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Topographic Differencing for Determining Reservoir Sedimentation Using Archival Cartographic Materials and Modern Measurement Methods

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Abstract: The aim of the study was to assess the sedimentation of the Klimkówka reservoir using topographic differencing (TD) analysis of digital elevation models (DEMs) created for two periods: before the reservoir was filled and after 30 years of operation. The archival model was developed from a scanned and calibrated analogue large-scale (1:5,000) topographic map with contour lines and elevation points. The current model was obtained by integrating unmanned aerial vehicle (UAV) photogrammetry and bathymetric measurements with a GNSS-positioned dual-frequency echo sounder. The accuracy of both models was analysed in detail, taking into account cartographic errors, map shrinkage, the scanning and calibration process, and the heterogeneous accuracy of the archival elevation data. Based on the DEM difference, the estimated sedimentation volume was considered unreliable. A detailed analysis of selected cross-sections revealed local accumulation processes in the backwater zone and slope erosion, but did not permit a reliable assessment of the siltation of the entire reservoir. The authors conclude that the reliable application of the TD method requires comparing two models produced with similarly high accuracy (e.g. UAV + bathymetry), while analogue cartographic materials from the 1970s do not meet current accuracy requirements for this type of analysis.

Keywords: reservoir basin, dam, bathymetry, digital elevation model (DEM), UAV photogrammetry, archival cartographic data, measurement errors, alluvial accumulation, sedimentation

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1. Introduction

Sedimentation of a reservoir basin refers to the process of deposition and accumulation of solid material (sediment and debris) carried by the river in the reservoir basin, i.e. the area above the dam that is flooded with water [1]. These materials settle gradually, starting from the backwater area at the reservoir inlet [2], then progressing towards the dam along the reservoir bottom, reducing the reservoir's usable capacity and affecting its hydrological and operational properties [3].

Sedimentation in a reservoir basin is a natural ageing process associated with the accumulation of various types of materials, such as sand, silt, gravel, and other river sediments [4]. Over time, these sediments can reduce reservoir capacity, which necessitates monitoring and appropriate maintenance measures [5]. The deposited material varies in density and grain size [6, 7], which affects the sediment distribution in the reservoir. The greatest accumulation of sediments usually occurs in the upper part of the reservoir and at the inflow points of watercourses [8].

The reservoir basin is the area above the dam that stores water. Depending on the reservoir type, the basin may be permanently filled with water or flooded during periods of high water and rainfall. For dam safety, proper management of the basin is essential, including monitoring sediment levels and preventing debris deposition at the bottom outlets to prevent blockages and loss of reservoir efficiency [9]. Siltation of a reservoir is a layer of sediment and solid materials (debris) accumulated at the bottom of the reservoir basin, carried by inflowing water. In practice, it refers to excessive accumulation of debris and sediment, creating a more or less continuous layer at the bottom of the basin. This requires long-term monitoring and, if necessary, hydraulic engineering works to maintain the reservoir's retention capacity and safety [10].

Hydrotechnical works carried out to maintain a reservoir's retention capacity and safety include deepening the reservoir bottom by removing silt deposits and debris from the reservoir basin, restoring its usable capacity, and preventing further silting.

Methods for determining reservoir sedimentation can be divided into two main groups: direct methods and predictive methods [11].

Direct methods for determining sedimentation in a reservoir basin involve physical measurements and assessments of the distribution of sediments deposited and accumulated in the reservoir. These methods are based on measuring the depth and thickness of sediments at the reservoir bottom, usually using rod probes driven into the sediment to determine the thickness of the accumulated layer. Measurements are taken from a boat at specific cross-sections or points across various parts of the reservoir basin, with a geodetic spatial reference, enabling precise determination of the sediment location [12]. In addition, samples of sediments in a quasi-intact state are taken using specialised probes, which allow the determination of the sediments' volumetric density and other physical properties [13]. Some methods also use hydroacoustic techniques, such as sonar, to map the reservoir bottom and sediments without direct contact. These methods allow the direct determination of the degree of siltation and sedimentation in the reservoir basin, which provides the basis for further analysis and forecasting of the sedimentation process and for undertaking maintenance measures.

Hydroacoustic techniques for mapping the bottom of a reservoir involve using ultrasonic echo sounders and sonars to transmit sound waves to the bottom. These waves reflect off the bottom and return to the measuring device, allowing the determination of the depth and shape of the bottom with an accuracy of a few centimetres [14].

Measurements are taken from a vessel whose position is precisely determined in real time by a GPS system (e.g., GPS-RTK), enabling accurate mapping of measurement points [15].

The data collected by hydroacoustic devices is then processed and analysed by a computer, enabling the creation of detailed bathymetric maps that show the bottom topography, sediment distribution, and other morphological features of the reservoir. These techniques enable rapid and non-invasive bottom surveys, which are essential for monitoring the reservoir's condition and planning hydrotechnical works to maintain its retention capacity and safety.

Predictive methods use mathematical and empirical models based on the sediment transport rate entering the reservoir [16, 17]. Empirical methods include the Modified Universal Soil Loss Equation [18, 19] or the Monovariate Rating Curve [20].

Forecasts use catchment physiographic parameters and reservoir sediment retention rates. Analogy methods and hydrodynamic modelling can also be used to assess the sediment discharge process.

The described direct methods are complemented by an approach that analyses changes in reservoir bottom shape over time, resulting from sedimentation. Changes in reservoir basin sedimentation are directly related to changes in bottom morphology. Therefore, they can be identified by comparing precise bathymetric models constructed at different points of the reservoir's operation. With reliable bathymetric data from the beginning of the reservoir's operation and from the end of the analysed long-term period, it is possible to determine bottom elevation differences and then determine the volume of accumulated sediments [21, 22]. These methods, based on the analysis of differences in digital bottom models, known as topographic differencing (TD), are commonly used in studies of changes in the morphology of river beds and water reservoirs. They enable a quantitative assessment of the intensity of the siltation process as a function of time without the need for point sampling of sediments [23, 24]. This approach is only possible when older, high-quality data on reservoir bottom shape are available. Examples of the use of archival cartographic materials to determine TD can be found in the international literature [25]. This approach allows the sedimentation process in a reservoir to be determined over a longer period. However, this approach causes numerous problems in the statistically significant assessment of the sedimentation volume because of the quality of the archival data [21, 25]. In this study, an analogous approach was adopted to determine the process of sedimentation in the Klimkówka reservoir, using archival cartographic materials and current geodetic and bathymetric measurements.

2. Materials and Methods

2.1. Research Area

In Poland, there are approximately 100 large storage reservoirs [26] with a capacity exceeding 1,000,000 m^3, and over 4,000 artificial reservoirs used for retention, energy, and recreational purposes, the largest of which are Włocławek Lake and Solina Lake. One of these is the Klimkówka reservoir on the Ropa River.

The Klimkówka retention reservoir is located in the southern part of Poland, in the Beskid Niski Mountains range, 54.4 km along the course of the Ropa River (a left-bank tributary of the Wisłoka River). Its total capacity is 42.53 million m^3, and its surface area at the maximum water level of 398.77 m above sea level exceeds 3 km^2. It is 6.5 km long, 300–800 m wide, and up to 31 m deep (average depth: 13 m). The dam's crest is approximately 210 m long and 37 m high (Fig. 1). The main purpose of the reservoir is to equalise the low flows of the Ropa River in order to reduce drinking and industrial water shortages in Gorlice and Jasło, and to lower flood peaks [27]. In addition, the reservoir is used for energy production, with a small 1.1-MW peak-power plant located next to the dam. It also serves a recreational function. Construction of the reservoir began in the 1970s, and it was commissioned in 1994 [28].

