Geodetic Monitoring of Hydraulic Structures Using Remote Sensing Data

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Abstract *Regular monitoring is required to maintain engineering structures. The reliable operation of these structures requires continuous condition monitoring to detect potential damage, deformations and changes that could lead to various accidents or reduced efficiency. To address these issues, Earth Remote Sensing data is an indispensable tool for highly accurate and rapid monitoring of the condition of hydraulic structures. The aim of the research is to investigate the application of Earth Remote Sensing data for geodetic monitoring of hydraulic structures. The study aims to develop and implement methods of using Earth Remote Sensing data to improve the accuracy and efficiency of monitoring the condition of these objects. The research used satellite images from the Landsat and Sentinel series, which provide high resolution space images and unmanned aerial vehicles for highly detailed imagery. Processing and analysis of satellite and drone data was carried out using Agisoft Metashape, QGIS software. Data interpretation methods were used to assess the condition and identify changes in the design of hydraulic structures. The research showed the high accuracy and efficiency of remote sensing data in monitoring hydraulic structures. The developed methods of satellite data processing allow timely detection of deformations, erosion and other critical changes. The effectiveness of the proposed methods was confirmed by examples of using remote sensing data for monitoring the Shulbinsk hydroelectric power station and the Shulbinsk stopper. The results confirm that the use of remote sensing data significantly expands the possibilities of geodetic monitoring and improves the safety and reliability of operation of hydraulic structures.*

Keywords: *Hydraulic Structures, Monitoring, Remote Sensing*

Introduction

In light of the challenges posed by climate change and the growing demand for water, there is an increasing need for the monitoring of hydraulic structures. Regular and thorough monitoring allows timely detection of potential defects, structural deformations and other changes that can lead to emergency situations. Reliable functioning of these facilities requires continuous monitoring to ensure their safety and efficient operation [Scaioni et al. 2018, Huang et al. 2020]. Under conditions of climate change and increasing pressure on water resources, the importance of monitoring of hydraulic structures is increasing. Regular and thorough monitoring allows timely detection of potential defects, structural deformations and other changes that can lead to emergency situations. Reliable functioning of these facilities requires continuous monitoring to ensure their safety and efficient operation [Scaioni et al. 2018]. Modern monitoring techniques include the use of remote sensing (RS), geographic information systems (GIS) and big data analysis. These technologies provide highly accurate and timely data on the condition of structures. The implementation of advanced monitoring techniques not only extends the service life of hydraulic structures, but also minimizes the risks associated with their operation, thereby preventing accidents and reducing economic losses that may occur due to interruption of power generation or other related activities. It might be suggested that these technologies have the potential to significantly extend the capabilities of traditional geodetic surveying methods, which are known for being labour- and time-consuming. The goal of the research is to investigate the application of remote sensing data for geodetic monitoring of hydraulic structures. The research is aimed at developing and implementing methods of using remote sensing data, analyzing their advantages and examples of application to ensure safety and reliability of hydraulic structures. The objects of the research are Shulbinsk hydroelectric power station (HPS) and Shulbinsk stopper - important hydraulic structures located on the river Yertis in the Abai region of the Republic of Kazakhstan. These objects play a key role in power generation, water management and navigation.

