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CLIMATE CHANGE AND ARCHAEOLOGICAL HERITAGE: RISK IDENTIFICATION AND MONITORING OF A LAKESHORE ARCHAEOLOGICAL SITE IN SMUSZEWO (POLAND) - A CASE STUDY

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EXTENDED ABSTRACT

Il cambiamento climatico rappresenta una minaccia crescente per il patrimonio culturale, in particolare per i siti archeologici situati sulle sponde dei laghi, dove le fluttuazioni dei livelli dell'acqua e i cambiamenti nell'equilibrio idrico influenzano direttamente le condizioni di tutela. Il documento presenta una strategia di identificazione e monitoraggio del rischio a più livelli, sviluppata per un insediamento fortificato dell'età del Bronzo Finale / Prima Età del Ferro a Smuszewo, in Polonia, come parte del progetto TRIQUETRA. Il sito, situato all'interfaccia tra ambienti terrestri e acquatici, è caratterizzato da strutture in legno ben conservate, identificate lungo la sponda orientale e nel Lago di Czeszewo, così come all'interno dell'insediamento fortificato. La conservazione di questi reperti dipende dalla stabilità idrologica del lago, che è stata influenzata da cambiamenti climatici a lungo termine e da attività umane.

La ricerca si basa su una metodologia di valutazione del rischio a tre fasi, che integra analisi di dati storici, tecniche di telerilevamento e monitoraggio in loco. Sono stati analizzati documenti cartografici storici, fotografie aeree e immagini satellitari per tracciare i cambiamenti ambientali, evidenziando l'impatto delle modifiche nell'uso del suolo dal XIX al XXI secolo, le attività di bonifica e i cambiamenti climatici. Inoltre, i dati meteorologici pluriennali hanno fornito approfondimenti sulle minacce indotte dal clima nella regione. Una sfida importante durante lo studio è stata la mancanza di misurazioni sistematiche dei livelli dell'acqua nel Lago di Czeszewo, che ha impedito di stabilire una correlazione diretta tra i cambiamenti idrologici osservati e il rischio associato alla conservazione dei reperti archeologici.

Per affrontare queste limitazioni, nel 2023 è stato avviato un sistema di monitoraggio che include banche dati geospaziali tematiche, l'acquisizione di immagini aeree con droni e misurazioni dirette dei livelli dell'acqua. Queste attività mirano a quantificare i principali fattori che influenzano le fluttuazioni del livello dell'acqua e il loro impatto sull'integrità strutturale del sito. I dati raccolti supportano la creazione di una mappa dinamica del rischio, necessaria per lo sviluppo di strategie di conservazione a lungo termine.

I risultati preliminari indicano che sia fattori climatici che antropici contribuiscono in modo significativo ai cambiamenti idrologici nel bacino del lago. La variabilità pluriennale e stagionale delle precipitazioni, l'aumento delle temperature e i periodi prolungati di siccità accentuano la variabilità del livello dell'acqua, accelerando potenzialmente il degrado delle strutture in legno. Allo stesso tempo, i progetti storici di bonifica e drenaggio hanno modificato la capacità naturale di ritenzione idrica, destabilizzando ulteriormente l'idrologia del lago.

Questo studio mette in evidenza la vulnerabilità dei siti archeologici sulle sponde dei laghi ai cambiamenti climatici e all'impatto dell'attività umana. Utilizzando un approccio interdisciplinare che combina analisi di materiali cartografici storici e contemporanei, dati di telerilevamento e monitoraggio in loco, i risultati dell'analisi possono fornire una base per la mitigazione del rischio e la protezione del patrimonio archeologico. La metodologia del progetto TRIQUETRA è intesa come un modello per condurre ricerche simili in tutta Europa, evidenziando la necessità di migliorare l'acquisizione e la raccolta dei dati, la modellizzazione predittiva e le politiche di conservazione adattative.

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ABSTRACT

The aim of this paper is to present a multi-level approach to risk identification and monitoring strategies for the lakeshore archaeological sites. Within a range of the cultural heritage typologies that are addressed by the TRIQUETRA project, the Late Bronze Age/Early Iron Age fortified settlement at Smuszewo (Poland) occupies a transitional position between mainland and water environment. Archaeological excavations and other surveys conducted between the 1950s and 2010s revealed well-preserved wooden structures on land and on the east shore of Czeszewo Lake. Crucial to their preservation is the waterlogged environment which is directly related to the condition of the lake, water balance and particularly the water level. The problem of deteriorating water conditions (*e.g.* decreasing water level) in neighboring areas - resulting in recurrent droughts – has already been identified. However, its impact on the fragile wooden relics of the fortified settlement has not yet been assessed.

Keywords: *climate change, cultural heritage, risk assessment, lakeshore archaeology, remote sensing, hydrological monitoring, Smuszewo*

INTRODUCTION

It is difficult to dispute the view that we are experiencing anthropogenic climate changes that impact the world around us, leading to numerous challenges. The multifaceted nature of climate change directly and indirectly modifies the conditions in which we live, affecting environmental contexts, economic activities, social relations, and the broader cultural sphere. Archaeological heritage is one such area that is and will continue to be affected by the consequences of climate change (Cassar, 2005; Hollesen, 2018). Considering that this heritage is non-renewable , the challenges associated with its protection become even more significant (Heathcote *et alii*, 2017; Rockman & Hritz, 2020). Among the most vulnerable cultural resources are archaeological sites located in transitional environments, such as lakeshores, where changes in water balance and hydrological dynamics directly threaten the preservation of organic structures (Holden *et alii*, 2006; Bonazza *et alii*, 2021).

This issue is increasingly recognized, leading to the formulation of research projects (both national and international) aimed at identifying threats on local and regional scales and developing strategies to minimize the negative impacts of ongoing climate and environmental changes (Bosher *et alii*, 2019; Howard *et alii*, 2016). TRIQUETRA: Toolbox for assessing and mitigating Climate Change risks and natural hazards threatening cultural heritage is currently one of the projects addressing the identification, assessment, and mitigation of risks to cultural heritage resources as a consequence of ongoing climate changes.

The identification of threats to cultural heritage involves the need to pinpoint the most significant factors and determine methods for recognizing and assessing their impact (Sesana *et alii*, 2020; Orr *et alii*, 2021). This can be done at both regional and local levels. Regional considerations permit the creation of general models that indicate trends across different areas of Europe. In the context of individual archaeological sites, general models provide a broader context for considerations, but the analysis of local conditions also seems particularly important (Daly, 2014). Taking this aspect into account in the assessment of a specific archaeological site, it is worth identifying local factors deemed significant. These can be categorized into relatively stable factors (*i.e.*, those not subject to rapid processes) and dynamic factors, which can be observed relatively continuously.

The objective of this study is to present a multi-tiered approach to risk assessment and monitoring at lakeshore archaeological sites, using the fortified settlement at Smuszewo (Poland) as a case study. This text was created as part of the TRIQUETRA project and contributes to its goal by investigating how environmental variability affects the structural integrity of organic (including wood) archaeological remains.

The diversity and specificity of relics from past human activities shape how questions are formulated. In the case of Smuszewo, site 3, the location of the archaeological remains particularly their position along the lakeshore gives rise to a range of site-specific questions (Fig. 1). Crucial to their preservation is the waterlogged environment which is directly related to the condition of the lake, water balance and particularly the water level (*e.g.* Broda & Hill, 2021; Lucejko *et alii*, 2020). The research addresses key questions: (1) how do water level dynamics in lake influence the preservation of wooden relics, (2) what are the main climatic and anthropogenic factors affecting hydrological conditions in the region, (3) can predictive tools and monitoring systems improve long-term conservation strategies? These questions arise from a broader need to understand how dynamic and static environmental variables intersect at vulnerable archaeological sites.

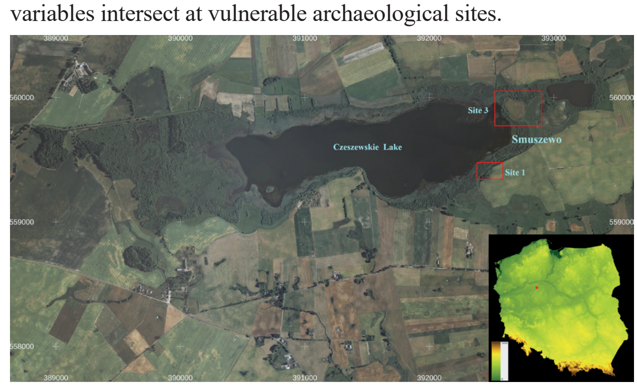

Fig. 1 - Location of the Smuszewo archaeological site (No 3) on the orthophoto map and hypsometric map of Poland (source: Head Office of Land Surveying and Cartography, orthophoto map of Poland 2023, hypsometric map 2024. Available at: https://www.geoportal.gov.pl)

CASE STUDY

The assumptions of the TRIQUETRA project led to the selection of a case study in Central Europe. The Smuszewo site 3 (AZP 42-32/95) consists of the remnants of the Late Bronze Age/Early Iron Age fortified settlement. These remains were identified in 1863 and referred to as the Czeszewo lake-dwelling, in reference to previously discovered pile dwellings in Germany and Switzerland. The wooden structures observed at that time were located in the coastal zone of the eastern part of the lake and were found underwater and in peat sediment layers outside the embankment surrounding the settlement. They were revealed due to the lowering of the lake's water level resulting from drainage works (Libelt, 1870-1871; Łepkowski, 1871). Archaeological excavations conducted in the 1950s and 1960s indicated the presence of wooden structures within the settlement, similar to those extensively excavated in Biskupin (Kostrzewski, 1938; Durczewski, 1985). These wooden structures related to internal buildings were located approximately 0.80–1.10 meters below the current ground level (Rajewski, 1957; Malinowski, 1961), which roughly corresponds to an elevation of 88.60/89.00 meters above sea level (Polish vertical datum – KRON86). Non-invasive investigations (geophysical surveys and interpretation of aerial photographs) conducted in 2004 and 2010 showed a very clear plan of internal structures (wooden buildings, paved wooden streets, hearths, etc.) (Harding & Rączkowski, 2010). Only a few such settlements have been recorded, but all of them share similar threats.