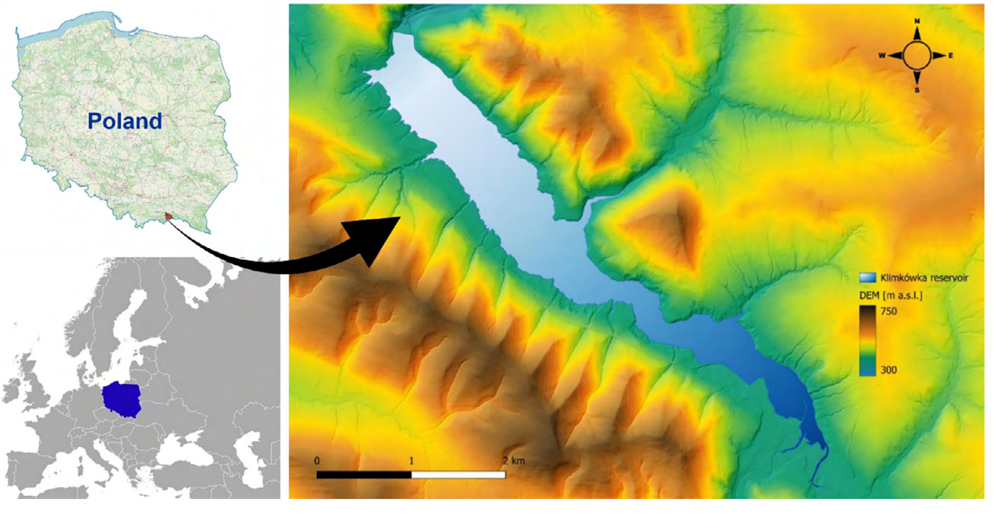

Fig. 1. Terrain of the Klimkówka reservoir basin and its location

Source: own work based on data from geoportal.gov.pl

Given the reservoir's main purpose, during periods of water shortage or hydrological drought it is emptied, which allows direct geodetic measurements of the reservoir basin to be carried out with the highest possible accuracy.

The aim of this study was to assess sedimentation in the Klimkówka reservoir basin. The assessment was based on a comparison of two digital elevation models (DEMs): one for the period before the reservoir was filled, using 1970s data, and the other for 2024, i.e., 30 years after its commissioning.

2.2. Characteristics of Archival Data and Its Processing

In Poland, the collection and dissemination of base maps are carried out within the framework of the state geodetic and cartographic resource, which is managed at the district level by District Centres for Geodetic and Cartographic Documentation. These centres archive data, issue paid copies of maps, and ensure their updating in accordance with the Regulation of the Minister of Development of 2023 [29] based on the BDOT500, GESUT, and EGiB databases. The Centre responsible for the study area is the District Centre for Geodetic and Cartographic Documentation in Gorlice.

Documentation concerning the reservoir basin is collected by the State Water Holding Polish Waters (Państwowe Gospodarstwo Wodne Wody Polskie), which manages reservoirs and maintains their technical documentation, including records of renovation and reservoir condition assessments. This documentation usually includes bathymetric measurements, siltation analyses, modernisation projects, and is stored at the Catchment Area Management Boards or Regional Water Management Boards (Regionalne Zarządy Gospodarki Wodnej – RZGW), depending on the reservoir's location. The Klimkówka reservoir analysed in this paper falls under the authority of the Regional Water Management Board in Rzeszów (RZGW Rzeszów), which granted the authors written consent to access archival cartographic materials held by the reservoir manager.

The Klimkówka reservoir flood area can be divided into two parts: the planned dam site and its immediate surroundings, and the remaining reservoir basin area. While the dam area is covered by 1:2,000 or 1:1,000 scale maps with relatively accurate detail and terrain representation for the relevant period, less detailed documentation is available for the remaining reservoir basin area. The documentation provided included analogue cartographic studies in the form of Ozalid prints:

- a topographic map covering the reservoir area at a scale of 1:5,000 (Fig. 2);
- a topographic map covering the part of the reservoir basin area near the dam at a scale of 1:2,000;
- longitudinal profiles of the Ropa and Zdynia rivers at a scale of 1:100/5,000;
- cross-sections of the Ropa and Zdynia riverbeds at a scale of 1:100/1,000.

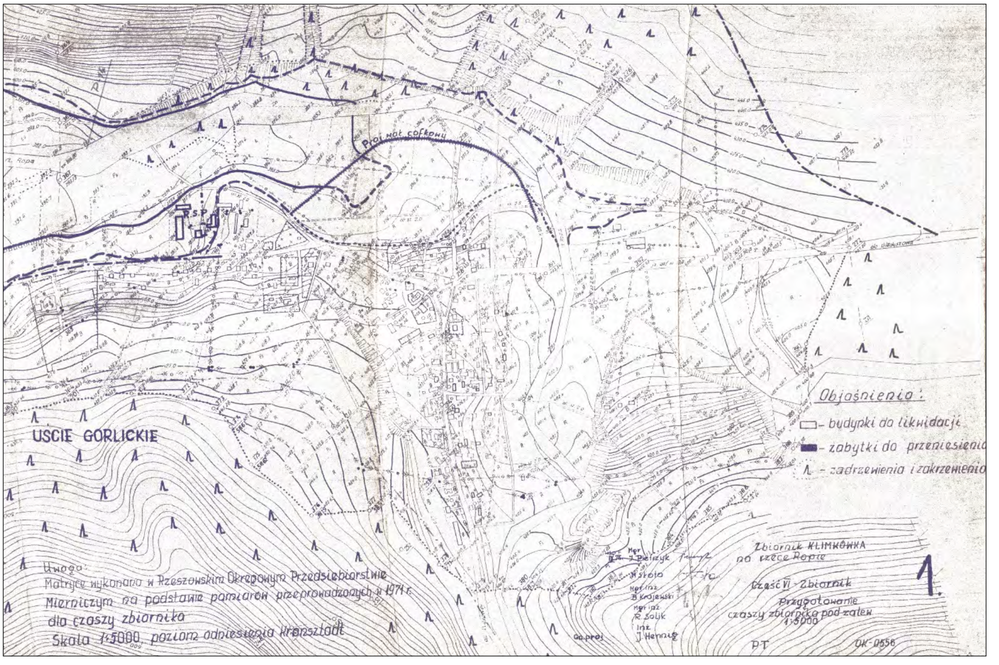

Fig. 2. Fragment of an archival topographic map of the Klimkówka reservoir area, developed at a scale of 1:5,000 in the 1970s

Source: Hydroprojekt Company, prepared in September 1976, based on the conditions in 1971

Topographic maps from the 1970s are of very poor quality by modern standards. Technical reports state that these materials were developed based on maps prepared in 1971. The scale of these maps (1:5,000) prevents the interpretation of terrain details with the highest possible accuracy using current technologies. According to the then-current standards, summarised in technical instructions 0-1 and 0-2 [30, 31], the XY position error of accuracy group I points should not exceed 0.5 mm for most terrain and 0.7 mm for covered and mountainous areas. Position errors of group I terrain details for a 1:5,000 map range from 2.5 to 3.5 m. Elevation points and terrain features belong to accuracy group III. Their position, determined with an accuracy of 1 mm on the map scale, represents an error of 5 m in reality. Such a situational error within the reservoir basin, where the terrain slopes reach 100%, increases the errors in elevation readings. An additional problem is that the analysed map is available in analogue form and has been subject to deformation in the form of shrinkage over a period of 50 years. All of the above-mentioned maps were prepared as single-item maps without coordinate grids, which prevents accurate map calibration. An additional difficulty is the limited possibility of selecting adjustment points due to the fact that a large part of the area shown on the maps is currently underwater or covered with tall vegetation. The contour interval on archival materials varies. Most of the area currently underwater is shown on contour lines with an interval of 1 m, while areas near the reservoir boundary are shown by contour lines at 5 m intervals. The technical regulations in force in Poland at that time [30, 31] specified the height accuracy of contour maps in such areas with an inclination above 2° as a permissible error of 2/3 to 1 contour interval.