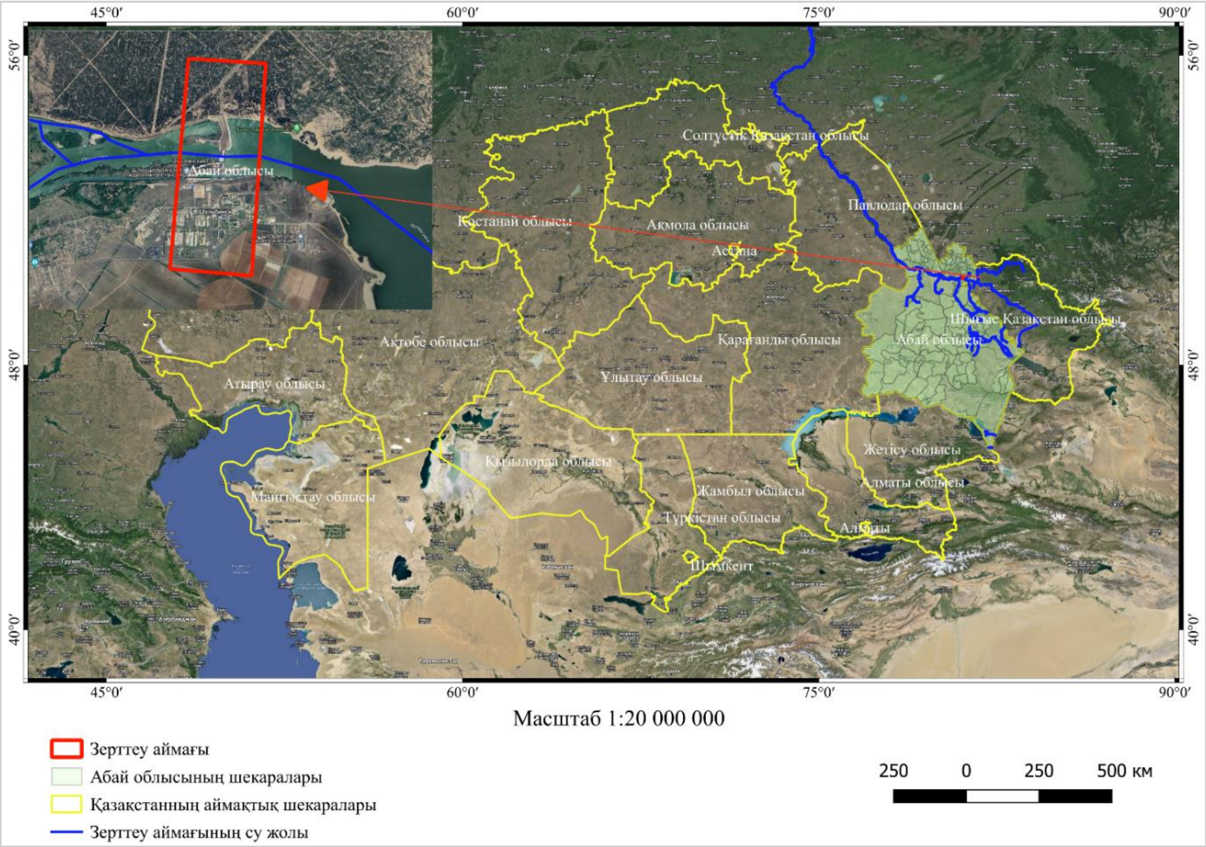
Literature Review

The application of remote sensing (RS) data for geodetic monitoring of hydraulic structures has been considered in a number of scientific papers and researches. Authors [Scaioni et al. 2018, Liu et al. 2023] note that the measurement of dam deformations has improved significantly in recent years due to the development of remote sensing technologies, including terrestrial laser scanning and satellite-based differential interferometric SAR, which has enabled higher levels of automation and accuracy. The integration of data from various geodetic and remote sensors provides comprehensive monitoring of the condition of hydraulic structures, improving their operational safety and reliability. In [Huang et al. 2020] remote sensing (RS) data are used to predict runoff in unrecorded catchments and poorly recorded regions. It is noted that there is potential to use remotely sensed data to calibrate hydrological models in regions with limited flow gauges. The advantage of space geodesy applications is also noted in the work of [Vázquez-Osén et al. 2022, Liu et al. 2023] who highlights the advantage of space geodetic methods over other traditional geodetic methods. In particular, the application of Interferometric Synthetic Aperture Radar (InSAR) technologies using the Permanent Scatterometer Interferometry (PSI) method is widely used to measure the deformations of hydraulic structures. Therefore, the application of remote sensing (RS) data for geodetic monitoring of hydraulic structures has significant advantages in improving the accuracy and reliability of measurements. The results of this research highlight the potential of using advanced remote sensing technologies to monitor the condition of hydraulic structures and prevent accidents.

Methodology

a. Characterisation of the research object:

The Shulbinsk hydroelectric power station (HPS) is located in Zhanasemey district, Abay region of the Republic of Kazakhstan, in the middle reaches of the Yertis River, 70 km upstream of Semey city (Figure 1). The area of the dam at normal support level is 255 km^2. The total and usable capacity of the reservoir is 2.39 and 1.47 km^3 respectively, which allows for seasonal flow regulation. The normal level of the reservoir lies at 240 m above sea level (Baltic altitude system), the accelerated support level is 243 m and the dead volume level is 232 meters. The HPS has an installed capacity of about 702 MW. The average annual electricity generation is approximately 2.3 billion kWh. The Shulbinsk HPS dam is a concrete gravity dam. The HPS was commissioned in 1987.



Source: Sentinel satellite imagery

Figure 1: Location of the investigated object

The main activity of Shulbinsk HPS is electricity generation. It’s designed for regulation of compensatory flow of the Yertys River, accumulation of flow of the Ulba and Chuma Rivers on floodplain meadows of Pavlodar region during spring floods.

The single-chamber Shulbinsk shaft-type sluice is designed for passing ships and rafts through the Shulbinsk hydroscheme. It’s located within the Shulba settlement, on the left bank of the Yertys River, 400 meters downstream of the HPS site (Figure 2). The Shulba lock is designed to provide navigation on the Yertys River. It allows vessels to pass through the Shulbinsk HPs dam, providing a link between the upper and lower embankments of the river. The Shulbinsk sluice works in conjunction with the Shulbinsk HPP, providing not only power generation, but also efficient utilisation of water resources of the Yertis River. The lock plays a key role in providing transport infrastructure for the region, facilitating economic development and trade.

Source: https://wikimapia.org/9652445/ru

Figure 2: View of Shulbinsk lock from above

b. Input data

The input data for the research were the following:

- Landsat, Sentinel, MODIS and SRTM satellite data providing imagery and terrain information.
- Mavic 3 Pro aerial photos.
- Processed topographic maps and digital elevation models created from SRTM data.
- Total station survey results from the Spectra SP60 GNSS receiver to produce accurate topographic survey and geospatial information.
- Field work on topographic-geodetic survey of the working area using modern tools and technologies, such as AutoCAD Civil 3D for data processing and creation of topographic plans.
- Data on water levels, water discharge and flow velocity, as well as other parameters of water masses necessary for analyzing and monitoring the condition of hydraulic structures.

