Calculating the water surface area - a comparative analysis between results obtained from open data of optical and radar sensors

Nikolay Mitev [1], Silviya Katsarska-Filipova [1], Dobromir Filipov[1], Paulina Raeva [1]

[1] University of Architecture, Civil Engineering and Geodesy (UACEG), Faculty of Geodesy, Dept. of Photogrammetry and Cartography, Sofia, Bulgaria - nikolaimitev17@abv.bg, filipova_fgs@uacg.bg, filipov_fgs@uacg.bg, paulina.raeva@gmail.com

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Abstract

Deforestation of large areas and climate change are potential flood threats. This necessitates the creation of an effective technological scheme for monitoring water bodies. The aim of this study is to analyse the results obtained from the application of open satellite data. The research team worked with radar and optical data from the Sentinel-1 and Sentinel-2 missions. The study was conducted over the period from January 2021 to December 2023. The research is focused of Koprinka dam near Stara Zagora in Bulgaria, where significant changes in the area of the water surface are observed, underlining the need for enhanced monitoring. A comparison was made between the results of optical, radar, and direct geodetic measurements. The need to compare results from optical and radar imagery arises from the fact that each has its own strengths and weaknesses, with the advantages of one type of imagery compensating for the shortcomings of the other. It is therefore crucial to determine whether the results are consistent to ensure that we have a solution at all times, regardless of climatic conditions and other factors. In order to be able to extract quantitative characteristics from the images, it is necessary to convert the resulting raster data into vector data. As a result, a vector layer with a mask of the water area of the dam for the corresponding date of the image is created from the input binary image. The final results of the research are presented in the form of a web map.

1. Introduction

In Bulgaria, the monitoring of dams is carried out using the methods of classical geodesy and the data are provided by the „Water Resources“ Sector, Production and Maintenance Planning Department of NEK EAD. The measurements with a total station of the flooded areas and water levels of the dam require too much time and resources.

This study presents a comprehensive analysis of water surface computation using both optical and radar satellite data, demonstrating the potential of Sentinel-1 and Sentinel-2 imagery for water resource management. Water body monitoring is an important part of environmental research. Collecting reliable and consistent data allows research and analysis to be carried out at any time and to cover longer time periods.

There are two main categories of sensors that are used to measure surface water: optical and microwave. Microwave sensors use long-wavelength radiation that allows them to penetrate cloud cover and certain types of vegetation. They can function independently of solar radiation, which means they have the ability to operate both day and night, in all weather conditions. Optical sensors are widespread in the field due to the large amount of data available and appropriate spatial and temporal resolutions (Huang, et al., 2018).

Radar (active) systems use electromagnetic waves of much longer length than optical systems, allowing the observation of a variety of physical processes. These waves, which have a length of about 1 cm to 1 meter, interact differently with the observed objects and the environment. One of the key features of radar systems is their ability to penetrate clouds relatively easily, although there is a reduction in the speed and strength of these waves. This allows observation in all weather conditions (Čotar, et al., 2016).

The Sentinel-1 mission comprises two polar-orbiting satellites operating day and night, performing C-band synthetic aperture radar imaging, enabling them to acquire imagery regardless of the weather conditions. The SENTINEL-1 mission is equipped with a C-band synthetic aperture radar instrument operating at a central frequency of 5.405 GHz. This instrument includes a right-looking active phased array antenna, providing rapid scanning in both elevation and azimuth (European Space Agency, 2022)

Various combinations of spectral bands can be used for different purposes.

This article is dedicated to the use of open-source products and data. The images used are freely available through the Copernicus Open Access Hub. The processing and analyses were performed using programs SNAP (Sentinel Application Platform) and QGIS.

The study was created using open data and open-source software to be able to contribute to reproducibility, community engagement, accessibility, reusability.

2. Study Area and Dataset

2.1 Study Area

The object studied in this article is the Koprinka dam (42°36'37.64 "N, 25°19'05.13 "E). It is located in Bulgaria, Stara Zagora region (Figure 1).