The matrix of the analysed archival topographic map of the Klimkówka reservoir area at a scale of 1:5,000 was prepared by the Rzeszów District Surveying Company based on measurements carried out in 1971. The Kronstadt 60 reference level was adopted in the study.

The base maps obtained from the archives of the District Centre for Geodetic and Cartographic Documentation (Powiatowy Ośrodek Dokumentacji Geodezyjnej i Kartograficznej – PODGiK) in Gorlice were prepared at a scale of 1:2,000 with a coordinate grid. Unfortunately, they cover only part of the reservoir area. A thorough analysis of these maps (Fig. 3) revealed that the elevation data were transferred from 1:10,000 site plans. Despite their different forms and larger scale, the accuracy of these maps is similar to or lower than that of the maps held by the dam administrator, as they were created by rescaling from a smaller to a larger scale.

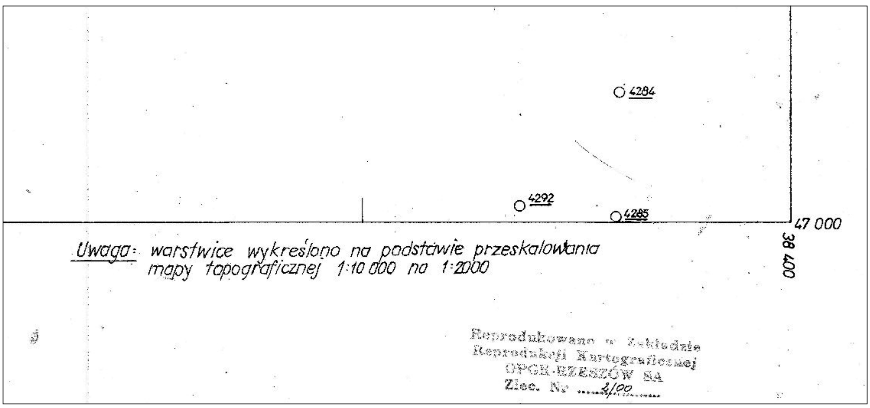

Fig. 3. Annotation on a fragment of the base map of the Klimkówka reservoir area from 1980 regarding the rescaling of the map

Source: scanned materials from the District Centre for Geodetic and Cartographic Documentation (PODGiK) Gorlice

The quality of the available archival 1:100/1,000 scale cross-sections of the terrain, taken before the reservoir flooding, also raised doubts about their usability, even though they were based on direct field measurements. Their technical value is high; however, the location of the cross-section lines is defined solely by river distance, which prevents precise reconstruction in the field. The terrain elevations shown in the cross-sections based on geodetic field measurements did not match those on the 1:5,000 scale topographic map. This made it impossible to use them for the present study.

Aware of the limitations described above, a 1:5,000-scale topographic map was used as the basis for developing the initial DEM. This map was scanned and then calibrated using the polynomial method. A significant challenge during calibration was finding the appropriate control points. Most of the land development elements shown on the archival maps no longer exist, either because they were removed during preparatory work for the reservoir basin or because they are located underwater. The reservoir is dominated by agricultural and forested areas, which lack class I control features (in accordance with regulations in force in Poland [32]) and are characterised by the determination of their positions relative to the points of the horizontal geodetic grid, with an accuracy of not less than 0.1 m.

The low water level in the Klimkówka reservoir in 2024 (Fig. 4) resulted from a hydrological drought that created problems with maintaining the capacity of retention reservoirs [33]. This exposed some surface features: the foundations of former buildings and roads, located in the southeastern part of the reservoir (Fig. 5), which allowed these details to be measured with the Hi-Target H32 GNSS receiver and used as adjustment points. In the remaining parts of the area currently underwater, the land boundaries visible on the archived map were used. It was assumed that these boundaries are identical to the plot boundaries, whose course has not changed significantly since the 1970s. After the land was expropriated for the reservoir basin, no land consolidation was carried out.

Fig. 4. Klimkówka reservoir in 2024 with a visible low water level (photo by M. Bodziony)

a)  b) 

Fig. 5. Fragment of the orthophotomap with terrain details constituting adjustment points for the calibration of the archival analogue map*:* a) remains of old buildings*;* b) remains of a road with a culvert on the exposed part of the reservoir bottom

Source: authors' own work based on UAV images

Twelve points were identified in the field, based on which the archival 1:5,000 scale topographic map was calibrated using a second-degree polynomial. The resulting Root Mean Square Error (RMSE) was 5.25 m. The prepared base map was vectorised in AutoCAD. The vectorisation included all contour lines and characteristic elevation points readable on the calibrated map. Based on the vectorised data, a DEM was generated for the first period (before the reservoir flooding).

2.3. Obtaining Current Elevation Data for the Reservoir Basin

Obtaining precise elevation data for the current morphology of the reservoir basin was possible due to the exceptionally low water level in the reservoir. Elevation measurements were taken using photogrammetric methods with a DJI Mavic 2 UAV. For this purpose, a total of 7,000 images were taken in 12 flights covering the entire Klimkówka reservoir and its dam on 20 and 23 October, 9 and 11 November, and 28 December 2024. To increase the precision of the DEM and verify its accuracy, 156 photopoints and control points evenly distributed throughout the study area were marked and measured using a GNSS satellite receiver. The measurement accuracy of the photopoints ranged from 0.02 to 0.03 m. Photogrammetric processing of the images allowed for the generation of an orthophotomap with a ground sample distance (GSD) resolution of 0.03 m and a DEM with a maximum resolution of 0.10 m (Fig. 6). The DEM accuracy measured at the control points was 0.08 m for the horizontal position of the points and 0.11 m for the determination of elevation coordinates. It should be emphasised that the reservoir basin area was not covered with vegetation, which might otherwise have affected the quality of the terrain model.

