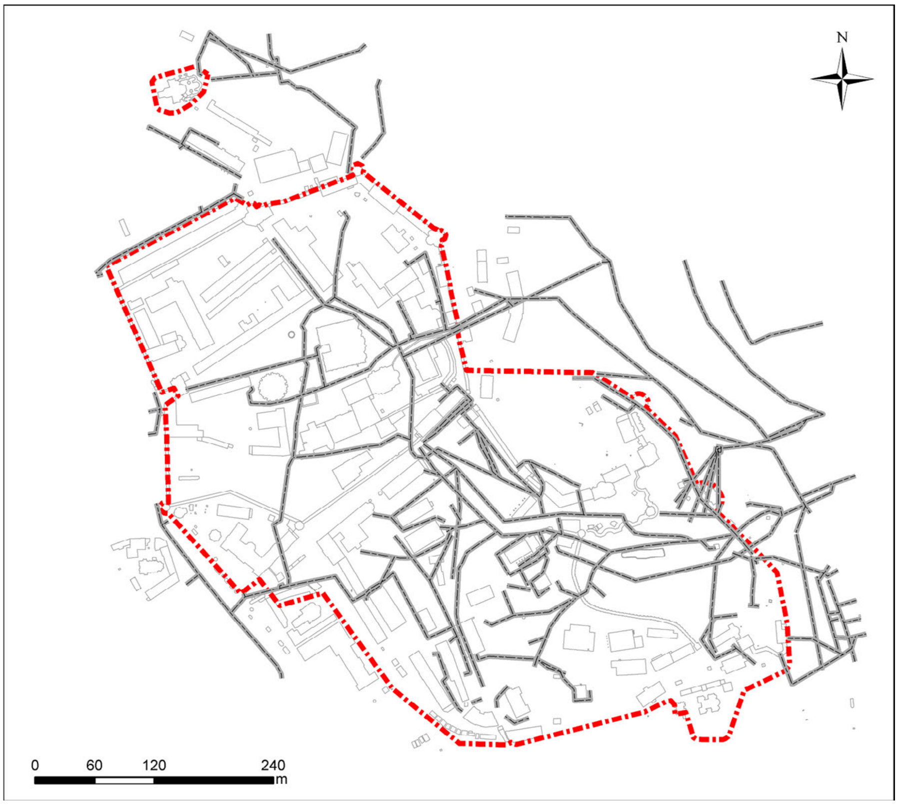

Fig. S2 - Subsurface drainages and storm collector pipelines at the territory of the Kyiv-Pechersk Lavra.

Fig. S2 - Drenaggi sotterranei e canalette di scolo nell'area del monastero delle Grotte di Kiev.