Field	Factor	Impact
Natural environment	Geomorphology	Assessment of terrain morphology and its susceptibility to erosion, landslides, and surface water runoff
	Hydrology	Analysis of threats to archaeological relics related to water, such as changes in lake water levels, flooding, droughts, and water erosion
	Climate	Assessment of the impact of climatic conditions (*e.g.* air temperature, precipitation, wind) on site degradation
	Geology	Evaluation of the geological stability of the site
	Land cover	Assessment of the impact of changes in land cover and land use on site stability.
Anthropopression	Threats posed by human activities	Development of agriculture - land reclamation and peat exploitation; building and infrastructure, industrial development; tourism; transformation of terrain topography, initiation of erosion processes
	Environmental pollution	Pollution of water and soil.

Tab. 1 - Factors considered in cultural heritage vulnerability assessment (Smuszewo case)

APPROACH AND DATASETS

The complexity of environmental variables requires an interdisciplinary approach. This involves geomorphological, soil, hydrological, meteorological, flora and fauna, archaeological data, as well as contemporary human activities. All these factors are interconnected but may highlight different aspects of threats.

The vulnerability of material relics of cultural heritage to threats is interpreted as the degree to which an object is exposed to damage or destruction due to natural factors or human activities (Sabbioni *et alii*, 2008). Assessing vulnerability is a complex process that requires considering many interrelated factors (Brimblecombe *et alii*, 2006). In this study, it was conducted based on the analysis of selected components of the natural environment and anthropogenic pressure factors (Table 1).

To assess the role of individual factors from a historical perspective, we utilized a wide range of data: archaeological, topographical, environmental (thematic), climatic, and remote sensing data (Table 2).

Additionally, in the years 2023–2024, detailed data about the immediate surroundings of the site were acquired through regular monitoring using RGB and thermal aerial photographs from an altitude of up to 120 meters (UAV) (Fig. 2). Simultaneously, regular water level measurements were conducted using a probe that measures the water level and records it with a Datalogger DL/N series 64.

Historical cartographic data were used in the analysis of environmental component transformations, while remote sensing and UAV-based surveys were employed in monitoring landscape

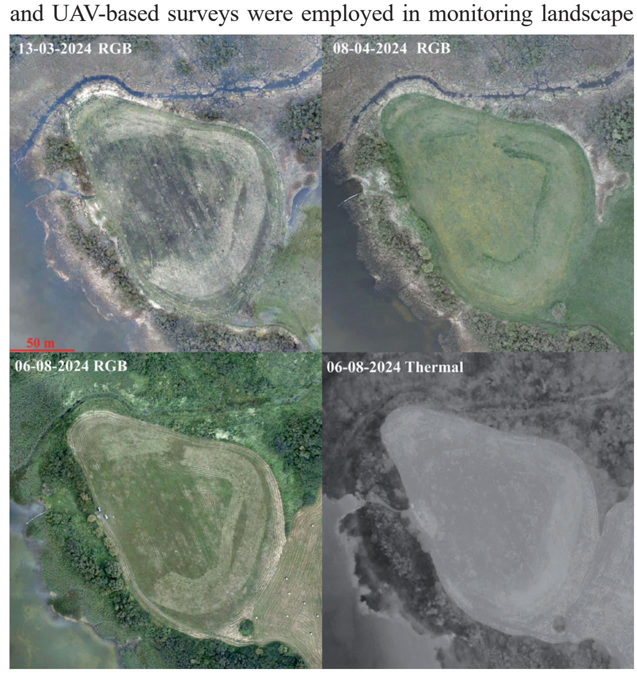

Fig. 2 - Examples of UAV's aerial survey/orthoimages for monitoring environmental conditions; with dates of acquisition

Sort of data	Database / Data source	Application	Format
Archaeological	Excavation research publications (1956, 1959–1966)	Registration of stratigraphic layers and wooden relics	Analog
	Geophysical surveys (2004, 2010)	Settlement layout analysis	Analog
Topographic	Cartographic materials: - Topographic maps from 1802–1803 at a scale of 1:150k (based on unpublished materials from 1793 at a scale of 1:50k) - Urmesstischblätter from 1830 at a scale of 1:25k - Various editions of Messtischblätter maps at a scale of 1:25k from 1870–1944 - 1:25k topographic map from the Military Geographic Institute (1933) - Modern editions of topographic maps at 1:10k and 1:25k (1960, 1976/87, 2000) - Digital database of topographic objects (BDOT, 2013, 2023)	Changes in landscape, land use, shoreline, and drainage network modifications	Analog /Digital
Environmental (thematic)	Hydrographic map 1:50k, 1:10k	Watershed analysis, hydrographic network layout, extent of wetland areas, shoreline changes	Analog /Digital
	Geomorphological sketch, DTM resolution 5x5 m	Terrain relief analysis, slope gradients, erosion susceptibility	Analog
	Detailed geological map 1:50k	Analysis of geological structure, lithology, deep-seated features, surface landforms (*e.g.*, landslides), and anthropogenic modifications (*e.g.*, excavations)	Analog
	Soil-agricultural map 1:5k (1966)	Soil analysis – soil types and agricultural suitability	Digital
Meteorological and climatic	Radar data (since 2010)	Analysis of precipitation structure, location, intensity, movement direction, and speed	Digital
	Meteorological station (Gołańcz, since 1954) Chrzastowo near Nakło from 1981)	Analysis of air temperature variations, precipitation, wind speed, and direction	Digital
Remote sensing	Archival satellite imagery from the CORONA and HEXAGON programs (1973–1984) obtained from the United States Geological Survey (USGS)	Monitoring climate change on a global scale, detecting trends and changes in different geographical locations	Digital
	Airborne laser scanning (2014)	3D topographic modeling, generation, and updating of DSM and DTM, detailed study of hidden structures	Digital
	Vertical aerial photographs for cartographic purposes (1966–2023)	Monitoring land use changes, vegetation cover, and hydrology, digital elevation models	Digital
	Oblique aerial photographs (2005, 2007, 2008, 2014)	Archaeological reconnaissance	Digital
	UAV vertical imagery from the Triquetra project (RGB, thermal, multispectral, 2023–2024)	Digital Surface Model (DSM), detailed mapping of changes over time	Digital
	High-resolution commercial or freely available satellite imagery (Google Earth application)	Monitoring land use changes, vegetation cover, and hydrology	Digital
	Medium-resolution satellite images with high revisit frequency (e.g., Landsat, Sentinel, Planet Lab)	Monitoring land use changes, vegetation cover, and hydrology	Digital

Tab. 2 - Data available and acquired for research purposes

and hydrological changes. Remote sensing data for this area have been available since 1966 and include aerial photographs with a spatial resolution of up to 25 cm collected in Poland for cartographic purposes, laser scanning used to develop a highly accurate terrain surface model, satellite spy images from the Corona and Hexagon programs, medium-resolution images from the Landsat programs (approximately 1000 cloud-free terms from 1984 to the present with the spatial resolution 15/30m), and from the Sentinel program (both radar and multispectral, with a spatial resolution of up to 10 m), as well as commercial high-resolution images (*e.g.*, WorldView, Ikonos, QuickBird, PlanetLab).

Meteorological records, including data from the Institute of Meteorology and Water Management – National Research Institute' (IMGW-PIB) meteorological stations and historical climate data sets, were used to assess trends in air temperature, precipitation, and extreme weather events. Hydrological databases supported the analysis of water regime transformations within the fortification's range and catchment area, as well as changes in the lake's water level to assess their impact on the site's wooden relics. Geological and soil data were used in the analysis of stability and susceptibility of the terrain to erosion and water retention for long-term environmental balance assessment.

IDENTIFICATION OF CONTEXTS AND PROCESSES

Geomorphological and geological contexts

The archaeological site in Smuszewo is located by Czeszewo Lake, a ribbon lake formed during the Baltic glaciation. Its morphology results from genetic conditions and subsequent processes that transformed the lake and its surroundings (Kozarski, 1981). The retreat of the ice sheet left behind a deep depression filled with mineral sediments and surrounded by a moraine upland zone (Krygowski, 1961; Bartkowski, 1965).

During the late glacial period, Czeszewo Lake took the form of a large proglacial lake, filling almost the entire ribbon lake depression. Studies by Sołowiej (1975) in the 1970s showed that the lake occupies only a small part of the original depression, extending along an east-west axis. Over time, the water level in the lake decreased, peatlands formed, and vegetation gradually encroached on the shallower areas, as documented by the presence of gyttja (lake sediment) directly deposited on clays. The layout and structure of the lake basin and its immediate surroundings were transformed by natural processes such as sedimentation, vegetation succession, and the accumulation of peat layers, as well as erosion processes, which were later intensified by human activities (land use changes, drainage works, cutting reeds, digging peat for heating).