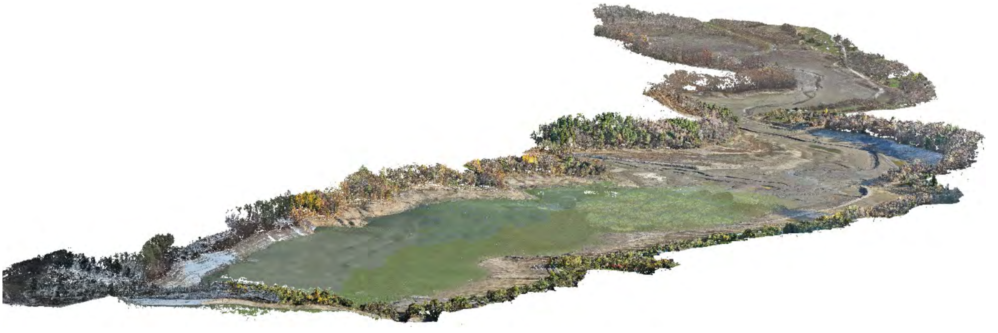

Fig. 6. Visualisation of point clouds obtained from UAV measurements in the Klimkówka reservoir area (at the end of 2024)

Because part of the reservoir remained underwater, determining the reservoir's bottom profile required bathymetric measurements. The bathymetric survey was carried out on 18 November 2024 from a boat using a Humminbird 718 dual-frequency echo sounder with readings positioned using a precise GNSS receiver. The data were acquired in discrete form (Fig. 7) within the area accessible for measurement, given the boat's draft.

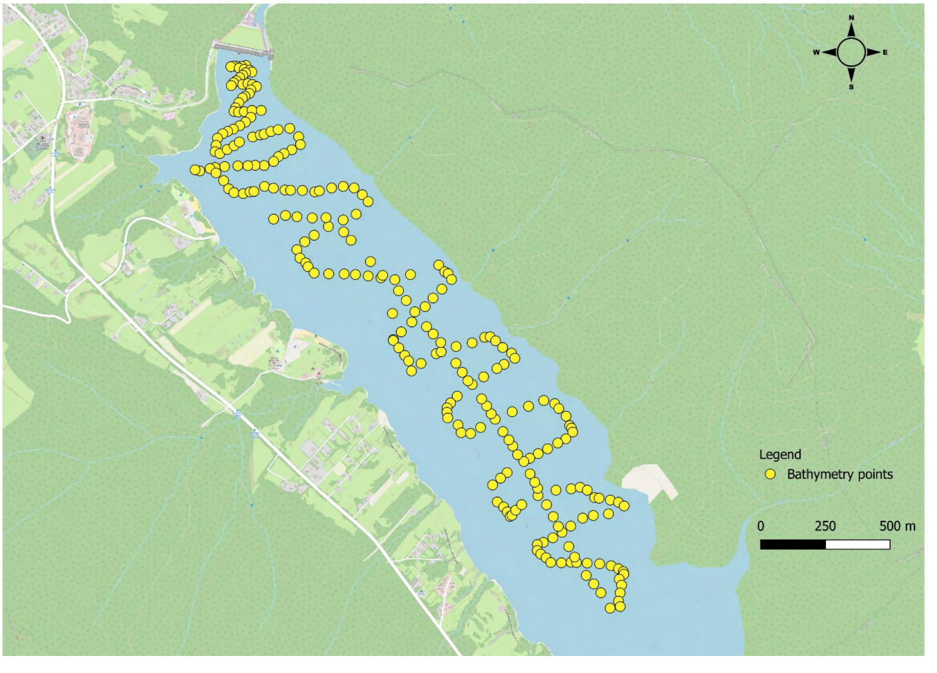

Fig. 7. Location of bathymetric measurement points in the Klimkówka reservoir basin, recorded on 18 November 2024

Source: own data with OSM background (www.openstreetmap.org)

The results of the photogrammetric analysis and bathymetric measurements were combined to create a DEM of the reservoir bottom (Fig. 8). The density of the measurement points used to generate the DEM was not uniform throughout the area. The lowest point density occurred in the nearshore zone, where it was not possible to take measurements with commonly available geodetic technologies. The elevations in the developed model were determined by linear interpolation using the triangulation method.

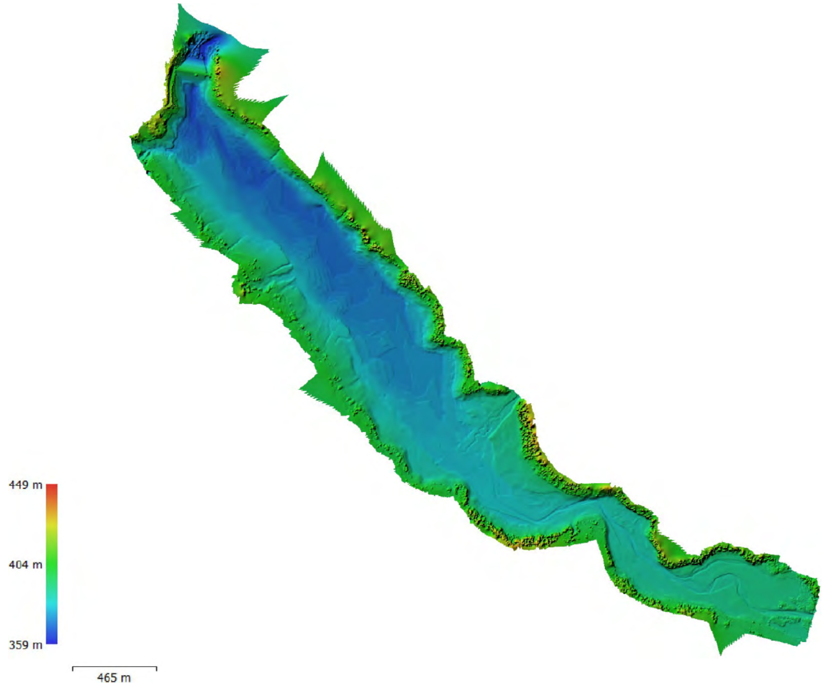

Fig. 8. Numerical model of the Klimkówka reservoir bottom created on the basis of bathymetric and photogrammetric data (at the end of 2024)

3. Results and Discussion

To analyse changes in the reservoir's morphology, two numerical elevation models were compared: a DEM developed from a vectorised topographic map of the reservoir's basin representing the state in 1976, and a DEM developed in 2024 based on bathymetric and photogrammetric UAV measurements.

The current and archived models were used to calculate the spatial distribution of elevation differences, which is illustrated in Figure 9. The archival and current DEMs were converted to a common elevation coordinate system (Kronstadt 86). For this purpose, models of elevation differences between the Kronstadt 60 and PL-KRON86-NH elevation systems, as well as PL-EVRF2007-NH and PL-KRON86-NH, were used, provided by the Head Office of Geodesy and Cartography in Poland (Główny Urząd Geodezji i Kartografii – GUGiK). The main aim of the study was to assess the reservoir's siltation. The volume of alluvia that had accumulated on the reservoir bottom or been displaced by bed erosion was determined from the elevation difference between the two DEMs.