c. Research methods

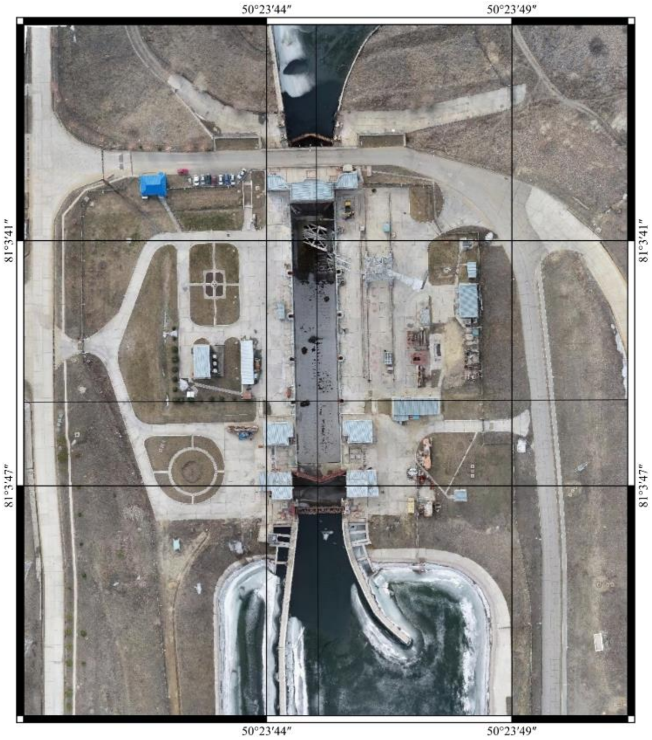
To perform geodetic monitoring of Shulbinsk HPS and Shulbinsk sluice, the following research methods were applied: topographic-geodetic survey of the site, use of high-resolution images (Sentinel) to analyze macro changes of the territory, relief and structures; results of Mavic 3 Pro drone imagery to obtain detailed photographs with subsequent processing in Agisoft Metashape software; processing of space images and SRTM DEM data in SAGA GIS software to create digital models and height maps; use of QGIS software for spatial analysis of relief and hydrological characteristics, as well as for creation of watershed models.

Results and Discussion

All field topographic-geodetic works on the studied objects were carried out in accordance with the requirements of the current regulatory documents, instructions, methodological guidelines for the production of large-scale topographic surveys.

The topographic survey was carried out by a combined method - the method of total station surveying using electronic total station Leica TS02 and TS06 and GPS-surveying in RTK mode using GNSS-equipment. The plan-altitude foundation was laid in the form of 3 ground control points Rp1, Rp2 and Rp3 on the basis of static GPS measurements and leveling. On the basis of the ground control points the survey foundation was developed in the amount of 10 temporary survey points along the route of works. Plan and elevation data were obtained from GPS observations. Topographic survey of the work area was made at a scale of 1:500 with relief cross-section in 0.5 m. The topographic plan was drawn up on the basis of the survey works without graphing. Office analysis of the field measurements of the total station survey was carried out on a daily basis using CredoMix and AutoCAD software.

Mavic 3 Pro unmanned aerial vehicle was used for aerial photography of Shulbinsk HPS and Shulbinsk sluice, which allowed to obtain detailed images of the study area with high spatial resolution. The aerial images were processed using Agisoft Metashape software, which allows creating three-dimensional terrain models and orthophotomaps based on aerial images. Photogrammetry methods were used during processing to generate digital elevation models (DEM) and accurate visualisation of objects. The final image obtained after processing shows topographical features and architectural elements of the HPS and sluice (Figure 3).



Source: Aerial photos from Mavic 3 Pro Drone

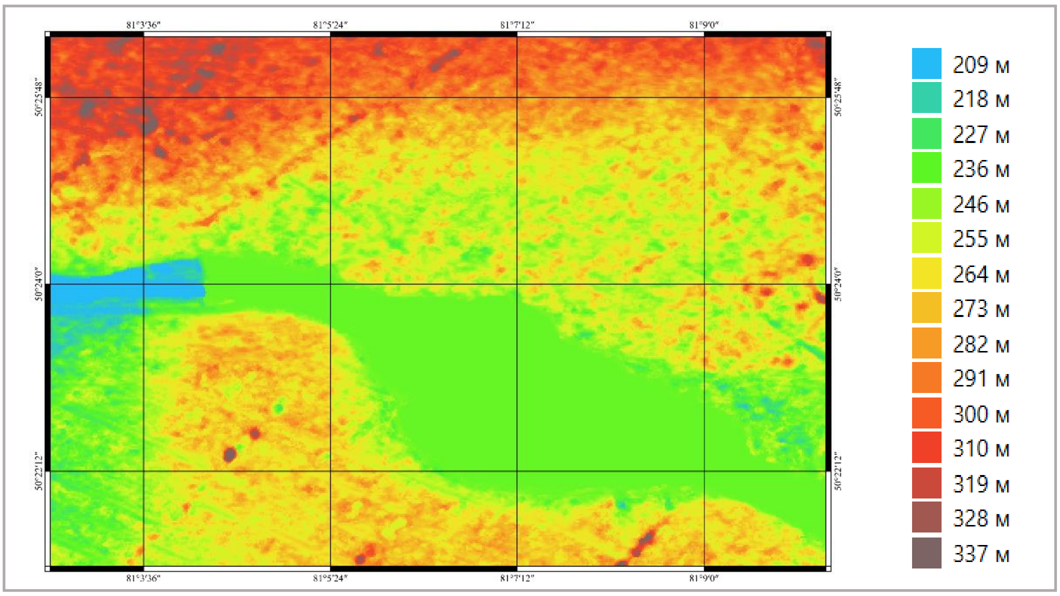
Figure 3: An Overhead View of The Gateway Captured by the Mavic 3 Pro Drone

SRTM DEM, QGIS and SAGA GIS programmes were used to perform the monitoring of the hydropower station. These tools were chosen for their ability to efficiently process and analyse multi-dimensional spatial data. SRTM data provides elevation information with a spatial resolution of 30 metres, allowing a detailed view of the terrain. To visualise the location of the study site (hydroelectric power station), the downloaded SRTM data was imported into QGIS software using a publicly available Google Hybrid map (Figure 4).