Considering the hypsometric criterion, three distinct levels were identified within the ribbon lake of Czeszewo Lake (Sołowiej, 1975) (Fig. 3):

- the lower level (approximately 87 m a.s.l.), constituting the contemporary bottom of the ribbon lake;
- the higher level (2.5-5.0 m above the bottom), with hills forming a kind of ‘islands’ in the peat-filled ribbon lake;
- the edges of the ribbon lake, more pronounced on the southern side (relative height over 12 m) than on the northern side (7.5-9.5 m).

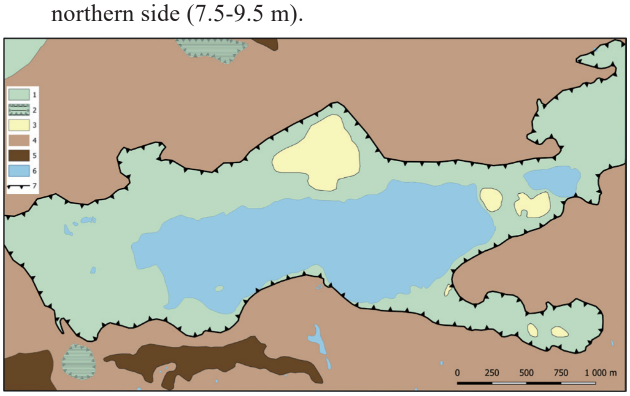

Fig. 3 - Geomorphological sketch of the surroundings of Czeszewo Lake. Legend: 1) ribbon lake bottom, 2) drainless depressions, 3) moraine outcrops in the channel bottom, 4) undulating moraine plateau, 5) dead - ice moraines, 6) surface waters, 7) edge of the subglacial channel. Source: own study based on DTM 5 x 5 m (https://geoportal.gov.pl) and explanations to the Detailed Geological Map of Poland (https://geologia.pgi.gov.pl/karto_geo)

The deposition of organic and inorganic materials over centuries has led to the gradual filling of the lake. Currently, the lake bottom, filled with organic and mineral sediments, has a slight slope towards the west and is characterized by constrictions made of mineral formations surrounded by peat. The sediments reach a thickness of up to 0.5 meters, and vegetation covers 98% of the shoreline and 25% of the lake basin (Fig. 1).

The coexistence of sedimentation processes and vegetation growth has contributed to the formation of peatlands in shallow areas and, in some places, to the quasi-stabilization of the shoreline, reducing erosion activity. The northern edge of the ribbon lake, more geomorphologically stable, limits erosion and anthropogenic influences. In contrast, the southern edge features numerous erosional incisions, which drain the upland. This zone is characterized by more intense erosion processes. Additional morphological elements increasing the dynamics of the slope zone include anthropogenic scarps and denudation basins, while within the ribbon lake and kettle holes, there is a dense network of drainage ditches and channels that emphasize the features of the discussed landscape.

Morphological changes in the Smuszewo site area are associated with the presence of two genetically distinct groups of surface forms: postglacial (organic accumulation plains, dry and wet closed depressions, erosional valleys, erosional edges, alluvial fans) and anthropogenic (peat extraction pits, excavations, trampling and plowing terraces) (Sołowiej, 1975).

The geological-lithological stability (quasi-stability) of the area results, among other things, from the nature of morphological structures, lithological types, and sediments forming the deeper geological substrate. The analysis of the geological and soil-agricultural maps of the Smuszewo settlement area and its surroundings (Fig. 4) highlights key features of the area related to the presence of various lithological types, such as sands and glacial tills, the appearance of

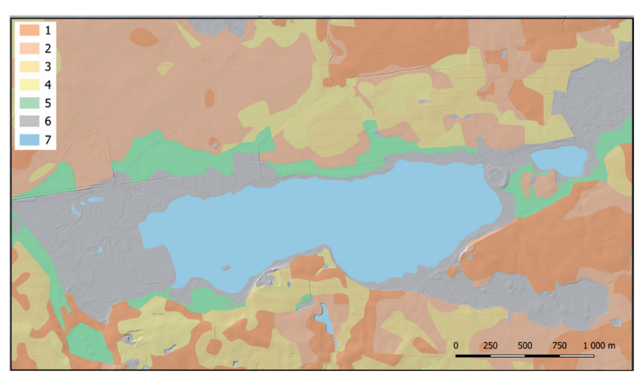

Fig. 4 - Lithological map of the surroundings of Czeszewo Lake. Legend: 1) clays, 2) clayey sands, 3) sands on clays, 4) sands, 5) peat and muck soils, 6) no data (bottom of the ribbon lake), 7) surface waters. Source: own study based on digital soil-agricultural map at a scale of 1:5k (https://geoportal.gov.pl)

organic soils, and products of washing and leaching in closed depressions and the ribbon lake. This indicates the dynamics of processes leading to changes in the lithology of formations and, indirectly, changes in soil conditions related to lithology.

The organic deposits and peatlands surrounding most of the lake are associated with wetland areas. Compared to mineral soils, they are generally less stable; peat itself is prone to compaction, subsidence, and oxidation upon drying. The sands and sandy soils near the lake indicate past fluvial or glacial processes. Sandy soils provide moderate stability but are susceptible to erosion, especially on slopes or areas with concentrated water flow. In contrast, glacial tills, common in the moraine upland surrounding the lake, provide a more stable substrate. Their stability can be compromised by human activities that disrupt their structure.

The analysis of the stability of the edges of the Czeszewo Lake ribbon lake, considering the lithology of the formations, indicates significant differences between its southern and northern parts. The southern edge of the ribbon lake, characterized by a higher proportion of loose sandy formations and greater slope, is more prone to erosion processes and potential landslides, especially during heavy rainfall. The slope map (Fig. 5) confirms that areas with the highest slopes (>12°) are found in this part of the ribbon lake, making them particularly vulnerable to degradation.

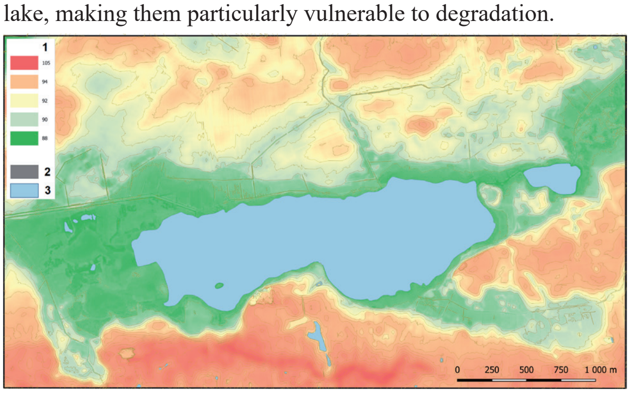

Fig. 5 - Hypsometric map of the surroundings of Czeszewo Lake. Legend: 1) hypsometric color scale (values in meters above sea level), 2) steep slopes (>12°), 3) surface waters. Source: own study based on a 5×5 m DTM (https://geoportal.gov.pl)

The northern edge of the ribbon lake is gentler (slopes <9°), with a higher proportion of glacial tills that stabilize the slope structure. An additional factor limiting erosion is the vegetation cover, which reduces surface runoff and soil loss.

The slope map with enhanced contrast (Fig. 6) confirms that the southern edge is more susceptible to destructive processes, and this is evidenced by the preservation state of another fortified site (Smuszewo, site 1, north side) dated to the early medieval period (Fig. 6). Field studies by Sołowiej (1975) showed the presence of results of abrasion processes. In the past, these processes may have led to the destruction of part of the fortification (site 3), as seen in the analyzed terrain profiles.

Fig. 6 - The erosion of the shoreline slopes has led to the destruction of parts of the fortified settlements, as shown on the synthetic slope gradient map. Smuszewo, site 1 (early medieval hillfort) – the north section of the rampart (on the lakeside) is missing. Smuszewo, site 3 (Late Bronze Age/Early Iron Age fortified settlement) – the most severe damage affects the western part of the ramparts on the lakeside

Climate changes and monitoring

Currently, it seems that climate change can be considered a significantly dynamic factor shaping environmental conditions in the region of Czeszewo Lake. Historical, contemporary, and projected changes are observed, which may be crucial for the functioning of the lake's ecosystem and the preservation of archaeological relics. Archaeological relics are particularly susceptible to climate-related changes. Their wooden structures are located in the lake's coastal environment and 'islands' in the peat-filled ribbon lake, where water level fluctuations, seasonal changes in precipitation, and air temperature variations play a significant role in their conservation processes.

The climatic region (central Greater Poland), in which the Smuszewo fortified site is located, is characterized by more frequent occurrences of very warm and simultaneously cloudy weather without precipitation compared to other regions of Poland (Woś, 1999). Measurements of basic meteorological parameters – precipitation and air temperature – allow us to identify the main trends in this part of Poland. The nearest measurement station to the fortification is the IMGW-PIB station in Gołańcz (9 km northwest of the fortification), where precipitation is recorded. The nearest IMGW-PIB measurement station where air temperature is recorded is in Chrząstowo (32 km north of the fortification).