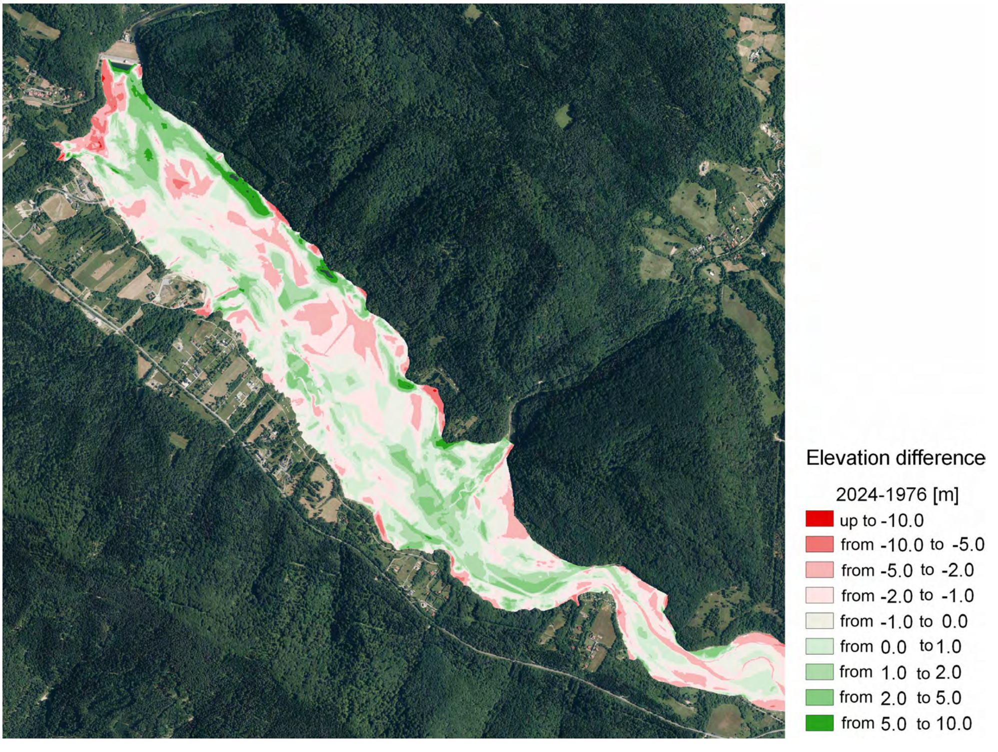

Fig. 9. Elevation differences between the current (2024) and archived (1976) DEM surfaces

The calculated sedimentation of the reservoir was 222,951 m^3 (Table 1). Given that the surface area of the analysed reservoir is 2,344,446 m^2, assuming a uniform distribution of the deposited volume, the sediment thickness would be approximately 10 cm. Based on the experience of other researchers [34–40] analysing sedimentation processes in other reservoirs, it is difficult to consider this thickness reliable. The obtained sedimentation value during the 50-year period of the reservoir's operation represents only 0.5% of the reservoir's volume.

Table 1. Accumulated and eroded alluvial volumes calculated by comparing the two DEMs

Volume of alluvia transported/removed by the river as a result of bed erosion [m^3]	Volume of accumulated alluvia [m^3]	Difference in volume of alluvia (siltation) [m^3]
1,551,045	1,773,996	222,951

As shown by the calculations in Figure 9, in the northern part of the reservoir, the reservoir's banks exhibit very high variability in ground elevation, reaching up to 10 m. The terrain slopes there reach 100%. On the western bank of the reservoir, significant changes indicating a lowering of the terrain surface elevation may result from a 50-year period of abrasion or earthworks related to the construction of the dam. On the eastern bank, the accumulation of alluvial deposits, causing elevation changes of 5 to 10 m, cannot be regarded as reliable. Based on an on-site inspection, erosion in the form of terraces is visible on this very steep bank (Fig. 10).

Fig. 10. Erosion terraces on the right bank of the Klimkówka reservoir (photo by M. Bodziony, 2024)

A more likely explanation for the discrepancy between the calculated values of accumulated material and the actual terrain may be the low accuracy of the elevation data obtained from an archival elevation map at a scale of 1:5,000. Due to the very steep slope and forest cover, this area is difficult to access for measurements, especially during the period concerned (the 1970s). At that time, only classical geodetic measurement techniques were used, relying on topographic and elevation data obtained from a low-density point grid.

Based on the current DEM and on-site inspection, accumulation processes are occurring in the reservoir's backwater area. These are the result of material being deposited by inflowing rivers or mass movements on the reservoir's eastern slopes, activated by flowing water undercutting the slope (Fig. 11).

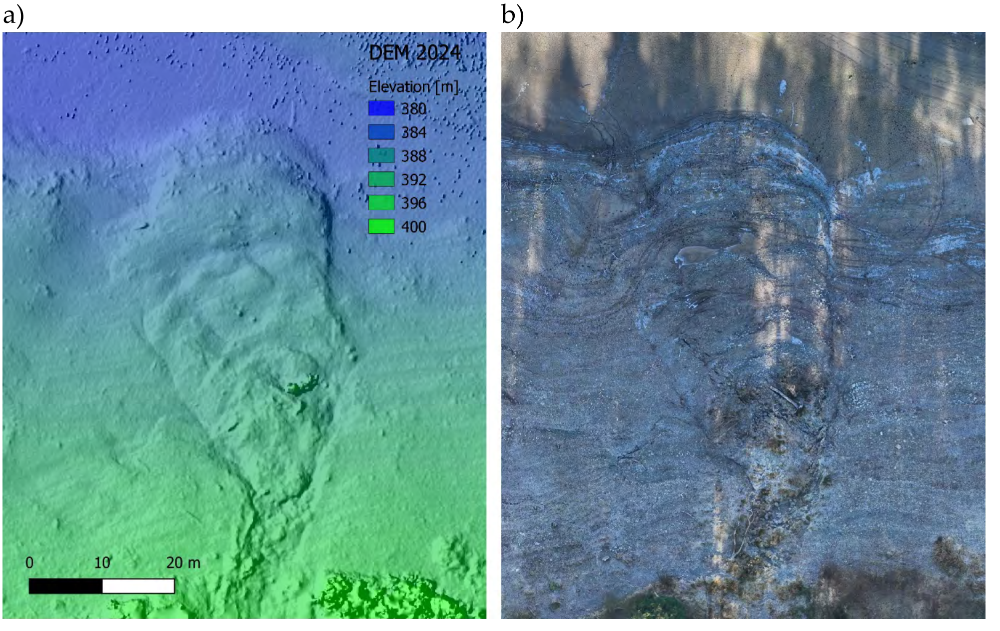

Fig. 11. Example of accumulation processes (formation of a landslide tongue) on the western bank of the Klimkówka reservoir: a) DEM; b) fragment of the UAV orthophotomap

Due to the low quality of the DEM developed for the first period, it was not possible to reliably determine the reservoir's sedimentation. The results obtained in this study regarding material accumulation and leaching may indicate either low data accuracy or unusual processes occurring in the analysed reservoir. The analysed reservoir has areas where erosion occurs at the bottom, and sediment accumulates along the edges.

According to the specialist literature and available studies on the functioning and operation of reservoirs, accumulation typically occurs at the bottom of reservoirs, whereas abrasion occurs on the original slopes of the river valley [7, 34–40]. Therefore, it is not possible to analyse the sedimentation of the entire reservoir basin using the presented method. However, it is possible to interpret the erosion and accumulation processes occurring in selected areas of the basin. The authors selected characteristic cross-sections (Fig. 12) for which DEM elevations can be corrected using elevation control points.

Three cross-section locations, marked as 1, 2, and 3 in Figure 12, were selected for further analysis of the accuracy of the available data to assess the feasibility of determining siltation in the Klimkówka reservoir.

Fig. 12. Location of cross-sections within the reservoir area, comparing archival and current elevation data

Source: own work with orthophotomap background from geoportal.gov.pl

3.1. Accuracy Analysis of Two Digital Elevation Models in Selected Cross-Sections

The accuracy of cross-sections generated from digital elevation models (DEMs) varies. In the archival model, accuracy varies by reservoir size, with higher precision for reservoir bottom elevations and lower precision for slope elevations. For the current model, accuracy is the same regardless of the reservoir area.