Source: Google Hybrid maps

Figure 4: Location of the study site on the publicly available Google Hybrid map

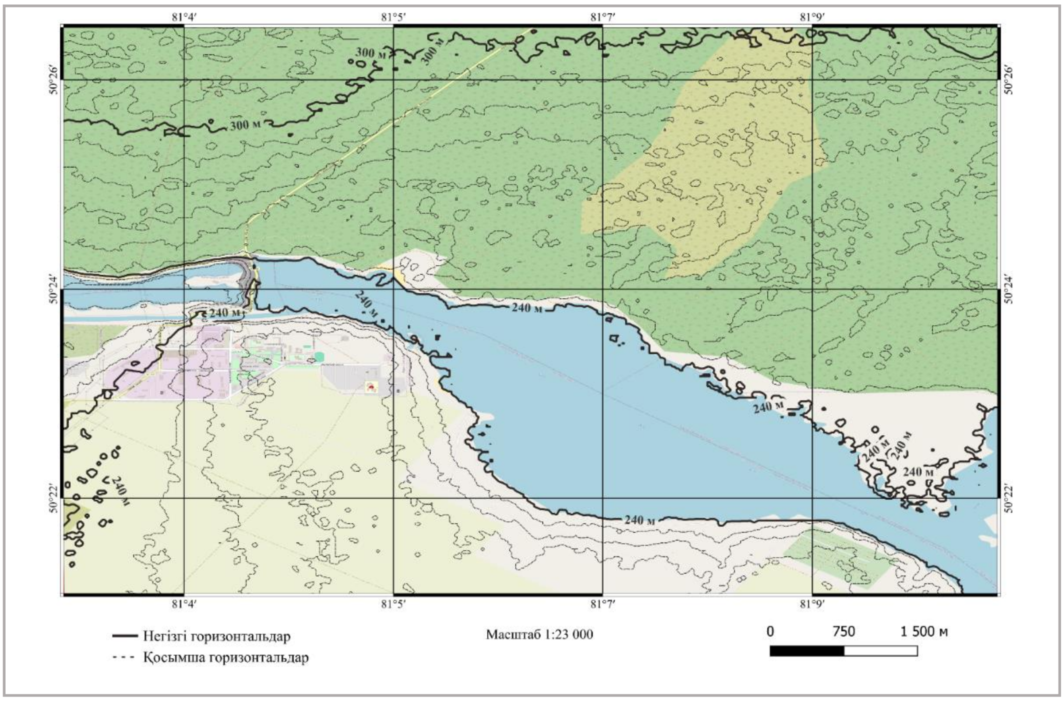
As a result of data processing, a height map was obtained (Figure 5).



Source: SAGA GIS program

Figure 5: Elevation Map

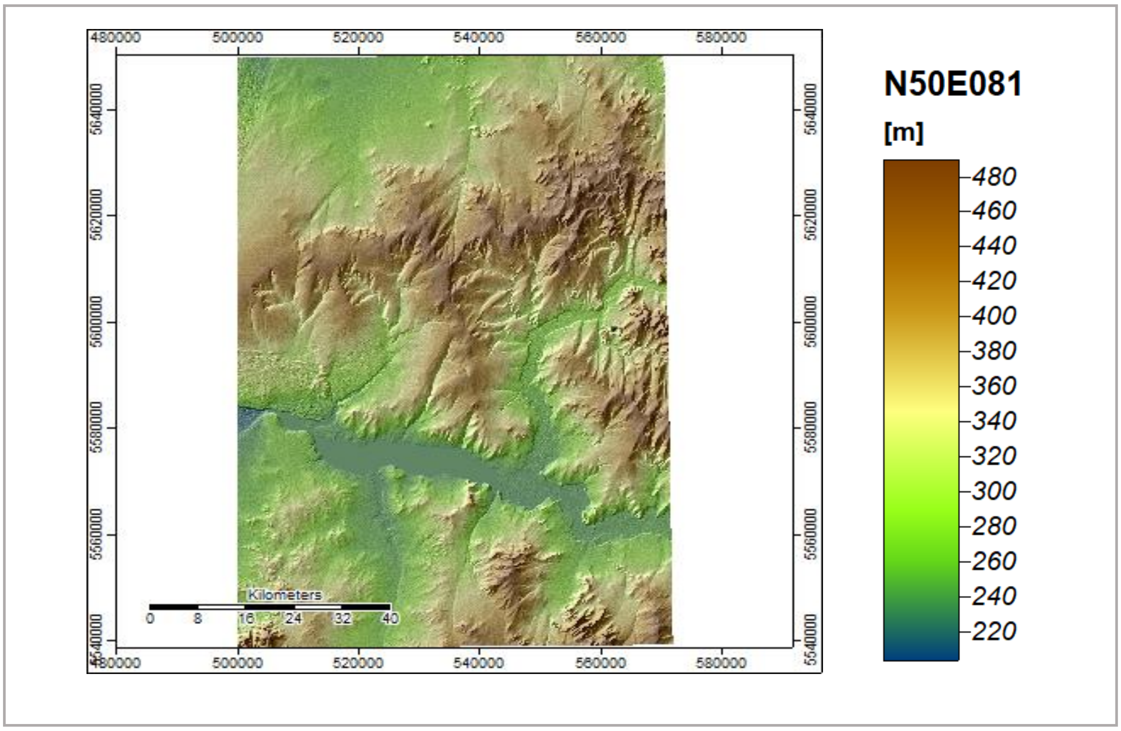
Such a map allows for detailed analysis of the relief of the investigated area. The obtained elevation data were converted into a raster in which each pixel represents an elevation value at a specific point of the terrain. This raster serves as the basis for subsequent visualisation and analysis of the topography. Each pixel of the elevation map derived from SRTM data represents the elevation characteristics of the corresponding point in the study area. Different colour schemes were used to make the topography more visual. For example, a gradient scale from green (for low elevation values) to brown (for high values) allows easy visualisation of elevation and elevation changes within the study area. The use of different colour palettes greatly enhances the perception and analysis of altitude data, making it easier to identify elevations and lowlands in the region. Based on the constructed elevation map, the topography of the study area was analysed. The minimum elevation within the site is 209 m and the maximum elevation is 337 m. It should be noted that the lower level of the reservoir is at 209 metres, while the upper level is at 246 metres. This suggests that the height of the dam is 37 m. Visualization of the elevation map using color gradients, construction of contour lines, relief profiles, and analysis of slopes and terrain exposures are key to a comprehensive assessment of the relief features of the study area. This allows the precise identification of zones with different elevation characteristics, which is important when planning further research or engineering works [Wang et al. 2023, Entezami et al. 2024]. Topographic maps are important for analyzing the territory in the design and operation of hydraulic structures. An accurate understanding of the elevation characteristics of the territory contributes to a correct assessment of reservoir volumes, flooding levels of adjacent lands, and hydraulic parameters of the flow. Horizontals allow the steepness of slopes, possible erosion zones, and areas with the highest risk of flooding during water level changes to be determined with high accuracy. Figure 6 shows a map of the horizontals obtained from SRTM image processing.