The average annual precipitation for the Gołańcz station in the period 1954-2023 is 511 mm, one of the lowest in Poland – the average for Poland is 600 mm (Table 3). The figure (Fig. 7) shows the annual precipitation totals for the Gołańcz station, divided into the winter-cold half-year (months from November to April) and the summer-warm half-year (months from May to October). Annual precipitation totals show an upward trend, particularly noticeable after 2000, but also exhibit significant variability, ranging from 290 to 720 mm. During the measurement period, three years

Decade	Average total precipitation [mm]
1954-1960*	480
1961-1970	579
1971-1980	505
1981-1990	482
1991-2000	468
2001-2010	507
2011-2020	539
2021-2023	529
1954-2023	**511**

Tab. 3 - Average total precipitation for Gołańcz station by decades for the period 1954–2023

with precipitation totals exceeding 700 mm were recorded, namely 1967, 1970, and 2017. The lowest precipitation totals were recorded in 1982 and 1989 (Fig. 7). From the perspective of Czeszewo Lake's water balance, the amount of precipitation during the cold season, along with periods of persistent snow cover that delay surface runoff and contribute to retention, is significant. The precipitation total in the cold half-year shows an upward trend, in contrast to the trend of precipitation totals in the warm half-year, which shows a weak downward trend. The graph in the figure (gray line) shows that there may be periods when the precipitation total in the cold season may be close to or less than 100 mm, with an average of 189 mm (1995/1996 and 1996/1997). The highest precipitation total in the cold half-year was recorded for the 2023/2024 season, 339 mm. Precipitation change forecasts for Poland until 2100 indicate that in future climate conditions, the precipitation total may further increase, but with noticeable seasonality (Raport, 2020). Forecasts based on climate change scenarios suggest more intense precipitation during the autumn-winter periods and a potential decrease in summer precipitation totals. However, observational data from the Gołańcz station (Fig. 7) show only weak trends with high interannual variability and do not yet clearly confirm these projected seasonal shifts.

Figure 8 shows the average monthly air temperatures for the Chrząstowo Station from 1981 to 2024, located 34 km north of the Smuszewo site. An upward trend in air temperature is visible, with a notable increase in average monthly temperatures during

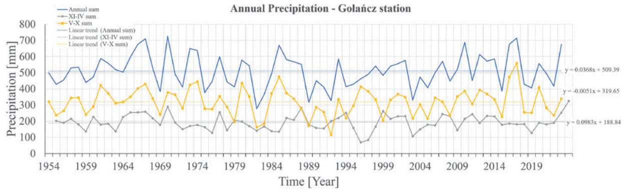

Fig. 7 - Annual precipitation at Gołańcz station (1954–2023), with divided into cold (months X–III) and warm seasons (months IV–IX)

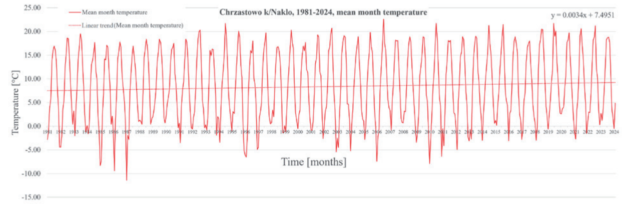

Fig. 8 - Annual precipitation at Gołańcz station (1954–2023), with divided into cold (months X–III) and warm seasons (months IV–IX)

the winter months. In the 1980s, the average monthly temperature in winter (January/February) even dropped below −10°C. This increase in evaporation and decrease in water accumulation during the cold period for Czeszewo Lake may, in turn, affect the minimum water level in the summer season.

Hydrology and its dynamic

According to the hydrographic division of Poland, Czeszewo Lake is located in the Wełna River catchment area (a tributary of the Warta River), with which it is connected via the Wapno–Laskownica Canal flowing into the Gołaniecka Stream (a tributary of the Wełna River) (Fig. 9). The watershed delineating the total catchment area of the lake, covering 81.9 km² (JCWP Czeszewo Lake Card: https://wody.isok.gov.pl/pdf/JCW/LW10215.pdf), is mostly clearly marked in the terrain's topography. The direct catchment area of the lake constitutes only 3.3% of the total catchment area. In the immediate vicinity of Czeszewo Lake, about 0.4 km to the east, lies Małe Lake (or Smuszewo, or Kujawki) with which it is connected by a section of the Wapno–Laskownica Canal. Extending westward from Czeszewo Lake are large peatland areas, intersected by drainage ditches and canals, while closed depressions are present in the upland area.

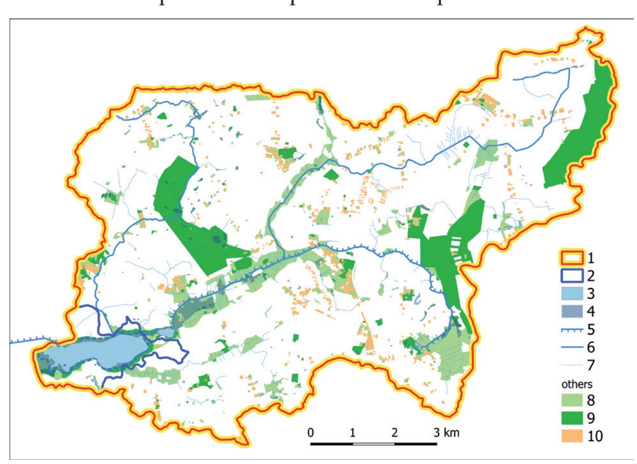

Fig. 9 - Total (1) and direct (2) catchment area of Czeszewo Lake with hydrographic objects: 3) surface waters, 4) wetlands, 5) Wapno-Laskownica Canal, 6) main streams, 7) other streams and drainage ditches. Other designations: 8) meadows and grassland, 9) forests, 10) built-up areas. Source: own study based on the Database of Topographic Objects 1:10k (https://geoportal.gov.pl)

The area is characterized by an unfavorable water balance structure. The average annual precipitation here is among the lowest in Poland, amounting to 508 mm for the Gołańcz station for the period 1961-2000, and 511 mm for the years 1954-2023 (see above). Additionally, the region is in a low runoff zone, with runoff levels even below 100 mm, compared to the average runoff for Poland of around 165 mm. The average unit runoff values in the Czeszewo Lake catchment area are about 2 l/s km², compared to the Polish average of 5.5 l/s km². These low values result from very high evaporation in the lake's catchment area and weak contact between the canal waters and groundwater. The drainage streams in the region are shallowly incised into the upland area, thus usually draining only the shallow and typically poorly endowed aquifers. Additionally, the main stream, the Wapno–Laskownica Canal, has been regulated for the needs of the Wapno mine and the developing agriculture in the region.

Research conducted in this area by Sporakowski (1969) already confirmed high evaporation (477 mm) and very low runoff (85 mm) during that period, despite significant drainage works being carried out in the region. This situation results from the constriction in the lake's ribbon, which hinders flow. Large areas of peatlands and the lake, thus areas of increased local evaporation, undoubtedly contributed to reduced runoff. The effects are deepening water deficits, prolonged periods of low water levels in the lake, and periodic water disappearance in the canal and other smaller streams.

According to Gilly's topographic map, the so-called Special Karte von Sudpreussen (1802-1803), the area around Czeszewo Lake was marked as swamps. Their area was approximately 300 ha at that time (sołowiej, 1975). Measurements from 1955 showed that 2/3 of the swamp areas had been transformed by humans. This process began in the first half of the 19th century when drainage led to a rapid reduction in the lake's area, by about 1/4 of its original area (Libelt, 1870-1871). The rate of shrinkage of the original basin area, due to sediment filling, significantly accelerated in the last decades of the 20th century. This is evidenced by the reduction in the water surface area from 148.3 ha in 1961 (The Stanisław Sakowicz Inland Fisheries Institute in Olsztyn) to 125 ha in 1989 (Choiński, 1992) (Fig. 10).

Generally, it can be stated that in terms of hydrographic changes in the studied area over the last 150-200 years, there has been a lowering of groundwater levels, a reduction in the extent and depth of the lake, and the elimination of post-glacial kettle holes in the upland (most of the 'kettle holes' have become peatlands). In the former wetland areas in the immediate vicinity of Czeszewo Lake, small water bodies have formed as a result of peat extraction.

In its current form, Czeszewo Lake can be classified as a dimictic stratified lake: max depth 8 m and average depth 3.7 m

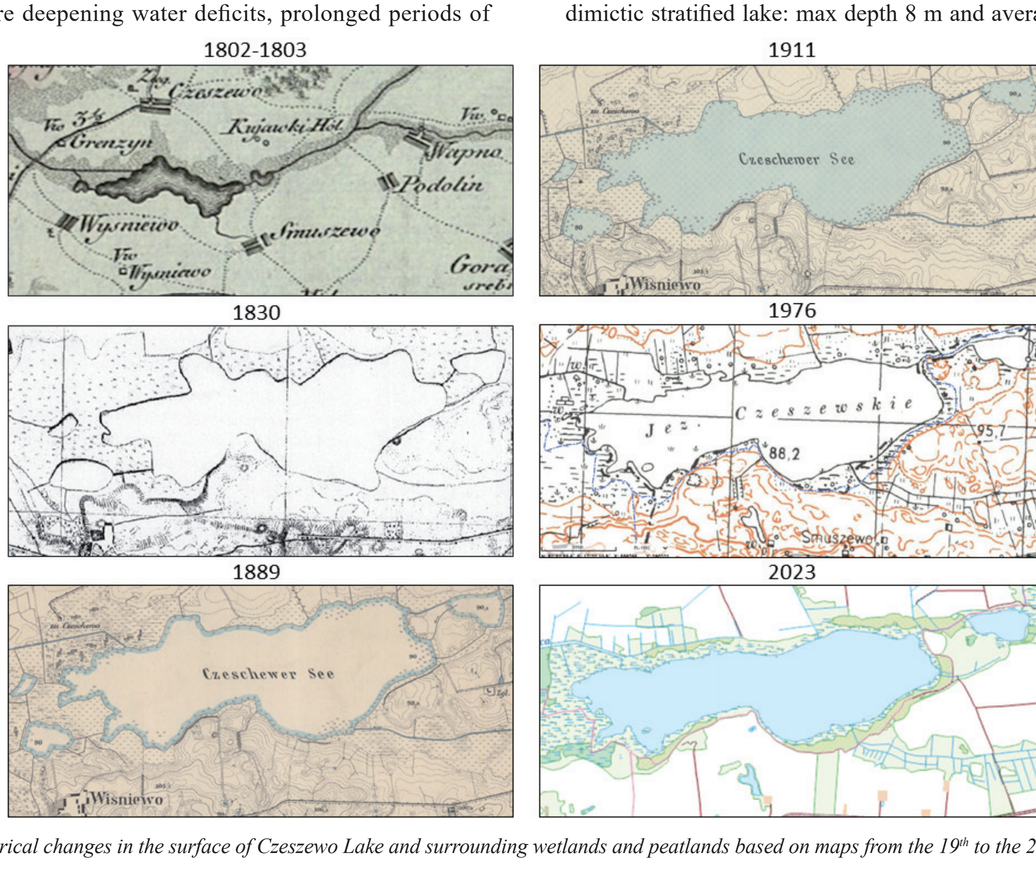

Fig. 10 - Historical changes in the surface of Czeszewo Lake and surrounding wetlands and peatlands based on maps from the 19th to the 21st century