Accuracy of the Analysed Current Cross-Sections

For sections of exposed terrain, UAV-based surveys achieved very high accuracy in determining elevations to within several centimetres. For sections of the flooded area, elevation accuracy depends on the echosounder's measurement accuracy. According to the manufacturer, the depth-measurement accuracy of this class of DualBeam PLUS devices ranges from several centimetres to approximately 0.1 m under typical freshwater conditions.

Accuracy of the Analysed Archival Cross-Sections

For archival analogue maps, the accuracy of a 1:5,000 scale-topographic map (*D*) is determined primarily by graphical accuracy (*d*), which is typically 0.20–0.25 mm on the map, corresponding to 1.00–1.25 m in the field.

The accuracy of a topographic map is determined by the formula:

$$D = d \cdot M \tag{1}$$

where M – map scale denominator.

In the case discussed here (a 1:5,000 scale map), it should be assumed that the location of contour lines is determined with an accuracy of ±1.25 m.

Additionally, shrinkage of a 1:5,000 scale-analogue map causes uneven changes in the lengths of the sheet's frame sides (longitudinal S_p and transverse S_g), leading to distortions in distances and areas and reducing the map's cartometric and graphical accuracy. Given that the analysed map is 50 years old and is an ozalid print on paper, it was assumed that irregular shrinkage ($S_p - S_g$) does not exceed the permissible value of 0.16 mm. Exceeding this value increases the positional errors of terrain details by more than 0.3–0.4 mm at the map scale, which corresponds to 1.5–2.0 m in the field. For the map under consideration, it was therefore assumed that shrinkage did not exceed the permissible value, and its effect on the field accuracy, taken as 2.0 m, was assessed.

Accuracy is also influenced by the process of scanning, calibration, and vectorisation of the map, which was performed with the utmost care. The accuracy of this process was estimated at 0.5 mm on the map, which corresponds to 2.5 m in reality.

Taking into account the mean errors resulting from the accuracy of the topographic map, map shrinkage, scanning, calibration, and vectorisation processes, the mean error of a function composed of multiple observations was determined in accordance with the law of error propagation (also known as Gauss's law). The general formula for the mean error m_F of a function $F(x_1, x_2, ..., x_n)$ is [41]:

$$m_F = \sqrt{\left(\frac{\partial F}{\partial x_1} m_{x_1}\right)^2 + \left(\frac{\partial F}{\partial x_2} m_{x_2}\right)^2 + \cdots + \left(\frac{\partial F}{\partial x_n} m_{x_n}\right)^2} \tag{2}$$

where: m_{x_i} – mean errors of input variables, $\partial F/\partial x_i$ – partial derivatives defining the sensitivity of the function to changes in each variable.

The mean error m_F of the function with three input variables with mean errors $m_{x_1} = 2.5$ m, $m_{x_2} = 2$ m, $m_{x_3} = 1.25$ m and identical partial derivatives $\partial F / \partial x_i = c$ (for i = 1, 2, 3) is:

$$m_F = |c|\sqrt{2.5^2 + 2^2 + 1.25^2} = |c|\sqrt{10.3125} \approx |c| \cdot 3.2 \text{ m} \tag{3}$$

Assuming c = 1, the cartometric accuracy (horizontal accuracy of cross-section points) of the archival map is 3.2 m.

In the next stage, the accuracy of contour lines drawn on the archival analogue map at a scale of 1:5,000 was determined to calculate the vertical errors of cross-section points.

Referring to the then-current instructions [30, 31], the average contour height errors do not exceed 1/3 of the elevation difference (for terrain slopes up to 2°). For terrain slopes between 2° and 6°, the error is 2/3 of the elevation difference; above 6°, it is the full contour interval. For the analysed 1:5,000 topographic map, the contour interval is 5 m for slopes and 1 m for the reservoir bottom. The error of the read elevation coordinates for slopes with an inclination exceeding 6° is ±5 m, and for the bottom of the reservoir, where the inclination is from 2° to 6°, the error of the read elevation coordinates is ±0.7 m.

Cross-sections with mean elevation error ribbons for the archival and current profiles are shown in Figures 13–15.

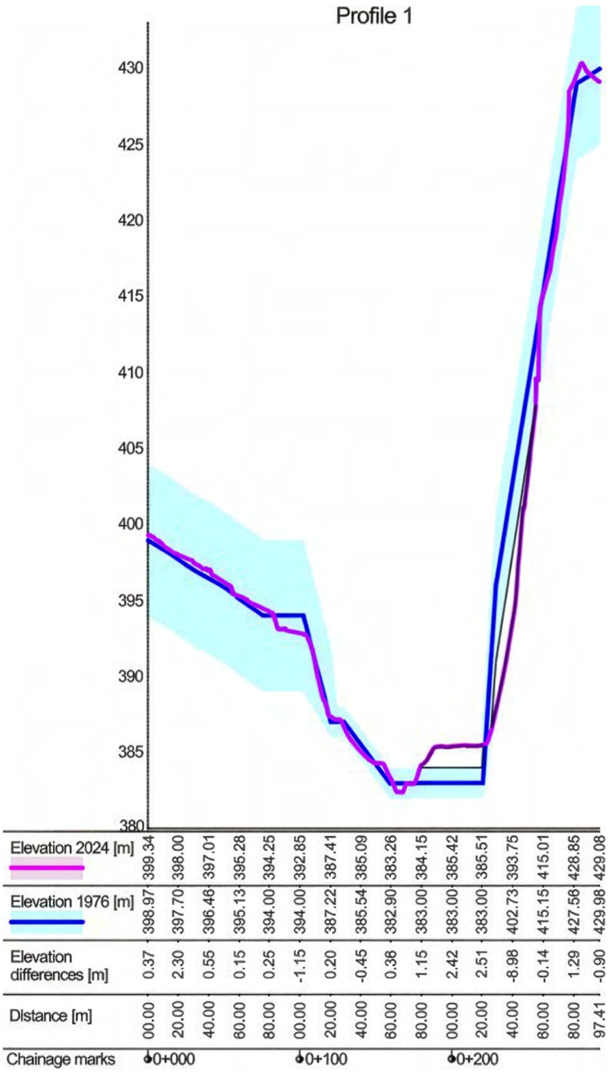

Fig. 13. Cross-section no. 1 through the Klimkówka reservoir basin with elevation point error ribbons