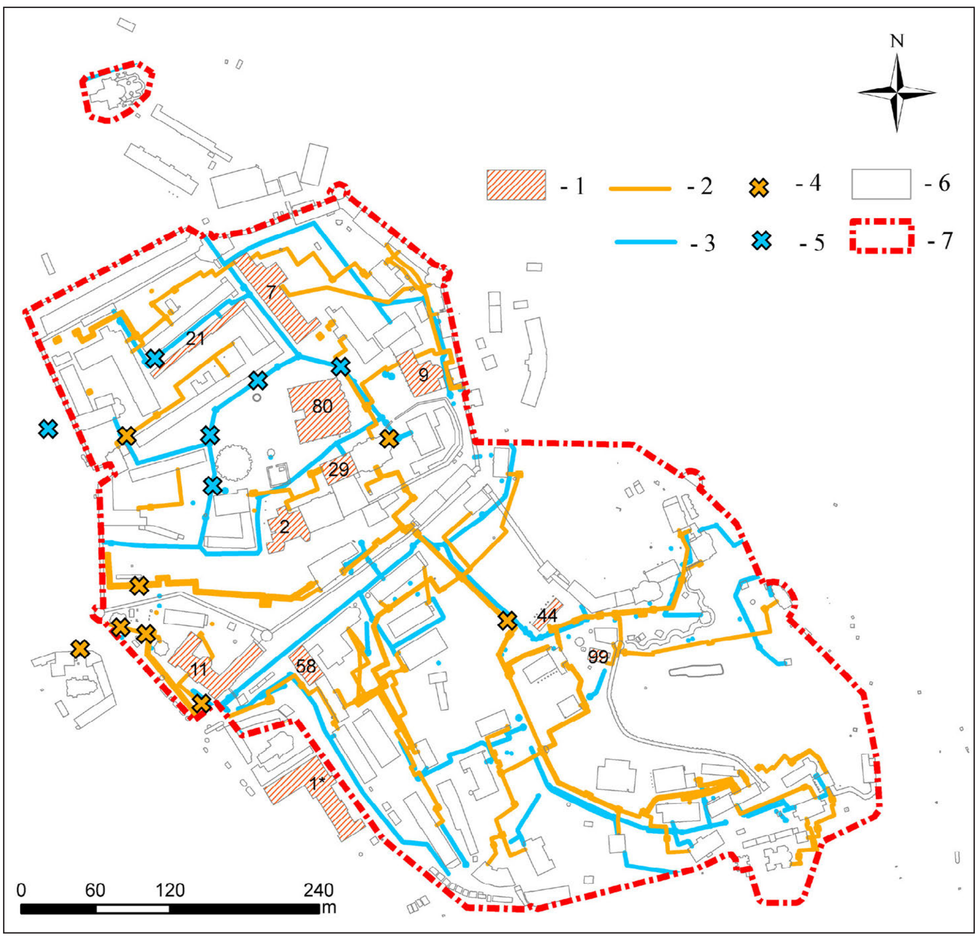

Fig. S3 - Schemes of the water mains on the territory of the Kyiv-Pechersk Lavra with marked locations of accidents caused by water mains breaches. Legend: 1 – buildings, which were impacted by accidents, 2 – heated water pipelines (hot water - 60°C), 3 – water mains, 4 – accidents on heated water pipelines, 5 – accidents on water mains, 6 – buildings, 7 – the boundary of Lavra.

Fig. S3 - Schema delle condutture per acqua nell'area del monastero delle Grotte di Kiev e posizione degli incidenti causati da rotture nelle condotte. Legenda: 1 – edifici che sono stati danneggiati da incidenti, 2 – condotte per acqua calda (60°C), 3 – condotte per acqua, 4 – incidenti avvenuti nelle condotte per acqua calda, 5 – incidenti avvenuti nelle condotte per acqua, 6 – edifici, 7 – estensione del complesso.

Section 2. Technical specifications of selected monitoring wells

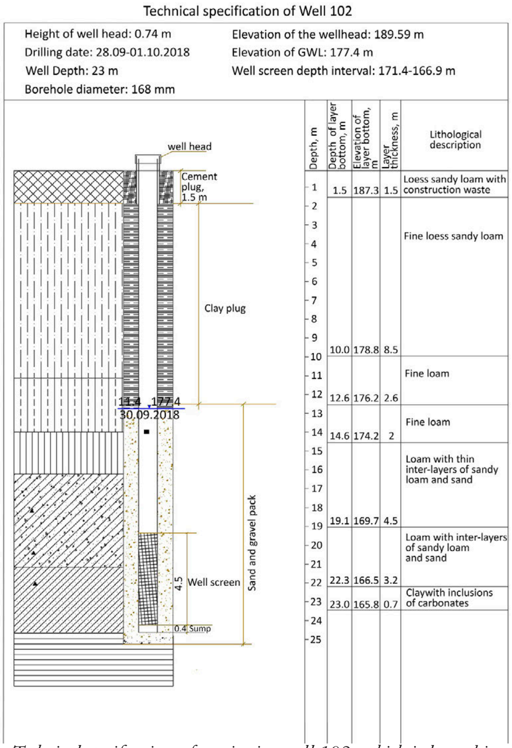

Fig. S4 - Technical specifications of monitoring well 102, which is located in the Upper Lavra. The location of the well is shown in Fig.S6.

Fig. S4 - Scheda tecnica del pozzo di monitoraggio 102 che è situato nella parte alta del complesso. La posizione del pozzo è riportata nella Fig. S6.