(Choiński, 2007). However, the waters filling the lake basin are continuously mixed by wind action (wavy water surface is often visible in available remote sensing data), making it effectively a polymictic pond-type lake (Kajak 1989; Szybowski & Tonder, 1989). During the peak summer seasons, the maximum temperature differences between the surface and bottom layers do not exceed 5.50°C. There have also been instances where the temperature difference did not exceed 0.20°C (Ziętkowiak & Choiński, 1991; Szymańska, 1993). There is no observed stratification of the lake waters, or it is very short-lived. Frequent, complete mixing of the lake waters means that the lake basin has an active bottom throughout. This increases the lake's ability to self-purify its waters, although it also hinders the deposition of suspended material in the water. The high intensity of water exchange in the lake (170% per year), involving the entire water mass, is a factor that limits the accumulation of nutrients (Szybowski & Tonder, 1989). Since the 1980s and 1990s, no changes have been observed in the species composition of emergent and submerged plants in Czeszewo Lake. The reduction in the range of some of them was more related to the introduction of intensively feeding silver carp into the lake than to the slow increase in water mineralization (Ziętkowiak *et alii*, 1995).

The polymictic nature of the lake (frequent mixing of water due to wind) prevents long-term stratification, resulting in significant dynamics of the thermal and hydrological regime. Water level fluctuations in the flow-through lake, such as Czeszewo Lake, are related to the seasonal variability of meteorological factors (precipitation and air temperature) and the dynamics of the river network. The character and area of the direct catchment, as well as the morphometry of the lake basin (area and depth), the extent of shoreline vegetation, and the degree of lake overgrowth (development phase), also influence it.

Local monitoring of water levels in Czeszewo Lake, conducted since May 2024 as part of the TRIQUETRA project, has shown their dynamic nature (Fig. 11). From January to December 2024, the amplitude of water level fluctuations was 0.96 m, with a maximum of 89.20 m above sea level recorded on February 23rd and a minimum of 88.24 m above sea level noted on January 5th, 2024. The highest water levels in February and March were the result of winter rainfall and snowfall in the preceding months. At the turn of February and March 2024, some of the highest water levels in the lake in recent decades were recorded. Meteorological data confirm that precipitation totals from October 2023 to March 2024 were among the highest since 1954 for the Gołańcz station. From January 5th, 2024, to February 23rd, 2024, the water level in the lake increased by 0.96 m, while from February 23rd, 2024, to August 6, 2024, a systematic decrease of 0.80 m was recorded.

This very high-water level (late February and March) was also recorded using UAV aerial photographs (Fig. 2). The UAV image from March 13, 2024, shows the high-water level under the

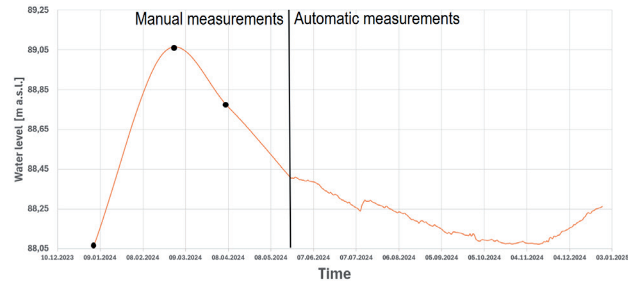

Fig. 11 - Changes in water levels in Czeszewo Lake in 2024-2025

settlement embankment, both from the lake side and the eastern side. An increase in soil moisture within the embankments was also recorded. In August (August 6th, 2024) and September, the water level in the lake stabilized at 88.30 m above sea level, while from November, it began to rise slowly.

The water level in Czeszewo Lake shows clear seasonal changes in the annual cycle (the amplitude of fluctuations exceeds 1 m), as confirmed by hydrological monitoring data conducted in 2024. The dynamics of water level fluctuations in the lake are related to both meteorological conditions and changes in the lake's water balance structure. The highest level was recorded at the end of winter, and the lowest at the end of autumn (Fig. 11). The winter-spring period is characterized by an increase in water level due to snow-rainfall replenishment. Gradual lowering of the water level, associated with intense evaporation and limited surface water inflow, is observed in the summer-autumn season. However, with the intensification of atmospheric precipitation at the turn of autumn and winter, a slow increase in the water level in the lake occurs. In early autumn 2024, despite the increase in precipitation totals, groundwater runoff and retention caused a further lowering of the water level in the lake, resulting in the extension of the lowest levels until mid-November 2024.

Seasonal changes are related to the manner and intensity of reservoir replenishment processes, especially in extreme situations such as floods or droughts, when replenishment is limited or slowed (atmospheric and hydrological droughts). The lake's response to increased or limited replenishment can be inferred from differences in the lake's shoreline extent identified based on materials from different periods and interpreting the spread of waterlogged areas in its surroundings. Satellite images and UAV orthophotos clearly identify temporal-spatial changes in the eastern part of Czeszewo Lake (Fig. 12). At the site, changes in land use (from arable land to regularly mowed meadow) can be observed, preventing shoreline vegetation from encroaching on its area. This allows it to remain well visible in the field. Elevated parts of the embankment often have separate mowing treatments, and in these places, the vegetation cover is less dense. Consequently, after some time (up to one month), these surfaces are more prone to erosion by very intense rainfall. All subsequent images show a gradual increase

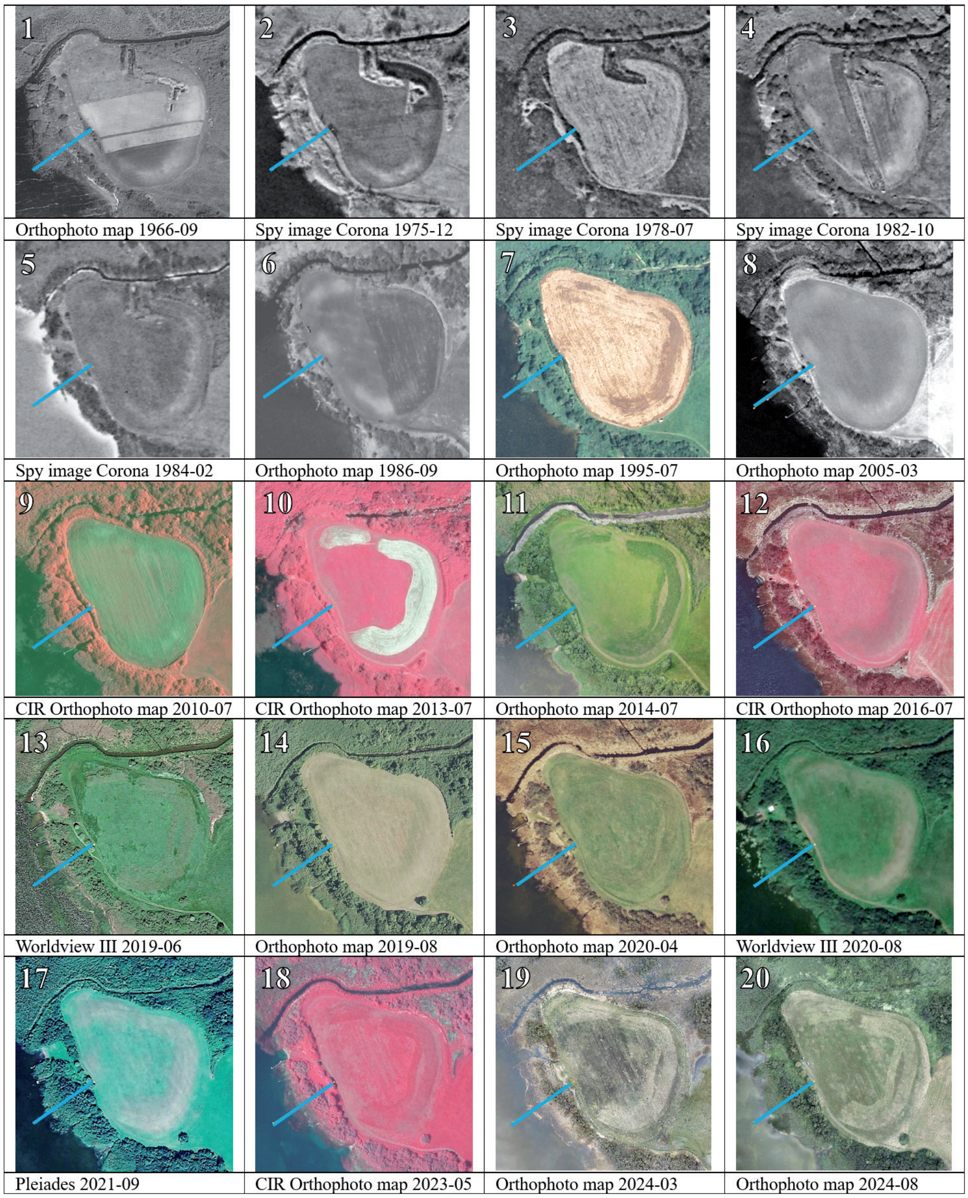

Fig. 12 - Smuszewo, site 3 (Late Bronze Age/Early Iron Age fortified settlement) in aerial and satellite images 1966-2024 (source: USGS – 2-6, GUGiK – 1, 7-10, 12-15, Google Earth – 13, 16, 17; authors' acquisition – 11, 19, 20). The bright blue line effectively demonstrates the fluctuations in shoreline vegetation extent

in the area occupied by shrubs in the lake's shoreline zone.