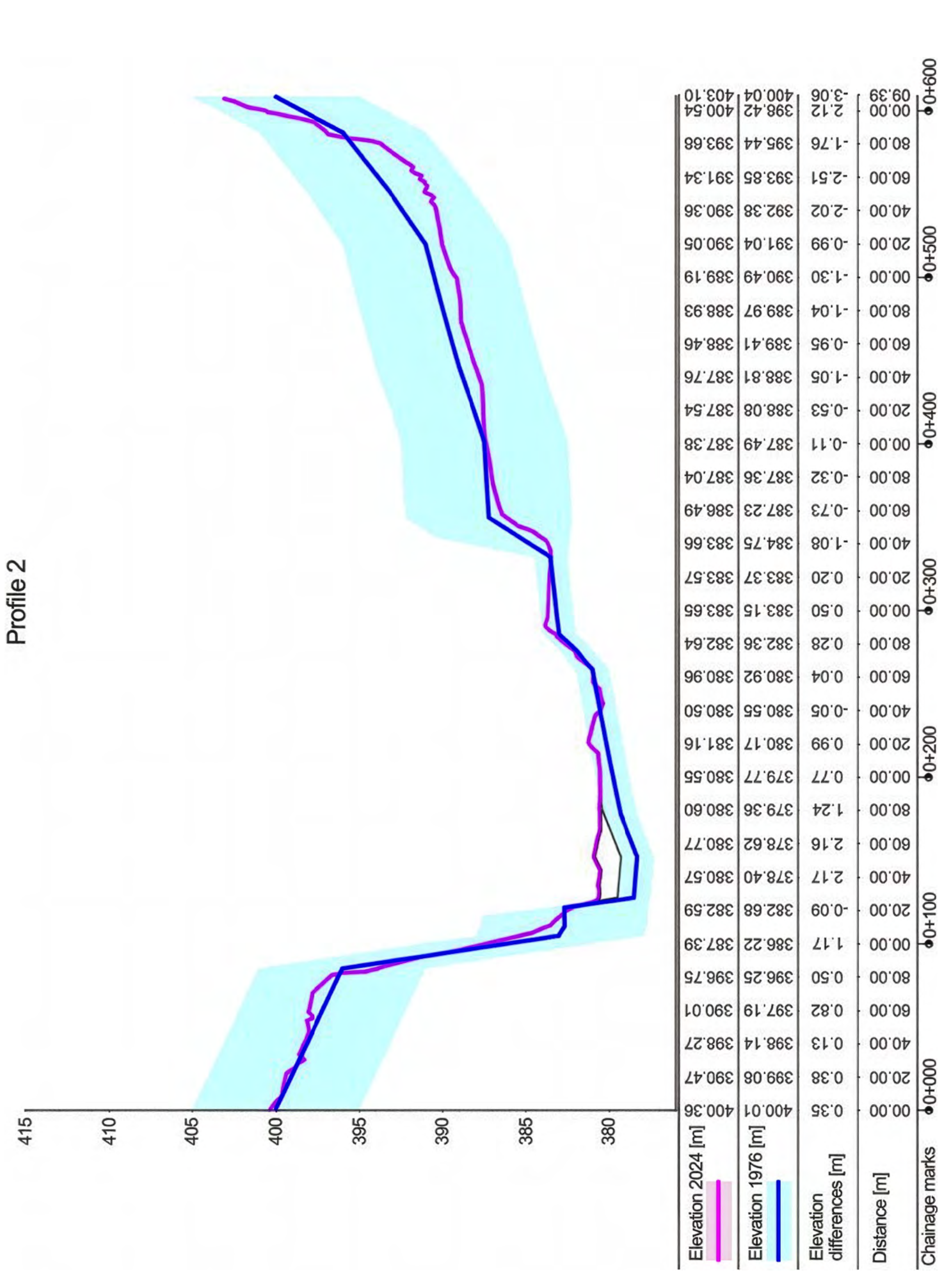

Fig. 14 Cross-section no. 2 through the Klimkówka reservoir basin with elevation point error ribbons

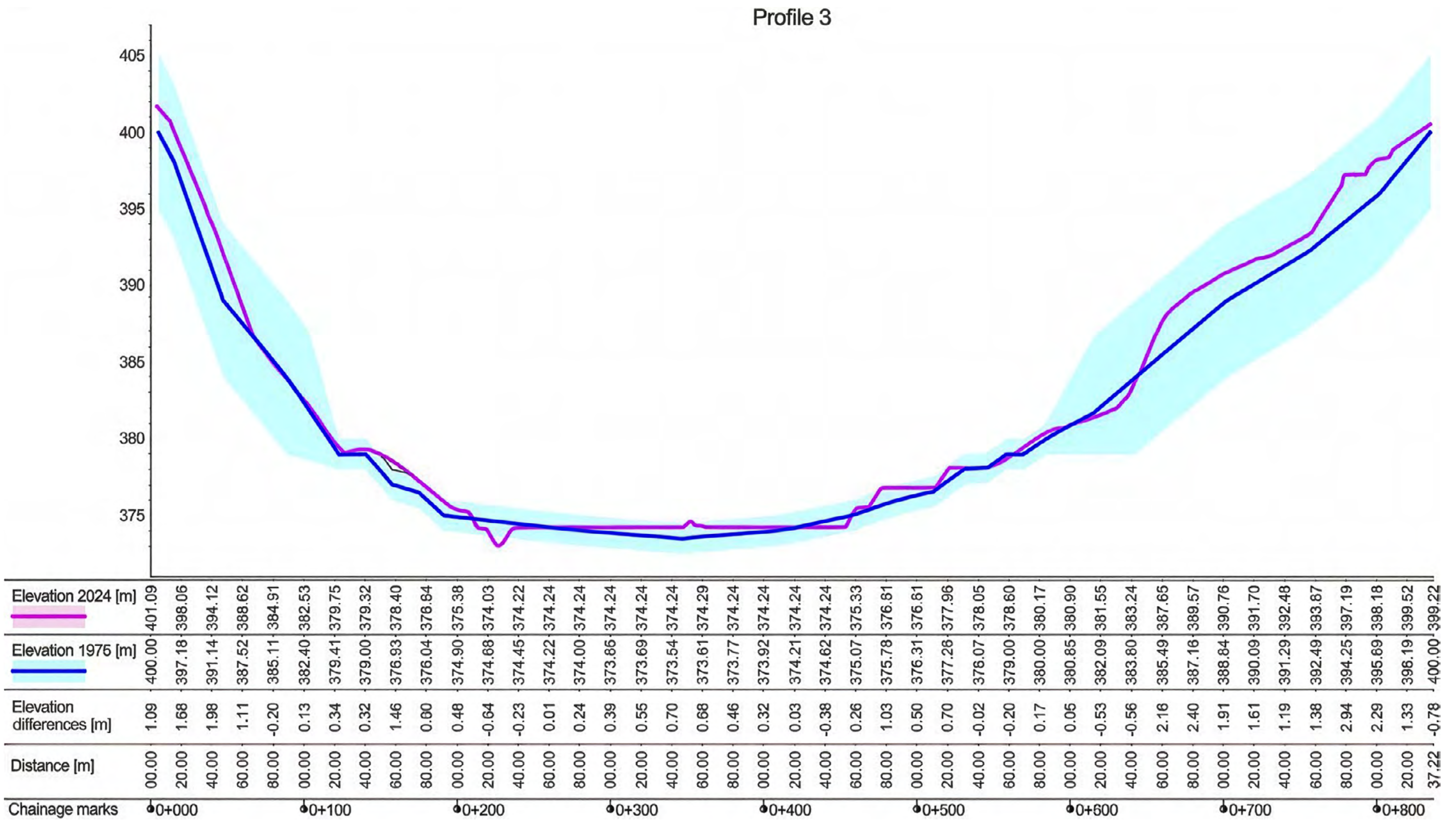

Fig. 15 Cross-section no. 3 through the Klimkówka reservoir basin with elevation point error ribbons

3.2. Analysis of Sedimentation Processes in Selected Cross-Sections

The cross-sections obtained from the archival model (1976) and the current model (2024), shown in Figures 13–15, were analysed for the occurrence of accumulation and erosion processes and for the factors that may influence them. Three representative cross-sections were selected based on the highest possible accuracy of both models at these locations, resulting from the largest number of adjustment points. Additionally, they account for differences in morphometric parameters (e.g., slope inclination and valley width) characterising individual cross-sections. The analysis considered the mean errors in the elevation determination of individual cross-sections, and elevation differences were considered statistically significant when they exceeded one propagated mean error.