Figure 1. Geographical location of Koprinka dam (42°36'37.64 "N, 25°19'05.13 "E)

The dam was built on the Tundja River and is a major part of the Koprinka hydroelectric dam, located west of the town of Kazanlak.
The dam is intended for irrigation, water supply and power generation. Stara Zagora and Koprinka hydropower plants, which were put into operation in 1955 (NEK EAD, 2023).
Over the last few years, dynamic changes have been observed in the water volume and, consequently, in the water surface area of the Koprinka dam.
The presence of multiple settlements and the strategic importance of the dam for irrigation, water supply and power generation are prerequisites for enhanced monitoring.

2.2 Dataset

The space images used in the paper, acquired by the Sentinel-1 and Sentinel-2 sensors, were downloaded from the Copernicus Browser platform. This Copernicus Data Browser is a key resource for accessing, exploring and exploiting the vast variety of Earth and environmental observational data provided by the Sentinel satellites of the Copernicus missions. Using Sentinel Hub's EO Browser, users can visualize, compare, analyze, and download this data for applications ranging from environmental monitoring and disaster management to urban planning and agricultural activities.
The study period of the Koprinka dam is January 2021 - November 2023. One image was downloaded for each odd month during the year, i.e. 6 images per year or 18 images in total for the period of 3 years (36 images in total with both sensors). Due to the fact that the Sentinel-2 optical images have some disadvantages compared to the Sentinel-1 microwave images, such as dependence on a power source (sunlight) and good weather conditions, they were selected first.
There are two approaches to selecting optical images. The first approach is to set a minimum cloud cover, month and year, then manually evaluate the images that meet the specified parameters. The second approach is to set the desired parameters, resulting in a list of images. We have chosen to use the first option due to the shorter time to evaluate the image quality.
As opposed to optical images, microwave images are more convenient to set parameters in the "SEARCH" window, because there is no need to make a preliminary visual assessment. We have selected the acquisition mode IW (inferometric wide-range) with a resolution of 10x10m. The highest possible resolution is 3.5x3.5m., but such products are not available for the period studied. Another criterion by which the demand for the products can be specified is polarisation. The polarization of the radiation, plays an important role, when considering the propagation and scattering of microwave energy. The polarisation of a plane electromagnetic wave is determined by the orientation of the electric field vector in the plane perpendicular to the direction of propagation. The amplitude of the wave is expressed by the length of the vector and the frequency of the wave by the rotational velocity of the vector. Polarization determines the orientation and shape of the waves, distinguishing them as predetermined (polarized) or random (unpolarized), or a combination of these. In the latter case, the degree of polarization describes the ratio of polarized power to total wave power. Wavelength and polarization affect the way the radar system "sees" the elements in the scene. Therefore, radar images collected with different combinations of polarizations and wavelengths can provide different and complementary information. Furthermore, when the three polarizations are combined into a color composite, the information is presented so that the image interpreter can infer more information about surface features.

3. Workflow

Sentinel application platform (SNAP) provides functions for fast automatic processing of multiple images, by setting the necessary parameters in advance. Such functions are Graph Builder and Batch Processing. These are used to achieve automatic interpretation of all optical and radar images with a single preset of the required processing parameters.