Additionally, they show seasonal changes in the extent and expansion of wetlands around the site. Areas prone to periodic flooding, revealed during periods of increased precipitation and enhanced underground retention, are particularly identified in the northern and eastern zones. Changes related to vegetation encroachment along the shoreline are also visible, with aquatic vegetation dominating in shallow zones. The rate of sediment deposition, combined with the increase in areas occupied by vegetation, has accelerated the filling of the lake bottom, transforming open water zones into wetlands or peatlands.

Anthropopression

Among the anthropogenic factors significantly influencing the transformation of the topography and hydrography of the study area, land use changes and drainage works related mainly to agricultural land use should be highlighted.

The analysis of source materials showed changes in land use around Czeszewo Lake over approximately 200 years. A clear increase in the area designated for arable fields at the expense of meadow and wetland areas can be observed (Fig. 13; Table 4). The significant percentage of arable land in 1830 and the absence of wetlands result from the limitations of the measurement technologies available at that time and the cartographic model used in the Urmesstischblätter map. This also contributed to the inaccuracies in the analysis of land cover changes for the period 1830-1889.

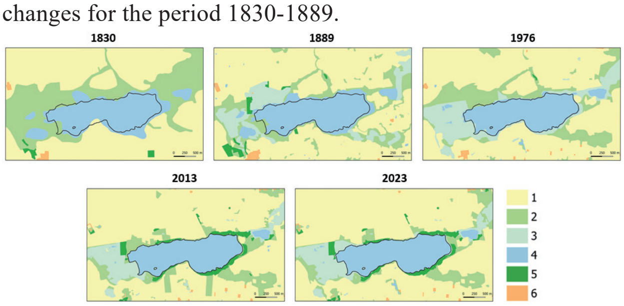

Fig. 13 - Changes in land cover in the surroundings of the fortified site and Czeszewo Lake in selected time sequences (1830–2023). Legend: 1) arable & other land (AL), 2) meadows & grassland (MG), 3) wetlands (WL), 4) surface waters (SW), 5) woodland (W&F), 6) built-up areas (BA). The extent of the lake according to aPGW (Shoreline of Czeszewo Lake according to the Water Management Plan (2023, https:// apgw.gov.pl/pl/III-cykl-informacje-ogolne, accessed 17/02/2025))

No	Land-cover forms	1830	1889	1976	2013	2023
1	Arable & other land (AL)	54.7	58.2	58.6	63.9	64.6
2	Meadows & grassland (MG)	25.7	12.5	14.3	11.7	9.4
3	Wetlands (WL)		9.6	11.4	7.0	8.2
4	Surface waters (SW)	18.6	17.6	15.0	14.1	14.2
5	Woodland (W&F)	0.5	1.4	0.1	2.8	3.1
6	Built-up areas (BA)	0.5	0.7	0.6	0.4	0.4

Tab. 4 - Land cover changes from 1830 to 2023 based on historical topographic maps and contemporary databases [% area]

The transformation of surrounding wetlands into arable fields changed the natural water retention conditions and increased surface runoff into the lake, accelerating sediment deposition. Noteworthy are the forms of destruction in the ribbon lake and kettle holes as a result of anthropogenic landscape changes around the lake. These include peat extraction pits and excavations created during the construction of drainage ditches. The process of draining water from the lake began no later than the 1830s and 1840s (Libelt, 1870-1871), which aimed to transform its floodplain into meadows and pastures and enable peat extraction. The high groundwater level and the presence of wetlands increase the risk of soil instability. Peat soils and water-saturated soils around the lake may undergo local subsidence, especially where drainage systems disrupt the natural hydrological balance. The historical reduction in the lake's area and the transformation of wetlands for agricultural purposes contributed to increased soil destabilization in these areas, as dried organic soils compacted and lost their natural structure.

A significant impact on Czeszewo Lake, which is a flow-through lake, was the regulation of flow leading to the creation of the Wapno–Laskownica Canal, flowing out in the Srebrna Góra area, east of the village of Wapno (see Fig. 9). The canal was used to discharge post-exploitation waters from the salt mine in Wapno. Throughout its (1911-1977), water from its drainage was discharged via the Wapno-Laskownica Canal into Czeszewo Lake and further, through the Gołaniecka Stream, into the Wełna River. After the mining disaster in 1977, the pumping of mine waters was stopped. The interruption in the inflow of saline mine waters to the lake lasted until August 20, 1987 (excluding a short period from June 19 to July 11, 1984). After this date, mine waters began to replenish the canal waters and, consequently, Czeszewo Lake again. Highly polluted and highly mineralized waters were discharged from the sedimentation tank through a sluice, with varying intensity depending on the intensity of mine water pumping into the Wapno-Laskownica Canal.

The eastern shore of Czeszewo Lake is also an area used by the local population for fishing (this is also the zone where wooden construction remains were found) (Fig. 2 & Fig. 12). This leads to legal (with the consent of the relevant water administration) or illegal reed cutting and the construction of piers or boat launching sites.

Drainage ditches and canals and the transformation of land use for agricultural purposes have changed the water relations in this region and affected the water quality of Czeszewo Lake. The monitoring of lake water quality, conducted in 2024 in conjunction with historical data on the physicochemical properties of the waters, provided information on the anthropogenic pressure on the lake ecosystem and their potential impact on the preservation of wooden archaeological relics. Czeszewo Lake is significantly influenced by the catchment area on the water quality status (JCWP Czeszewo Lake Card: https:// wody.isok.gov.pl/pdf/JCW/LW10215.pdf) and is particularly susceptible to surface runoff of pollutants from agricultural areas and the inflow of municipal sewage from scattered rural settlements and improperly managed sewage systems.

Indicators determining the water quality status of the lake include total nitrogen as a primary nutrient and conductivity, which in most measurements were below good status (RMI, 2021). To a lesser extent, the lake waters are burdened with phosphorus, whose elevated levels may indicate the inflow of municipal (domestic) sewage. The increase in total nitrogen concentrations in Czeszewo Lake waters even above 5.0 mg N/l (with a total nitrogen norm of ≤2.0 mg N/l for this type of lake) is observed especially in spring and early summer, suggesting that the main source is the inflow of agricultural pollutants into the lake (nitrogen fertilizers), increasing the nutrient load in the waters. The expansion of agricultural land at the expense of wetlands and natural buffer zones has intensified erosion and sediment transport into the lake, which may have contributed to increased organic matter accumulation.

The lake exhibits high values of specific conductance (SPC) above 800-900 μS/cm, suggesting increased water mineralization, i.e., the degree of salinity. SPC values above 1000 μS/cm (1021 μS/cm on May 22nd, 2024) were also recorded, likely indicating anthropogenic water pollution. High conductivity was also determined for the waters of the Wapno–Laskownica Canal (above 1300 μS/cm on January 5th, 2024), which may indicate the continuous supply of mineralized waters through the inflow to the lake.

The entire JCWP Czeszewo Lake catchment area is sensitive to eutrophication caused by pollution from municipal sources, understood as the enrichment of waters with nutrients, particularly nitrogen or phosphorus compounds. This can cause accelerated algae growth, resulting in undesirable disturbances in the biological relationships in the aquatic environment and deterioration of water quality. On the other hand, an important feature of the lake is the high intensity of water exchange, which can limit the accumulation of nutrients (Szybowski & Tonder, 1989). Anthropogenic influences on Czeszewo Lake, primarily agriculture, sewage discharge, and land use changes, significantly affect water chemistry.

DISCUSSION

Identification of the main natural and anthropogenic phenomena and processes in the Smuszewo area allows for a critical reflection on their role, especially in the context of observed climate changes, in the emerging threat to archaeological relics. The complexity of these factors requires an assessment of both their dynamics and significance (Howard, 2012), as well as their interrelationships at various time and spatial scales: from the landscape level, through the catchment area and the immediate lake basin, to the level of the archaeological site itself and relics, which are located in the aquatic environment. In addition to relatively stable environmental components, dynamic factors play an important role. Direct effects should be distinguished – those that have an immediate or primary impact on the state of preservation of relics, and indirect mechanisms that connect primary factors with final effects, often through a series of interactions and feedbacks (Sesana *et alii*, 2020). This allows for a better connection between the scale of threats to archaeological site and the mechanisms of impact.