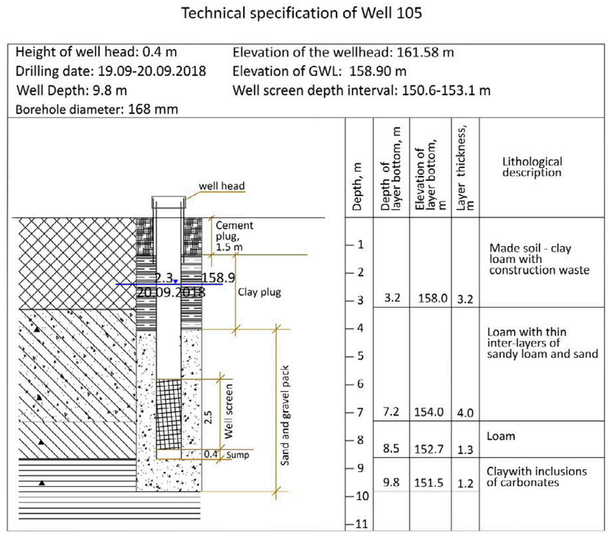

Fig. S5 - Technical specifications of monitoring well 105, which is located in the Lower Lavra. The location of the well is shown in Fig.S6.

Fig. S5 - Scheda tecnica del pozzo di monitoraggio 105 che è situato nella parte bassa del complesso. La posizione del pozzo è riportata nella Fig. S6.