Cross-section 1 (Fig. 13) is located 3.83 km from the dam and is characterised by the steepest valley slope on the right bank of the reservoir and a narrow, V-shaped valley. The elevation difference is approximately 45 m over a current length of approximately 40 m, resulting in a 113% slope. At this bank, a statistically significant lateral erosion is observed, with a maximum of 6.8 m. The maximum elevation of the right bank is approximately 431 m above sea level, and the left bank is approximately 399 m above sea level. At the bottom of the reservoir, accumulation is visible (probably of eroded material from the slope), as a result of which the thickness of the deposited material is at most 1.5 m. In the considered cross-section, the area of eroded material on the slope (determined on the basis of a statistically significant elevation difference) is approximately 80 m^2, and the area of material accumulated in the reservoir is approximately 50 m^2.

Cross-section 2 (Fig. 14) is characterised by a wider valley than cross-section 1 and is located 3 km from the dam. Both banks have comparable elevations (approximately 401 m above sea level), with the left bank being steeper than the right. The slope on the left bank is approximately 30%, and on the right bank, it is 7%. Accumulation is visible at the reservoir bottom, resulting in an average thickness of 1.2 m. No statistically significant areas of erosion were observed in this cross-section, while the area of accumulated material at the bottom of the valley is approximately 50 m^2.

Cross-section 3 (located 2.06 km from the dam – Fig. 15) was determined at the location with the widest U-shaped valley. Similar to cross-section 2, it is characterised by a similar bank elevation and comparable slope values on both banks, at 8% and 5% for the left and right banks, respectively. In this cross-section, there is a small area of accumulated material on the left bank, amounting to approximately 4 m^2.

Across the three selected cross-sections, the accumulation process is evident, with the amount of deposited material increasing with distance from the dam. This is confirmed by the authors' direct field observations, which indicate that more material accumulates in the reservoir's backwater area.

Statistically significant erosion was observed only in the narrow V-shaped valley on the right bank. Elevation errors in the remaining cross-sections preclude assessment of statistically significant erosion values. However, direct field observations indicate that this process is occurring (Fig. 10).

The analysis of sedimentation and erosion processes in the three selected cross-sections, as well as the comparison of the volumes of deposited and eroded materials between the two DEM models, does not permit an assessment of reservoir siltation. The results indicate that the Klimkówka reservoir's capacity has decreased by approximately 223,000 m^3 after 30 years of operation, which represents only 0.5% of its initial capacity. The calculated sedimentation value for the reservoir falls within the measurement error, which makes it unreliable. Bąk et al. [16] reported the average annual sedimentation rates obtained in Hartung researches are 0.5% for small reservoirs and 3.0% for medium-sized reservoirs, which further confirms the low reliability of the sedimentation results for the Klimkówka reservoir.

This is primarily due to the quality of the archival model, which was created based on imprecise analogue studies. Obtaining more reliable results is possible by comparing models derived from measurements made with the accuracy typical of currently used measurement technologies (UAVs). Furthermore, the quality of current models is higher because the available data are continuous (area-based) rather than discrete, as with archival data.

According to the international literature, sedimentation rates are poorly monitored due to difficulties associated with observation and modelling. The most direct measurements are obtained through periodic bathymetry. For example, measurements at two different times are often used to estimate sediment volume loss over a given period [42, 43].

According to observations by other Polish researchers, the deposition process in the backwater zone depends on hydrodynamic conditions and reservoir operation (low and high flows and water-level fluctuations).

During high flows and when the dam's capacity is relatively high, rapid sediment transport through the reservoir reduces sedimentation. Most material is transported in narrow reservoirs with steep longitudinal slopes and high flow velocities [45].

4. Conclusion

The sedimentation process directly impacts the functioning of a reservoir, such as the Klimkówka reservoir, by limiting its storage capacity, which can threaten the stability of water supply and hydropower generation. Therefore, monitoring this process within the reservoir basin is crucial. This can be achieved using various computational methods based on direct measurements or modelling. The use of appropriate computational methods depends on the type and quality of available data. Current technological advances in measurement methods and processing of measurement results allow us to obtain cartographic materials characterised by significantly greater detail and accuracy than those available approximately 50 years ago. Acquiring such data is rapid and can be performed remotely. The use of UAVs, scanners, and robotic total stations creates entirely new opportunities for acquiring data to model the reservoir bottom, unlike several decades ago.

In the case of analogue (paper) cartographic materials, another issue that requires attention is the timeliness of the data. The analysed materials often lacked information about their creation date and the validity of the data on which they were based. Approximate information on this subject was obtained from the surveys that incorporated the materials in question.

In this study, the authors used modern measurement and computational methods. UAV measurements and bathymetry were used to create a digital elevation model of the reservoir bottom and compare it with a model generated from the vectorisation of archived reservoir maps. The height-determination accuracy of the UAV measurement (the current model) is at least one order of magnitude higher than that of the archived model, which was created by vectorising analogue map contour lines using linear interpolation methods. This is one possible solution for assessing reservoir siltation.

The design of reservoir basins in Poland, commissioned in the 1970s and 1980s, was based on available analogue maps. Due to the lack of formal requirements at the time, these maps were not updated to reflect earthworks conducted before the reservoir was flooded. Therefore, it should be recognised that the method of assessing siltation by comparing two digital elevation models, namely an archival model and a current model, is not optimal. For such an assessment to be statistically significant, the volume of accumulated material should exceed the volumes resulting from errors in both models.

If the dam were constructed using current measurement technology, which enables significantly more accurate data acquisition, a precise digital elevation model of the basin would be necessary before the reservoir was filled and again after a specified period of use. In this case, a direct method based on comparing two models would reliably assess both the reservoir's silting and slope erosion and provide results that enable a comprehensive surface-based analysis of erosion and alluvial accumulation processes.

Based on the experience gained in this study, the authors plan to repeat the measurements using new technologies in a few years, thereby allowing for a more accurate assessment of the reservoir's sedimentation.

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CRediT Author Contribution

B.B.: validation, formal analysis, resources, data curation, writing – original draft preparation, writing – review and editing, visualisation.

M.B.: validation, investigation, resources, data curation, writing – original draft preparation, writing – review and editing, visualisation, supervision.

C.T.: conceptualisation, methodology, validation, formal analysis, investigation, resources, data curation, writing – original draft preparation, writing – review and editing, visualisation.

A.S.: conceptualisation, methodology, validation, formal analysis, investigation, resources, data curation, writing – original draft preparation, writing – review and editing, supervision.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Archival cartographic data are the property of the Klimkówka Dam Administrator and were made available to the authors upon written request. The authors would like to express their gratitude for the opportunity to analyse these cartographic materials in this work.

Current data on the reservoir shape were obtained as a result of direct measurements carried out by C.T. (unmanned aerial vehicle) and A.S. and M.B. (bathymetric measurements). These data can only be made available through direct contact with the authors.

Use of Generative AI and AI-Assisted Technologies

No generative AI or AI-assisted technologies were employed in the preparation of this manuscript.

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