Source: SAGA GIS program

Figure 6: Topographic Map

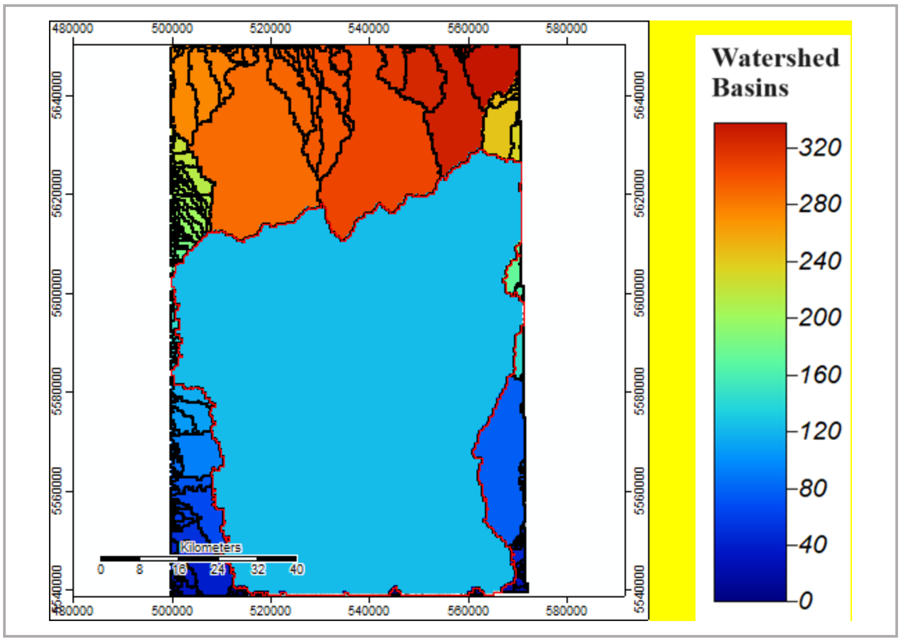
To conduct spatial analysis of the study area, a Digital Elevation Model (DEM) was downloaded using the 30-Meter SRTM Tile Downloader software, which provides access to elevation data at 30 meter resolution. This data formed the basis for subsequent elevation processing and analysis within the study. Elevation visualization and detailed topography analysis were carried out using SAGA GIS specialist geographic information software. This software provides a wide range of tools for analyzing spatial data, including the construction of 3D terrain models, calculation of slopes, exposures and other morphometric characteristics. Visualization of the DEM allowed not only to visualize the relief of the study area, but also to carry out a comprehensive analysis of its characteristics, which is an important step in assessing the suitability of the territory for the design of hydraulic structures (Figure 7).



Source: SAGA GIS program

Figure 7: Map of The Area

For the hydrological analysis of the study area, data pre-processing was performed using the Fills Sinks command (Wang & Liu), which removes closed depressions and prepares a digital elevation model for further calculations. This step is key to correctly determining the direction of surface runoff and calculating catchments. During processing, the minimum surface slope value was adjusted from 0.1 to 0.001 to improve the accuracy of flow direction and catchment formation. The result of this operation was the creation of layers showing flow directions, basins and water accumulation zones, as well as an analytical relief shadow that helps visualize topographic features of the terrain (Figure 8).