3.1 Workflow for optical images

Images from Sentinel-2 are divided into several levels of processing before being displayed in the Copernicus Browser. Images used are from Level-2A. This level is the finished product that the Copernicus program offers. All radiometric and geometric corrections are applied to it, so it is not necessary to perform them when processing the images in the SNAP software product.
Before creating a workflow, we decided to try out different color composites to choose the methodology where the water is seen as contrasted as possible. We used four different approaches - true color composite, NDWI (Normalized Difference Water Index), NDMI (Normalized Difference Moisture Index) and mNDWI (Modified Normalized Difference Water Index) when working with Sentinel-2 (Figure 2).
In the true-color composite, water is not of good contrast and may not be fully recognized. In the presence of NDWI or mNDWI, the water appears white and the vegetation appears dark. The modified normalized difference water index, gives better results at water bodies surrounded by urban terrain or dense vegetation, but unlike the regular normalized difference water index, biases the results at high soil moisture.
Very often, the Normalized Difference Water Index is mistakenly used as a synonym for the Normalized Difference Moisture Index, but the two indices work very differently. The NDWI successfully emphasizes water bodies, while the NDMI emphasizes differences in water content in foliage and soil.
Based on this analysis, we concluded that our methodology should be developed by calculating the NDWI and mNDWI as a ways to extract surface water.

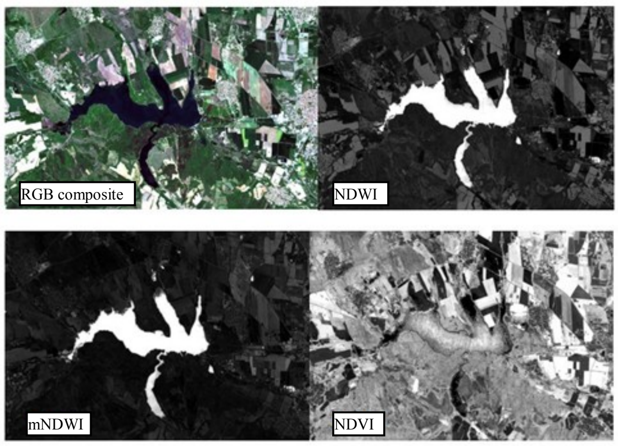

Figure 2. State of the Koprinka reservoir on 5th Jan. 2021 seen in true-color composite, NDWI, mNDWI and NDMI

Figure 3 shows the attached technological scheme for the overall optical image processing and analysis.

The spectral reflectance of water is primarily characterized by the absorption of energy in the near-infrared and farther regions of the spectrum (>0.8 μm). Water demonstrates this absorption

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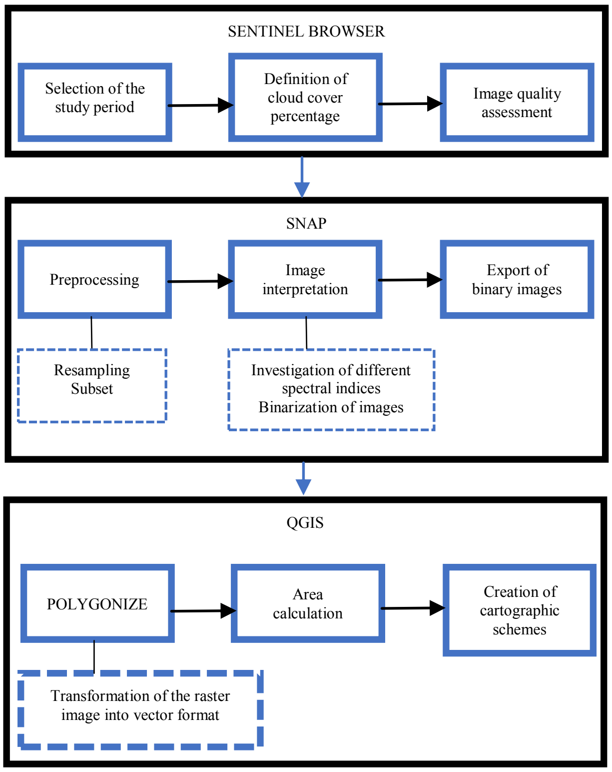