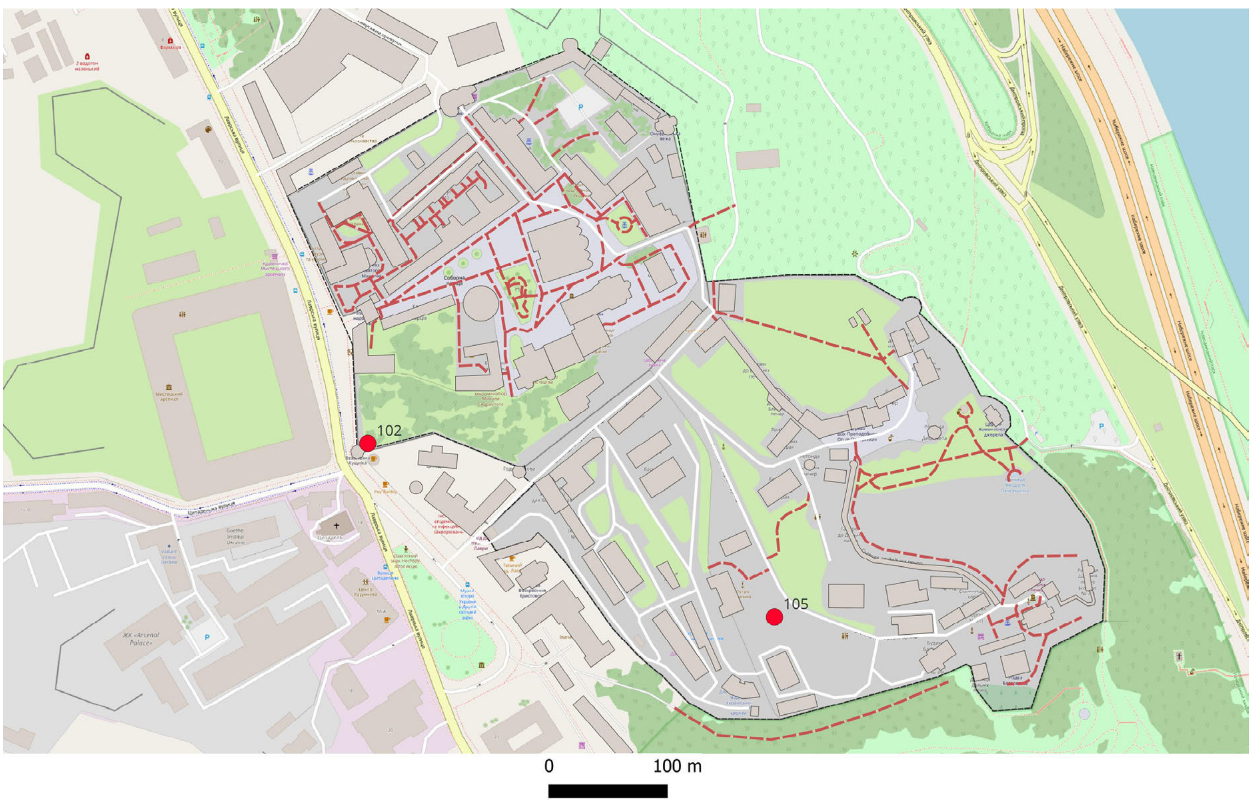

Fig. S6 - Schematic map showing the location of wells 102 and 105. The technical specifications of these wells are shown in Figure S4 and S5.

Fig. S6 - Carta schematica che riporta la posizione dei pozzi 102 e 105. Le scheda tecniche di questi pozzi sono riportate nelle Figure S4 e S5.

Section 3. The role of various stakeholders in monitoring geological hazards and planning mitigative measures

The architectural monuments of the Kyiv-Pechersk Lavra are taken care of by the National Preserve "Kyiv-Pechersk Lavra" (Preserve). It is a state institution subordinate to the Ministry of Culture and Information Policy of Ukraine. Part of the buildings of the Lavra are used as museum premises. At the same time, religious organizations use several buildings, in particular churches and caves, on lease rights.

Hydrogeological monitoring of the Kyiv-Pechersk Lavra is carried out by the Department of monitoring the territory and monuments of the Preserve. The work of the department is subordinated to the service of the Chief architect of the Preserve. Monitoring works are financed from the state budget of Ukraine.

In situations where hydrogeological monitoring data indicate the existence or potential for the development of a hazardous geological process, the Preserve initiates the issue of the need to implement mitigative measures. With this initiative, the Preserve addresses interested parties: the State (Ministry of Culture and Information Policy and Cabinet of Ministers), religious organizations that use the Lavra, city authorities, charitable organizations, and grant donors (UNESCO, The Getty Foundation).

After the decision on the allocation of funds, mitigative measures are implemented by the Preserve or religious tenants. At the same time, appropriate specialized scientific and technical and design organizations are involved in conducting additional surveys and developing project designs for mitigative measures (in particular, the Institute of Geological Sciences, Kyiv National University of Construction and Architecture, Institute of UkrNDIPROEKTRESTAVRATIYA (Ukrainian Scientific-research institute of restoration projects), others). Developed projects of mitigative measures must undergo state construction expertise.

Section 4. Geophysical studies

This section provides a brief overview of the geophysical studies used to study the geological environment of the Kyiv-Pechersk Lavra.

Rybin et al. (2004) and Starostenko et al. (2006) determined the vertical distribution of soil density and moisture content in the profiles of boreholes directed from the territory of the Upper Lavra (plateau) in the downhill direction (slope) using methods of gamma- and neutron- logging of boreholes. The goal was to delineate "weak zones" (characterized by lower soil density and increased moisture content) in the Quaternary deposits of the plateau and the landslide massif of soils on the slopes of the Kyiv-Pechersk Lavra. The results were used to develop recommendations for engineering measures aimed at increasing the geotechnical stability of the geological massif.

Starostenko et al. (2006) and Levashov et al. (2007) used a set of geophysical methods including vertical electrical soundings (VES), the electromagnetic short-pulse sounding, seismic-acoustic and ground-penetrating radar surveys to characterize lithological composition and moisture content of soils of the Near Caves Hill. The goal was to determine the pathways of the preferential flow of groundwater in the soils of the hill.

The results of the VES studies showed a good correlation between the electrical properties of the soils with their lithological composition and the ways of filtering the perched groundwater towards the caves. The results of the VES allowed a detailed lithological description of the geological profile to a depth of 10-12 m, including the location of the low permeability clay layer. Groundwater flow paths on the top of the clay layer were also précised.

Seismic-acoustic and ground-penetrating radar studies made it possible to identify the depths of subsurface voids (cave complexes), disturbed soils above the cave destruction zones, as well as areas with cracks and high soil moisture content in the clay layer above the caves. The latter are supposed zones of vertical flow of groundwater from the upper layers of soil into the sandstone layer below the clay layer, where the cave complexes are located.