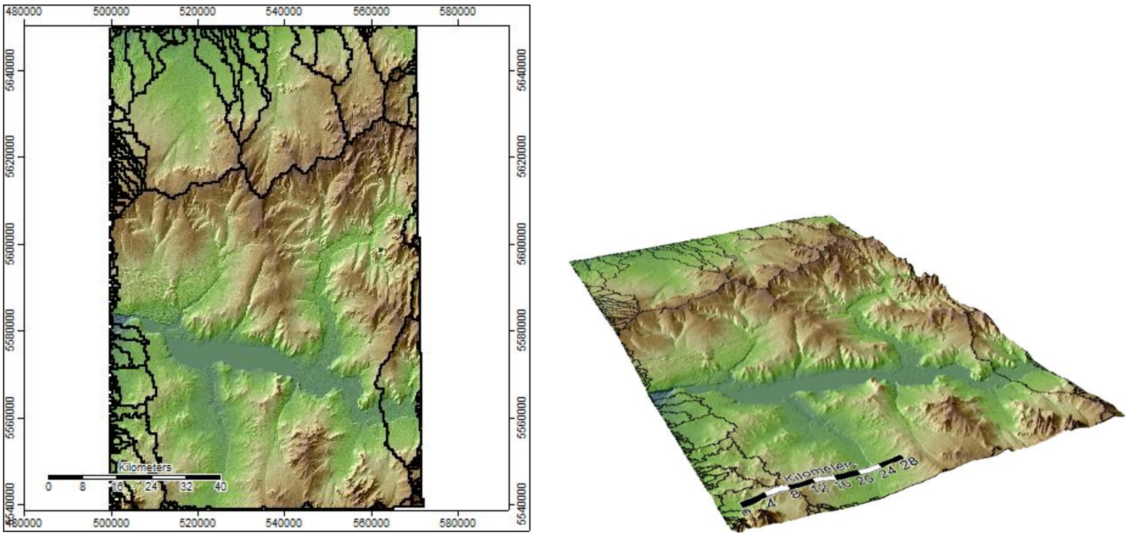


Source: SAGA GIS program

Figure 8: Map of the Main Boundaries of the Catchment Area

Hydrological model data are visualized and analyzed to produce a base layer of watersheds where water accumulation occurs. The processing results in a polygonal layer representing watershed contours based on topographic and hydrographic information. This layer allows the delineation of watershed boundaries within which water drains to specific water bodies or rivers.

The construction of watershed layers on a terrain map allows the identification of key zones of water resources accumulation and distribution. Such data is essential for assessing water availability, designing hydraulic structures and managing water resources. Visualization of catchments makes it possible to clearly define flow directions, analyze the dynamics of water flows and assess potential flood zones, which is particularly important for planning and monitoring of hydrological processes. The result of the analysis is the integration of a polygonal layer of catchments with topographic maps (Figure 9).



a *b*

Source: SAGA GIS program

Figure 9: Main basins where water is collected: a) topographic map of the area, b) 3D view

The parameters of the main catchment basins calculated in the SAGA GIS program allow a detailed analysis of catchment areas and their influence on hydrological processes in the study area. Table 1 summarizes the calculated characteristics of the catchments in the study area.

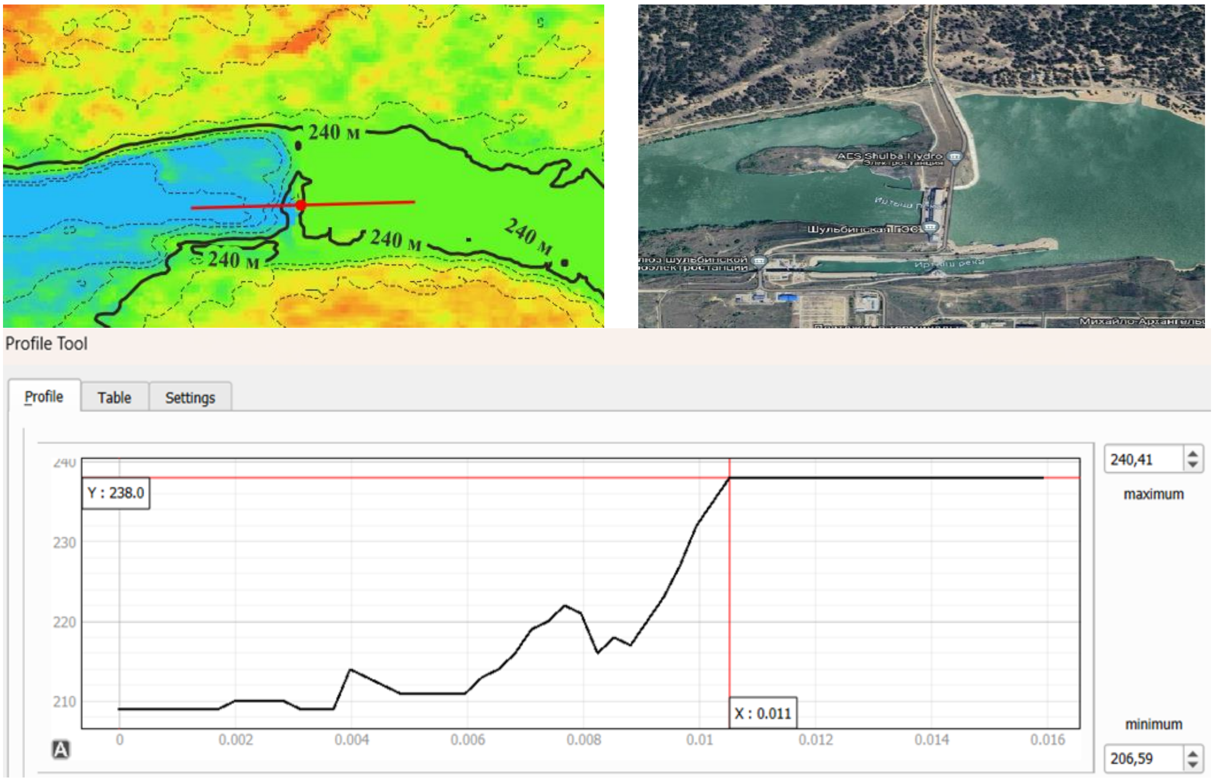
Table 1: Calculated catchment characteristics