Figure 3. Optical image processing and analysis

characteristic in its various forms, both in stand-alone bodies of water such as lakes and rivers, and in water that is part of vegetation or soil. Identification and tracking of water objects using remote sensing data are most effective in the near-infrared wavelengths because of this absorption capability. Energy-material interactions at these wavelengths are extremely complex and depend on many interrelated factors. For example, the reflection from a body of water may be an interaction with the surface of the water (specular reflection), with material in the water, or with the bottom of the body of water (Lillesand, et al., 2015).
There are many complex relationships between the spectral reflectance of water and certain characteristics.
A spectral index is an equation that combines pixel values from two or more spectral bands in a multispectral image using various algorithms, mainly focused on band ratio or feature scaling (e.g., normalized or standardized algorithms). These indices typically exhibit greater sensitivity than individual spectral bands for detecting spectral signatures. In the context of Earth surface observation, spectral indices have significantly contributed to a more thorough understanding of environments and ecosystems across space and time (Tran, et al., 2022).
The processing workflow is shown in (Appendix 1).
Automatical satellite image processing in SNAP consists of the following functions:
• Read – reading of a selected "input" product
• Resample – resizing the discretization step
• Subset – creating a subset (area of interest)
• Band Maths – create a multi-channel product based on mathematical expressions
• Write – record of the newly formed "source" product
• BandMaths A is NDWI – normalized difference water index – (B3-B8)/(B3+B8)

$$NDWI = \frac{G-NIR}{G+NIR} \quad (1)$$

where G is a value of a green band
NIR is a value of a near infra-red band

• BandMaths C is NDMI-normalized difference moisture index - (B8-B11)/(B8+B11)

$$NDMI = \frac{NIR-SWIR}{NIR+SWIR} \quad (2)$$

where NIR is a value of a near infra-red band
SWIR is a value of a short wave infra-red band

• BandMaths D is mNDWI mean normalized difference water index – (B3-B11)/(B3+B11)

$$mNDWI = \frac{G-SWIR}{G+SWIR} \quad (3)$$

where G is a value of a green band
SWIR is a value of a short wave infra-red band

• BandMaths B E is creating a binary image
If mNDWI>0 then 1 else 0 (4)
If NDWI>0 then 1 else 0 (5)

When an indexed image is created, the newly generated pixel values are in the range -1 to +1, with the pixel values reflecting the water areas in the range from 0 to +1. Using formulas (4) and (5), the images are binarized by setting the condition that if the pixel values of the indexed image are greater than 0, then in the binary image they get value = 1, and if they do not satisfy the condition, they get value = 0 (Figure 4.)

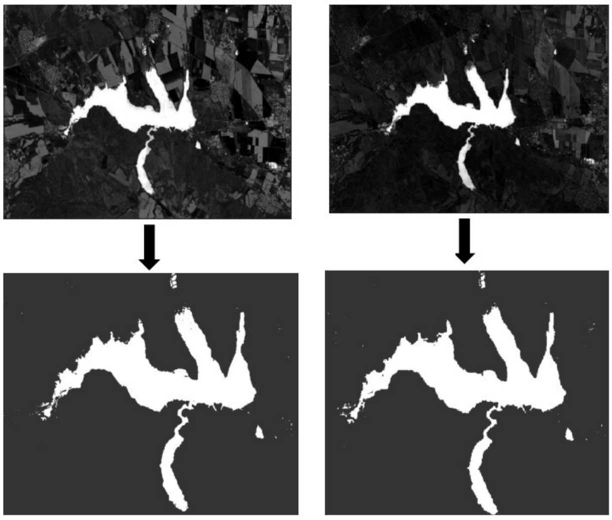
Figure 4. Binarization of index images

Batch Processing is a SNAP tool that allows a series of operations to be performed repeatedly on a large number of input images.
It is necessary to specify a pre-created template in .xml format, in which the desired operations and parameters for execution are specified. The (Figure 5.) shows the Batch Processing loaded with input data and operations.
The binary images obtained during image processing in the SNAP environment were saved in GeoTiff format. Then imported into QGIS to extract quantitative features.
In order to extract quantitative features from an image, it is necessary to convert the raster data to vector data. As a result, a vector layer with a mask of the water area of the dam is created for the corresponding image date.