It should be noted that geophysical methods provide indirect data on the physical properties of subsurface soils based on the measurement of electrical, seismic, and acoustic responses and other relevant parameters used by the respective methods. Therefore, for the interpretation of geophysical data, it is important to cross-check geophysical results (where possible) with direct determination of subsurface soil properties (e.g., from boreholes) and to cross-compare data obtained by different methods. For example, the conclusions from the described above VES geophysical studies were confirmed by observations on monitoring wells. A discussion of the capabilities and limitations of geophysical methods can be found in (Melehmir et al., 2016; Pazzi et al., 2019).

Section 5. Groundwater modeling

Groundwater flow modeling studies of the Kyiv-Pechersk Lavra were carried out to analyze the consequences of possible accidents on water mains near the heritage monuments and to assess the possible impact on the hydrogeological conditions of the reconstruction of the Dormition Cathedral (Rybin et al. 1995, 2001).

The Kyiv-Pechersk Lavra groundwater flow model was initially developed using the Institute of Geological Sciences (Kyiv) in-house finite-difference software code JVA (Rybin et al., 1995), and later converted to PMWIN software based on the MODFLOW code (Chiang, 2005).

The model simulates groundwater flow in the unconfined aquifer in the Quaternary aeolian-diluvial and lacustrine-glacial deposits on the plateau and slopes. The domain and boundary conditions of the groundwater flow model are shown in Figure S7. The model has 2635 cells, with a grid size of 10 x 10 m. The first-order boundary conditions were assigned values based on groundwater levels in observation wells measured during the groundwater monitoring program. The internal second-order boundary conditions are set on the contours of the subsurface drainage systems according to the available measurements of the drainage flow rates.

In the first step, the groundwater flow model was calibrated to match predicted and observed groundwater levels at control points (monitoring wells). For this, the groundwater flow model was run in a steady state. This resulted in the following values of the hydraulic parameters. The fitted value of the infiltration recharge rate to the unconfined aquifer was 100 mm/year on the plateau and 50 mm/year on the slopes. In cells with leakages from the water mains, the infiltration recharge rate was increased to 350 mm/year. The average hydraulic conductivity of the unconfined aquifer in the plateau was 0.4 m/day. The transmissivity of the unconfined aquifer varied from 0.4 to 12 m^2/day.

The calibrated model was used to predict the consequences of emergency scenarios involving significant leaks from water mains on the territory of the Kyiv-Pechersk Lavra or in nearby urban areas. The second set of scenarios considered the possible consequences of the construction of a pile foundation during the reconstruction of the Dormition Cathedral and the resulting "barrage effect" on groundwater flow. For these scenarios, the model was run in transient mode. Modeling of emergencies associated with water leaks from mains showed that under some extreme scenarios, the increase in the groundwater level under the foundations of the main architectural monuments of Lavra in the plateau can reach 1 – 3.6 m. As shown by the simulation results, the predicted rise in the groundwater level due to the combined effect of the barrage effect of the pile foundation of the Dormition Cathedral and leaks from water mains can reach 7.0 m (depending on the assumed foundation design and hydraulic parameters of the aquifer). Such a significant rise in groundwater levels may threaten the geotechnical stability of heritage monuments.