ID	VALUE	AREA, м^2	AREA, ha
0	2	4803520000	480352
1	4	611040000	61104
2	19	532800000	53280
3	56	241760000	24176
4	58	188960000	18896
5	66	106880000	10688
6	135	82400000	8240
7	140	82240000	8224
8	145	72800000	7280
9	166	70560000	7056
10	171	66880000	6688

Source: Data from the Saga GIS program

The results obtained allow us to analyze the relationship between surface runoff and the volume of water entering water bodies. Large catchments (AREA 480352 ha) have a significant impact on the increase in runoff and hence water volume. In addition, these data can be useful for modeling hydrological processes including flow velocity, water retention and filtration, which is important for flood risk assessment. Pollution control is an important aspect, as smaller catchments, (AREA 6688 ha), may be more vulnerable to localized pollutants, requiring additional environmental protection measures and water quality monitoring.

Water level analysis of dams using SAGA GIS tools allows the application of a wide range of functions for detailed investigation of catchment characteristics and hydrological processes. In particular, the terrain modeling and digital elevation model (DEM) analysis functions allow the precise definition of the elevation profile and the assessment of spatial variations in water level. In this case, using these tools, it was possible to identify that the lower water level is 206 m and the maximum level at which the water dam is located has an absolute height of 240 m. The receding water level of the weir was recorded at 238 m, indicating that there is a catchment reserve of 2 m. Application of the hydrological network analysis and stored water calculation functions in SAGA GIS (Figure 10) confirms these data, providing a scientifically sound approach to assessing the water reserve and current status of water bodies. This approach ensures regular and accurate tracking of water level changes and is an important indicator in analyzing risks associated with their dynamics.



Source: SAGA GIS program

Figure 10: Dam backup level monitoring

A comparative analysis of the use of traditional geodetic methods and remote sensing data for monitoring of hydraulic structures has shown that both approaches have their strengths and weaknesses and can effectively complement each other depending on the monitoring objectives and specifics of the objects. Traditional geodetic methods demonstrate high accuracy in localized monitoring of structural changes in hydraulic structures such as dams, sluices and dykes. These methods provide millimetre-level accuracy, which is particularly important for detecting small deformations that may precede major accidents. However, these methods require significant time and financial resources, as they involve on-site visits, expensive equipment and highly qualified specialists. On the other hand, remote sensing (RS) techniques, such as interferometric synthetic aperture radar (InSAR) and photogrammetry, allow monitoring over large areas at lower cost and on a regular basis. Remote sensing provides a high frequency of data updates, for example Sentinel-1 satellites can provide data every 6-12 days, making it possible to detect changes in the condition of hydraulic structures, such as deformation or erosion, in a timely manner. However, the accuracy of some remote sensing methods can be lower than that of traditional geodetic methods, although InSAR achieves accuracy at the level of a few millimetres. A comparative analysis of the use of geodetic and remote sensing (RS) methods for monitoring hydraulic structures is given in Table 2.

Table 2: Comparative Analysis

Parameter	Geodetic methods	Remote Sensing of the Earth (RS)
Measurement accuracy	High (up to 1 mm when using total stations and GPS)	Moderate for photogrammetric (up to 10 cm), high for InSAR (1-5 mm)
Area of coverage	Limited, depends on the accessibility of facilities	Wide, up to thousands of square kilometers
Monitoring rate	Depends on fieldwork schedule, usually 1-2 times per year	Regular, satellite dependent (every 6-12 days for Sentinel)
Data timeliness	Requires time for processing and field measurements	Data available a few hours after the satellite image
Monitoring costs	High due to the need to travel and use expensive equipment	Medium, especially for analyzing open source data (Sentinel)
Labour intensity	High, requires skilled personnel on site	Low Once the data is received, processing can be automated
Data availability	Limited geographically and by the inaccessibility of the site	High, data can be acquired even for remote and hard-to-reach locations
Scope of monitoring	Local, limited access to objects	Scalable, can cover large areas
Identification of small deformations	High accuracy for localised changes	High accuracy (InSAR) for millimetre-scale deformations
Erosion detection	Mostly localized assessment, depends on field conditions	Wide coverage, allows to detect erosion over large areas (photogrammetry, DEM)

Dependence on weather conditions	Possible weather restrictions (snow, rain)	Less susceptible to weather conditions (radar satellites, InSAR)
Long-term monitoring	Implemented rarely due to cost and logistics	Continuous monitoring with high frequency is possible

Based on the comparative analysis, a radar plot has been constructed which clearly demonstrates the comparison between traditional geodetic methods and remote sensing (RS) methods in terms of various parameters (Figure 11).