Vulnerability model

Among the discussed factors, we can distinguish those that are relatively stable and those that are much more dynamic (Fig. 14). The model reflects the complex relationships between climatic factors, environment and anthropogenic pressure, and their ultimate impact on the preservation of

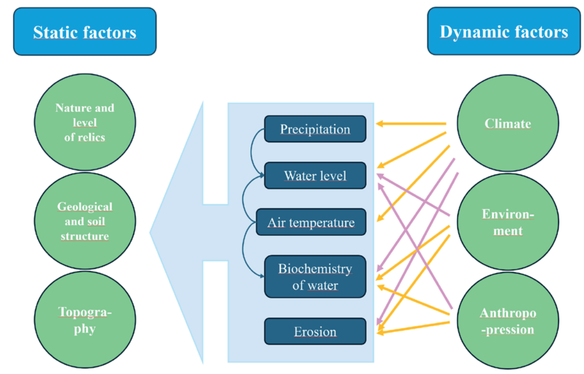

Fig. 14 - A simplified model of vulnerability to threats in the Smuszewo site 3 area

organic (incl. wooden) archaeological relics. It is therefore a basis for discussing the processes occurring in the area of the archaeological site and the possibilities of monitoring them.

The identification of contexts and processes occurring in the vicinity of the archaeological site indicates that hydrological factors play a key role, especially the water level in the lake and probably its biochemical characteristics. Hydrological factors are significantly conditioned by climate variability, human activity, and the environmental context. In particular, climate and human activity are characterized by high dynamics. Quasi - stable factors can be considered the level of archaeological relics, geological (lithological) structure, and terrain morphology.

Postglacial features of the studied area, including the presence of moraine uplands, erosional slopes, and zones of organic deposits, allow for the assessment of the long-term stability of the relics' region. Geological (nature of the formations building the area) and soil conditions confirm the predominance of glacial tills around the settlement and soils rich in organic substances, which contribute to maintaining the structural integrity of the relics in the subsurface zone and retaining moisture during periods of lowered lake water levels. Clay soils are not as susceptible to drought as organic soils.

The preserved ribbon lake system forms the morphological framework for the Czeszewo Lake basin, while historically, water level changes in the ribbon were shaped by both the activity and retreat of the ice sheet and Holocene climate changes, as well as later modifications related to human activity. The fundamental topographical features (particularly forms built of glacial tills) influence the catchment characteristics and have not undergone significant changes since the early 19th century despite agricultural activities.

Dynamic variables related to climate in the studied case refer to the recorded increase in air temperature, especially since the 1980s, and changing precipitation patterns, intensifying extreme hydrological phenomena, which affect lake water level fluctuations and soil stability. These factors modify the water balance of Czeszewo Lake, directly impacting the preservation conditions of organic archaeological remains. Increased frequency of droughts and intense rainfall increases the risk of erosion (though not in the immediate vicinity of the site and mainly on sandy soil surfaces) and sediment displacement.

The increase in air temperature correlates with the increase in water temperature (Fig. 15) which in turn affects the decomposition of oxygen and the rate of oxidation processes, which can accelerate the degradation of organic materials. The biochemical properties of water are crucial for maintaining the life processes of aquatic organisms and preserving organic materials (incl. wood). Therefore, changes in the chemical composition of lake water, caused by, for example, climate warming or pollution (agricultural and industrial pollution) can lead to a faster loss of integrity of the wooden structures of the settlement in Smuszewo and accelerate their degradation.

Regarding the observed water level in the lake, the seasonal variability of both precipitation and air temperature is also significant. Increased autumn and winter precipitation can positively affect groundwater replenishment and the preservation of wooden remains in moist layers. A decrease in summer precipitation totals along with rising air temperatures can lead to prolonged drought periods, negatively impacting the water balance and lake water level.

Water level fluctuations indirectly change soil physical properties, potentially leading to subsidence, especially in peaty soils. This results in densification and lowering of ground surface levels (Egglesmann, 1984; Reddy 2006; Grzywna, 2017). Including Copernicus EGMS data (https://egms.land.copernicus.eu/) could substantiate these deductions and help frame future scenarios involving relative water level rise. Given the organic, compressible soils identified around the Smuszewo site, also satellite-based interferometry (InSAR) could provide additional valuable data on surface deformations. Similar techniques have proven effective in identifying potential instability in heritage-rich urban areas (Palamidessi *et alii*, 2024).

However, the direct use of European Earth Monitoring Service (EGMS) data appears to be limited in case of Smuszewo site. EGMS products are based on radar interferometry (DinSAR), which requires stable reflecting points, generally located in area with buildings, bridges, other anthropogenic structures, or natural like bare rocks (mountains). In the area surrounding Smuszewo site there are no measurement points in the EGMS

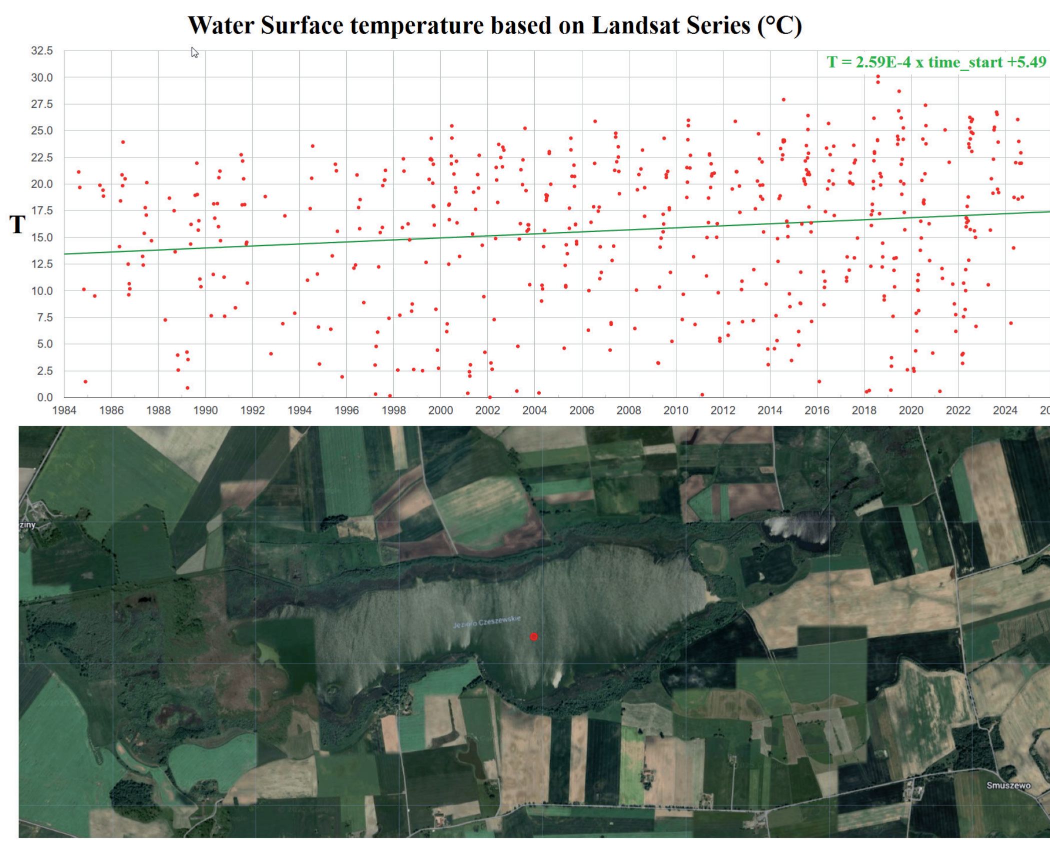

Fig. 15 - Water surface temperature at a selected point (red) in the area of greatest depth of Czeszewo Lake, in the period 1984-2025 based on Landsat imagery (series 4, 5, 7, 8, 9; data from Collection 2, Level 2, Tier 1), thermal channel. The graph contains a total of 561 cases including cases of cloudless sky (without temperatures beneath 0°C). Data processed in Google Earth Engine environment

service for agricultural areas, peat bogs, forest areas, bushes, etc. The measurement points cover only built-up areas or roads. Therefore, there is no information on natural surfaces to be able to conclude on vertical and horizontal ground movements (for example detail soil types like peat, muck or lessive soils) in the immediate vicinity of the Smuszewo site. The site itself consists of stable earth fortifications on the surface, which are covered with grass (currently mown once or twice a year), and the overall character of this surface therefore changes in a natural cycle. Despite this, this surface is not suitable as a measuring point for interferometric analyses, which is additionally confirmed by a literature review (Crossett *et alii*, 2025) discussing, among others, application of EGMS in archaeology.

Anthropogenic activity has marked the study area, especially in terms of land use (Table 4). Historical and ongoing land use changes are related to agricultural development (cultivation of arable land, use of grasslands), drainage (area drainage), and peat extraction. Factors related to the agricultural function development of the area disrupt the natural water cycle and can intensify erosion and sedimentation processes. Drainage and peat extraction activities modify the natural conditions of water flow and have a direct effect on lowering the groundwater level. As a result, surface runoff usually increases, which promotes the intensification of the transport of sedimentary material to the lake basin. Increased sedimentation leads to its shallowing and hydrological instability, which has an indirect effect on the preservation of wooden relics. The transformation of wetlands into agricultural land also changed the soil's retention capacity and seasonal and long-term vegetation changes affect soil stability and modify sedimentation conditions.

Changes in land cover can contribute to the protection of the site. Observing contemporary land use changes and the closure of the salt mine in Wapno has stabilized these factors for now. For several years, agricultural activities causing soil disturbance have ceased in the site area, stabilizing conditions and reducing the negative impact of agricultural practices.