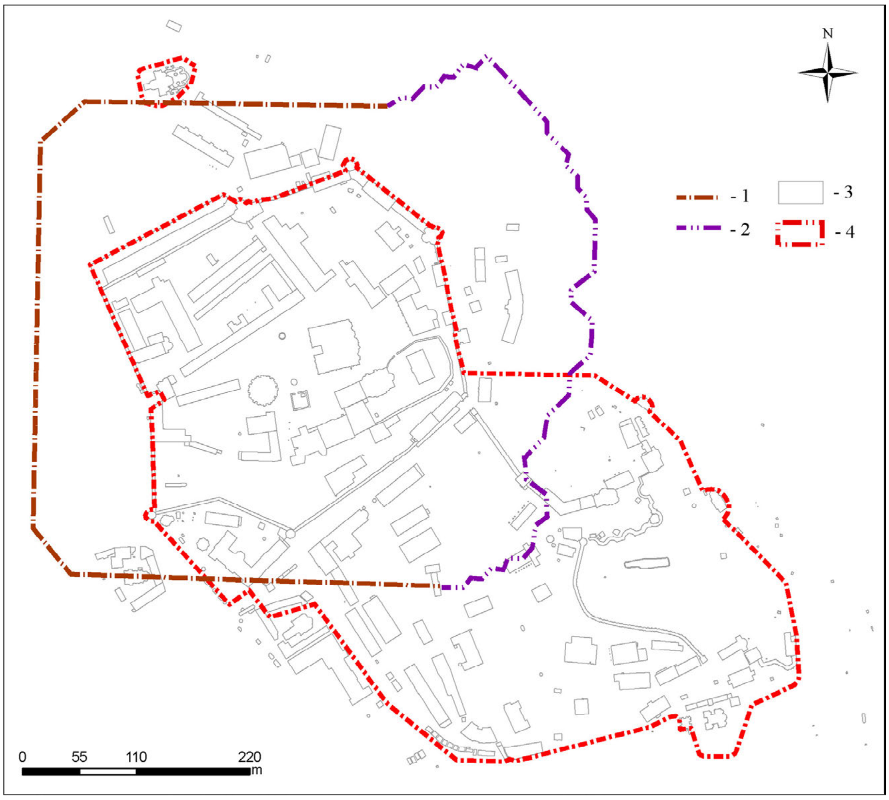

Fig. S7 - The filtration domain and boundary conditions of the groundwater flow model.

Fig. S7 - Estensione del modello numerico di flusso e condizioni al contorno.

Taking into account the results of hydrogeological modeling described in Rybin et al. (2001), the design of the pile base of the Dormition Cathedral by the Ukrproektrestavratsiya (Ukrainian Project Restoration) Institute was changed. In particular, the total number of piles was reduced to 560, and the depth of piles was reduced to 16-17 m. In 2000, all water-bearing communications on Cathedral Square (near the Dormition Cathedral) were replaced.

It should be noted that the developed groundwater flow model was a simplified description of the complex geological and hydrogeological system of the Kyiv-Pechersk Lavra. Therefore, the simulation results should be considered as possible scenarios (taking into account the relevant simplifying assumptions), and not as ultimate predictions of the behavior of the simulated hydrogeological system. For more discussion of the capabilities and limitations of groundwater flow models, the reader is referred to (Konikow & Mercer, 1988; Rojstaczer, 1994; Kumar, 2012).