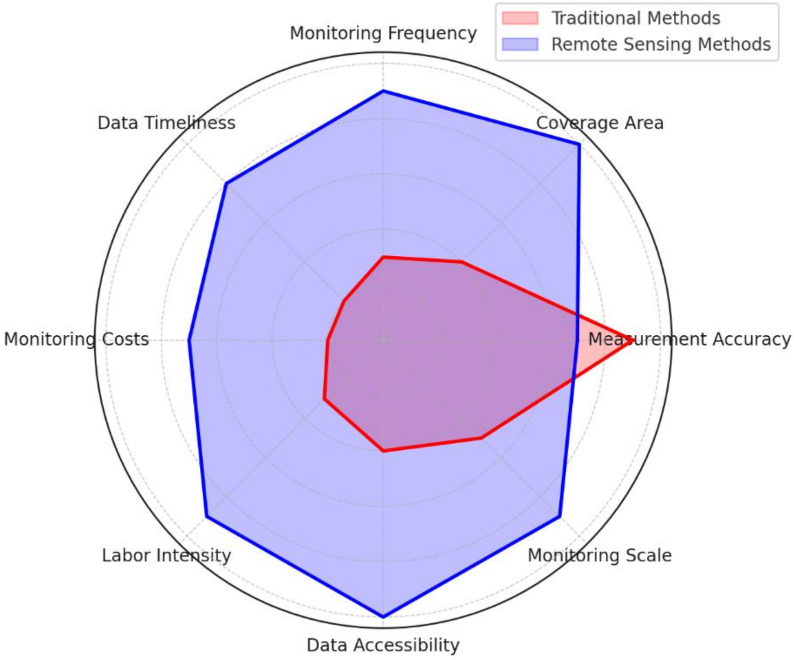


Figure 11: Comparison of Traditional Methods and Remote Sensing Methods

As can be seen, RS methods outperform traditional methods in terms of coverage area, monitoring frequency, data timeliness and accessibility, while traditional methods provide higher accuracy of measurements.

Thus, the results of the study show that the process of field data collection is quite automated. The productivity of work at this stage can be improved only by using RTK-enabled UAVs, which will allow to avoid ground-based identification in most cases. Despite the presence on the market of automatic interpretation systems (Erdas Imagine, GIS ‘Panorama’, etc.) their wide application is restrained by the complexity of their use - it is training on a large sample before application, the need for new training for different types of relief or buildings or the need to select individual parameters for each project. For small volumes (up to 1000 ha) the labour intensity and time spent on training or selection of parameters are comparable to the processing of these data by cameramen.

This is justified for large volumes of data within an entire state or a large company, but is not justified for volumes of medium or small firms. Promising directions in terms of automation of interpretation are cloud access to the capabilities of these complexes with server-based computing, as well as the use of neural networks for this purpose. Aerial photography for the purpose of topographic survey of 1:1000 - 1:2000 scales for the purposes of feasibility studies and HPP design in mountainous conditions has a number of advantages over tacheometric survey, namely:

1. Significant reduction of fieldwork time.
2. Significant reduction in the cost of geodetic surveys.

However, there are a number of complexities that need to be taken into account when working in a mountainous environment:

1. The need to predict the position of the satellite constellation when taking satellite measurements for the establishment of air defence sites and the coordination of identification marks.
2. The UAV flight mission software shall have the ability to change the UAV altitude during flight to maintain a constant distance from the ground to the UAV.
3. When using GPS receivers in RTK mode, use radio modem frequencies below 200 MHz.
4. When creating a flight task, take into account significant differences in altitude to avoid collisions with mountainsides and tall vegetation. Carry out manual test flights.

Thus, the comparative analysis has shown that the best results are achieved with the combined use of traditional geodetic methods and remote sensing. Traditional methods provide maximum accuracy for local measurements, while RS provides scalability, timeliness and regularity of data, which allows to effectively monitor dynamic changes over large areas. This combination of methods is optimal for ensuring reliable and safe operation of hydraulic structures.

Conclusion and Recommendation

The following conclusions can be drawn on the basis of the conducted research. The integrated application of traditional geodetic works with the use of remote sensing data, including satellite images and aerial photography, significantly improves the accuracy of monitoring of hydraulic engineering objects, such as dams and sluices:

- accuracy of interferometry with synthetic aperture (InSAR) in measuring object deformations is 1-5 mm, which makes this method extremely effective for monitoring even the smallest changes in the design of hydraulic structures;

- using Sentinel satellite data can reduce monitoring costs by 30-40% by reducing the need for regular fieldwork and using high-quality, open-access data;
- application of Sentinel satellite data and other remote sensing platforms can reduce the time for data collection and processing by 50-60% compared to traditional methods, where considerable time is spent on field work and desktop data processing;
- Sentinel-1 satellites provide data every 6-12 days, allowing regular monitoring without significant time delays. In comparison, traditional field surveys are conducted no more than 1-2 times a year, which makes them less effective in detecting dynamic changes;
- use of remote sensing reduces equipment costs, as satellite data is available for free or at low cost. For example, equipment for high-precision field surveys (total stations, GNSS receivers) can cost between 20,000 and 50,000 dollars, while data from Sentinel satellites are available free of charge;
- remote sensing techniques such as InSAR or drone photogrammetry can cover areas up to several thousand square kilometers in a single survey. In comparison, traditional methods are limited to localized areas and require significantly more time to cover large areas;
- use of digital elevation models (DEMs) based on SRTM and Sentinel data allows to detect elevation changes with an accuracy of up to 30 meters. This is especially important for monitoring erosion processes and other geomorphologic changes that may affect the condition of hydraulic structures.

One of the key results of the study is the confirmation of the high efficiency of remote sensing methods in geodetic monitoring, which allows reducing the risks of emergency situations and extending the service life of hydraulic structures. The data obtained allow to identify changes in the design and assess their impact on operational reliability. Analysis of water levels in dams using SAGA GIS tools, as well as watershed monitoring, demonstrate that these methods can be effectively applied to improve water management and prevent flooding.

Thus, the results of the research confirm that the use of remote sensing in combination with geographic information systems significantly expands the capabilities of traditional methods of geodetic monitoring, improving the safety and reliability of operation of hydraulic structures.

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