Risk assessment

In assessing the risk to the preservation of archaeological relics at site 3 in Smuszewo, four main areas can be identified where changes may have a crucial impact. These are: 1) climate dynamics (mainly temperature increase and uneven, seasonal precipitation distribution), 2) the related hydrological situation, 3) lithology and terrain morphology, and 4) contemporary anthropogenic pressure related to land use and pollution production.

The results of estimates based on various climate models indicate significant variability in the direction and intensity of projected changes in precipitation and air temperature in the coming years (Milly *et alii*, 2005; Dankers & Feyen, 2008; Raport, 2020). These will mainly concern the temporal distribution of precipitation, with slight changes in annual average values and changes in the structure and nature of precipitation. Snowfall may be replaced by rainfall, and in the warm season, there may be an increase in the share of more intense and shorter, heavy rainfall (IPCC, 2018). Increasingly frequent and prolonged hydrological droughts are expected, which may contribute to a decrease in water retention in Czeszewo Lake and deepen unfavorable seasonal and multi-year water balance components, as well as more frequent soil droughts and groundwater low flows. On the other hand, an increase in flood frequency is projected, resulting from the increased rate and intensity of hydrological processes, known as the intensification of the hydrological cycle (Gutry-Korycka & Jokiel, 2017). Projections of water resource evolution in Poland and the Smuszewo archaeological site area emphasize that unfavorable trends in hydrological conditions are revealed both as a result of climate change and increasing anthropogenic pressure.

A decrease in summer precipitation totals (see Fig. 14), combined with rising air temperatures, may affect increased evaporation and thus change the water balance, not only of Czeszewo Lake but also of the entire catchment area. Prolonged heat periods simultaneously increase the frequency of extreme hydrological phenomena related to water resource shortages (e.g., drought), and indirectly also the risk of archaeological material degradation. Successive lowering of the lake water level may contribute to increased material exposure, thus accelerating the destruction of wooden structures. On the other hand, increased autumn-winter precipitation positively affects the preservation of wooden settlement relics but may lead to increased surface runoff intensity and erosion phenomena on the shores of Czeszewo Lake. Changes in winter precipitation structure may alter the duration of the lake's ice cover, affecting sedimentation rates and shoreline stability. However, the limitation of multi-year hydrological data for Czeszewo Lake, may affect the interpretation of water balance components and analysis results obtained for shorter measurement series. Matteotti (2009) analyzed the hydrological error in the analysis of the lake mass balance, using the example of Emerald Lake (California, USA). He showed that the accuracy of input data (including precipitation, evaporation, and underground runoff) is crucial for assessing the lake's water balance. The presented methodology allows for estimating the error level with limited data availability - which can be very useful in the context of Czeszewo Lake, where there are also gaps in hydrological measurements.

Assessing the probability and intensity of events identified as threats in the Smuszewo site area in the past was possible through the integration of historical data sets, satellite images, and direct monitoring results. Historical landscape changes, illustrated on comparative maps from the 19^{th} century to the present, reveal significant transformations in the lake's morphology and surrounding wetlands. They highlight the reduction in the lake's extent and local water drainage zones, as well as the expansion of agricultural land.

Comparing land cover forms on maps from 1889 and 1976 showed the process of intense shoreline vegetation growth and the disappearance of water bodies associated with earlier peat extraction in the western part of the ribbon lake (Fig. 16). This was caused by water eutrophication and the lowering of the lake water level. This process continued from 1976 to 2013, resulting in the formation of a forest-reed zone along parts of the southern and northeastern lake shore. This contributed to the specific protection of the reservoir from pollution and significant shoreline areas from abrasion and erosion.

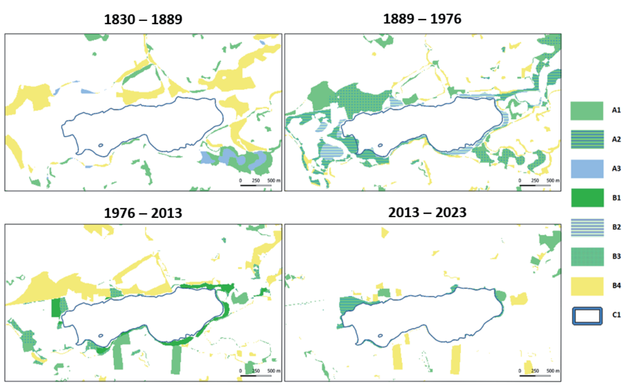

Fig. 16 - Directions of land cover changes in selected time periods. Legend: A – Transformations primarily caused by rising water levels: A1 – from arable land to meadows and grassland, A2 – from meadows and grassland to wetlands, A3 – from arable land to wetlands; B – Transformations primarily caused by land drainage and the introduction of agricultural and forestry management: B1 – afforestation of arable land, B2 – expansion of vegetation into surface water areas, B3 – drainage of meadows and grassland, B4 – transformation of meadows and grassland into arable land; C1 – Shoreline of Czeszewo Lake according to the Water Management Plan (2023, https://apgw.gov.pl/pl/III-cykl-informacje-ogolne, accessed 17.02.2025)

A multidimensional threat analysis, considering various factors and risk levels, enabled the determination of their interrelationships and impact on the site in Smuszewo. The integrated risk profile developed as a result of the analyses synthesizes the interactions of natural and human-induced factors. The integration of geological, hydrological, and archaeological variables into a coherent vulnerability model aligns with recent engineering-geological approaches to sites preservation, which advocates the use of stratified data sources for spatial risk evaluation (Feliziani *et alii*, 2024). The use of integrated vulnerability and risk assessment modeling (multilayer environmental model) is an important tool for developing strategies for the protection of archaeological sites. The analysis of threats of site in Smuszewo from a historical and contemporary perspective allows for the comparison of integrated risk models (Fig. 17). In the historical version (Past), threats related to land use dominate (e.g. development of agriculture and drainage systems, peat extraction), which also resulted in disruption of hydrological conditions (changes in runoff and water level in the lake). The impact of climate was relatively lower, which reflects lower risk in these categories. In the contemporary model (Modern), there was a significant change in the distribution of risk. Climatic and hydrological risks increased due to rising air temperatures, intensified precipitation and an increase in the frequency of extreme phenomena (droughts, floods). Pressure related to land use decreased due to the halt in the expansion of agriculture and the withdrawal of mining activities. This comparison illustrates the shift in the focus from anthropogenic pressure to growing climatic and hydrological threats.

Current understanding of the issues related to climate change and their impact on contemporary living and economic conditions has led to a significant reduction in activities that threaten the preservation of archaeological relics. This includes peat extraction, the expansion of drainage systems, and mining operations. On the contrary, there is a noticeable trend towards preserving and even restoring wetland environments. There is also no longer any space for expanding arable land areas (Fig. 16). Despite some stabilization related to geology and spatial development, the overall risk in the contemporary perspective shows greater intensity and a greater range between categories, which emphasizes the need for multi-level monitoring and adaptation strategies. The presented model allows for a better understanding of the mechanisms of direct and indirect impacts and their impact on the durability and protection of cultural heritage, in line with the recommendations of the systemic approach to risk assessment in the heritage environment.

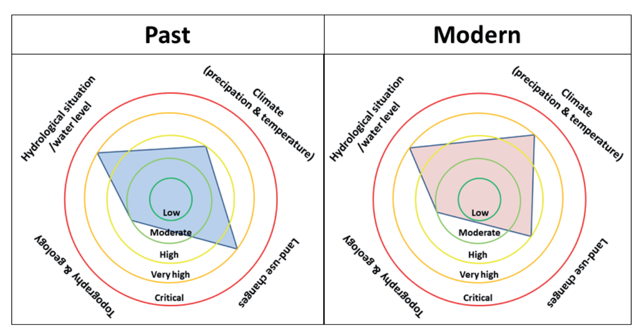

Fig. 17 - Integrated risk models taking into account threats to archaeological relics in Smuszewo from a historical and contemporary perspective

CONCLUSIONS

The developed risk profiles (Fig. 17) show how changes in land use (landscape dimension), hydrological changes (catchment dimension), climate, and lithological conditions collectively affect the overall level of threats to a specific archaeological site, as well as the entire region. For the Smuszewo site, they also identify high-priority areas for monitoring and intervention, such as the southern edges of the Czeszewo Lake ribbon lake with higher erosion rates and northern areas facing water retention challenges.

In the risk assessment of the archaeological site, various levels of data analysis were considered: 1) in the immediate vicinity of the archaeological site, 2) in the river and lake catchment area, and 3) landscape level. These allowed for identifying the main trends in both historical and contemporary dimensions. This does not mean that all aspects have been resolved and discussed. For example, the fundamental assumption about the importance of the lake water level for the preservation of archaeological relics requires a more thorough examination of their preservation state and burial level. This requires additional geophysical research. Additionally, indicating the importance of seasonal precipitation does not yet resolve the issue of the impact of short-term intense rainfall. It is necessary, on the one hand, to monitor the situation and, on the other hand, to model the runoff rate in the catchment under given conditions.

The TRIQUETRA project has allowed for the formulation of entirely new research and conservation questions and attempts to address the challenges will lead to the formulation of further questions. Future research should focus on improving mapping methodology to increase the accuracy of vulnerability assessments and risk modeling. The current study established preliminary frameworks for overlaying vulnerability zones on potential threat areas, providing insights into spatial risk patterns. The thematic risk profiles generated in this study offer a visualization of multifaceted threats, combining climatic and anthropogenic influences. Further integration of high-resolution remote sensing data, long-term monitoring, and predictive modeling may be necessary to improve risk assessment and develop targeted protection strategies for lakeshore archaeological sites like in Smuszewo and its surrounding environment.

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