Section 6. Groundwater monitoring data

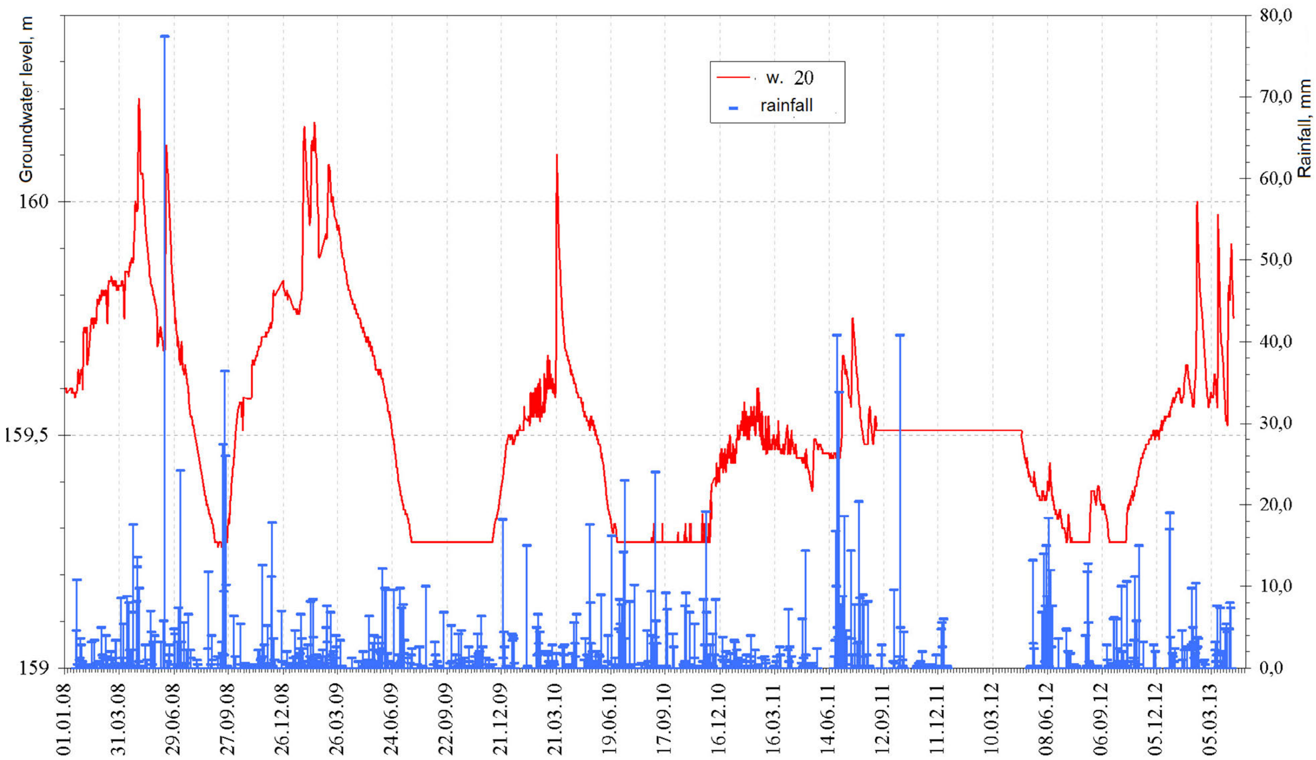

Fig. S8 - Groundwater levels and rainfall data for well 20 located in the upper part of Near Caves Hill from 2008 to 2013. Horizontal lines correspond to the periods when the well dried up. High-resolution time groundwater monitoring was carried out using the automated TD-Diver pressure sensor, https://www.vanessen.com/products/data-loggers/td-diver/. After 2013 automated monitoring of groundwater level was not conducted because of the end of the battery life of the pressure sensor.

Fig. S8 - Livello piezometrico misurato nel pozzo 20 situato nella parte alta del complesso vicino alle grotte "Near Caves" e precipitazione durante il periodo 2008 - 2013. Le linee orizzontali corrispondono a periodi in cui il pozzo era asciutto. Il monitoraggio del livello piezometrico è stato effettuato un misuratore automatico di pressione TD-Diver, https://www.vanessen.com/products/data-loggers/td-diver/. Il monitoraggio è stato interrotto nel 2013 dato che la batteria del misuratore è terminata.

Section 7. Information on accidents and resulting deformations of architectural monuments

Tab. 1 - The list of large-scale accidents on water mains heating water pipelines in Kyiv-Pechersk Lavra and adjacent territory from 1993 to 2023.

Tab. 1 - Lista degli incidenti principali che hanno interessato le condotte per acqua calda nell'area del monastero delle Grotte di Kiev e nelle zone limitrofe fra il 1993 e il 2023.

No.	Date	Description of the accident
1	June 1993	A break of the pressure water main in the Metropolitan Garden has resulted in the suffusion of soil along with water into the underground structure no. 11 (under Cathedral Square) and flooding of the part of this structure between buildings no. 2 and 80 with subsequent subsidence of the asphalt pavement (S = 36 m^2) near building no. 29
2	February 1994	An accident on the heating water pipeline in the basement of building no. 9 and subsequent infiltration of water to the soil has led to a significant suffusion removal of soil from below the foundation, the "detachment" of a part of the foundation, and development of cracks throughout the building
3	May 1994	A break of the pressure water main on the Economic Drive has resulted in flooding (the level of the water reached 0.5 m) of underground structures and foundations of building no. 7, and excessive wetting of the loess soils of the building basement. Subsequently, vertical cracks have formed overnight in the walls and ceilings of the building due to the subsidence of the loess soils.
4	July 1999	Following a break in the heating water pipeline, which was not detected and mitigated in time, the leakage of water into the soil continued for at least several months. This has led to the development of a sinkhole of about 20 m^3 in volume near the southwestern corner of building no. 44. The soil removed by suffusion has filled the underground structure below the building, almost completely silting it up
5	February 2000	A break of the pressure water main (and its delayed detection) in Cathedral Square has led to the oversaturation of soil with subsequent removal of the soil (with a volume of 100 m^3) into the subsurface drainage tunnel. This resulted in the formation of a sinkhole on the surface with a size of about 7.0 x 8.0 x 5.0 m. A tractor that was clearing snow fell into this hole.
6	February 2014	Flooding of the basement part of the Dormition Cathedral with a suffusion of soil near the northern apse of the eastern facade as a result of a fire hydrant accident. The accident led to the subsidence of the loess soils of the foundations and the uneven settlement of the cathedral structures with the formation of cracks (Fig. S9).
7	January 2017	A rounded sinkhole of about 1.6 x 1.2 x 2 m in size has formed as a result of soil suffusion to the subsurface drainage gallery on the lawn near the southwestern corner of building no. 99
8	February 2018	An accident of the heating water main at the corner of Citadelnaya and Lavrskaya Streets has led to the flooding of the basements of the building of the Museum of Ukrainian Folk Art and the nearby restaurant. The depth of the hot water column over the entire area of the basement reached 0.3-0.5 m.
9	February 2021	Two major accidents have occurred on the heating water mains at the corner of Lavrskaya and Citadelnaya Streets and on the territory of the former Infectious Disease hospital near building no. 113. These accidents resulted in the formation of numerous sinkholes and the flooding of architectural monuments on the territory of the Lavra (buildings nos. 111, 58). During the mitigation of these accidents, pipes with a diameter of 700 mm and a length of 6 and 7 m were replaced in both locations.
10	October 2021	A long-term leakage from the water main in the Upper Lavra has led to total excessive saturation of soils, uneven subsidence of foundations, and cracking in the eastern part of the northern facade of building no. 21 (the opening of the cracks reached 1.6 cm); all inspection wells along the water main were flooded. In addition, existing cracks were re-activated and new cracks were formed on the northern and southern facades in the interiors of the building (Fig. S10)
11	October 2022	An accidental leakage from the main heat water pipeline, which runs across the Upper Lavra through the territory of the Metropolitan's Garden resulted in were forming of three big up to 2 m deep sinkholes on the ground surface with a total area of 140 – 150 m^2. An underground structure – "Metropolitan's Wine Cellar" was completely flooded and partially ruined.
12	July – August 2023	A sequence of large-scale breaks of water mains and heat pipelines at the corner of the Citadelnaya and Lavrskaya Streets and along Lavrskaya Street resulted in flooding of the basement of the building of the Museum of Ukrainian Folk Art, rise of groundwater levels in the observation wells located along the Lavrskaya Street by 0.7 – 1.7 m an in increase of the groundwater temperature

Fig. S9 - Cracks in interior premises of the Dormition Cathedral (photo was taken in November 2023).

Fig. S9 - Fessure all’interno della Cattedrale della Dormizione (fotografia scattata nel novembre 2023).

Fig. S10 - Cracks on the facade (a) and in interior premises (b) of Building no.21 caused by uneven subsidence of foundations (photo was taken on October 2021).

Fig. S10 - Fessure sulla facciata (a) e all’interno (b) dell’edificio n. 21 causate da uno sprofondamento differenziale delle fondamenta (fotografia scattata nell’ottobre 2021).

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Fig. S11 - Crack in the defensive wall of Lavra (photo was taken in March 2024).

Fig. S11 - Fessure sul muro difensivo del complesso (fotografia scattata nel marzo 2024).

Fig. S12 - Drainage hole (hydro-auger) in the retaining wall of Near Caves Hill (photo was taken in March 2024).

Fig. S12 - Drenaggio (hydro-auger) nel muro di contenimento del colle "Near Caves" (fotografia scattata nel marzo 2024).

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