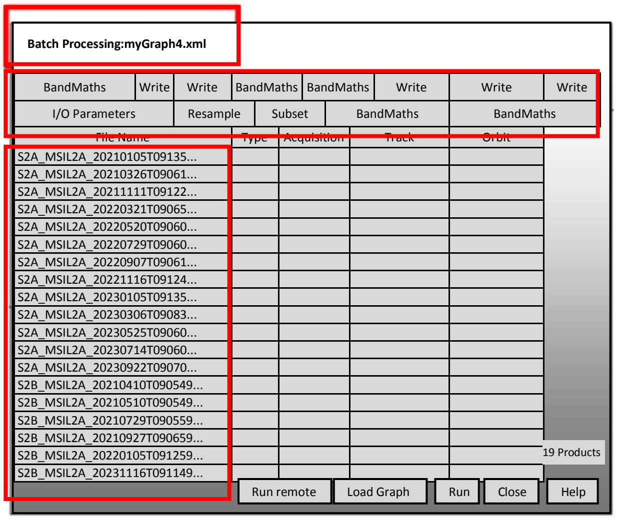

Figure 5. Batch processing for all optical images for the study period

Each layer has an attribute table, attributes carrying information about the object can be added to it. The area of the dam is such an attribute. To be calculated area, the calculator of the attribute table is used.
If the project has an ellipsoid set, the area will be calculated as ellipsoidal. If no ellipsoid is specified, the calculated area will be planimetric. Since the unit of measurement for area is m² in the project settings, the `$area` function is divided by 1000.

3.2 Workflow for radar images

Figure 6. shows the attached technological scheme for the overall radar image processing and analysis.

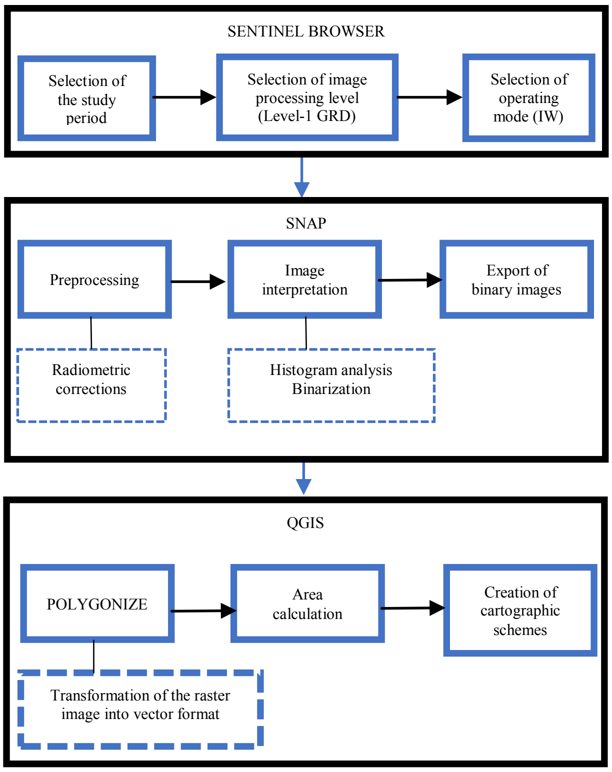

Figure 6. Radar image processing and analysis

Unlike optical images, automation in radar images can only be reduced to applying radiometric and geometric corrections (Appendix 2). In order to determine the water areas of the scene, it is necessary to analyse the histogram of each image and visually evaluate the obtained results.
As a result of the calibration of the images, calibrated values of the backscatter (σ^0) are obtained. After applying the texture filter and terrain correction, the linear backscatter values were transformed into logarithmic. By performing this transformation, a scaling of the values is achieved, which contributes to a more visual comparison and analysis of the image.
From each input image, a geometrically and radiometrically corrected image is obtained whose values reflect the calibrated backscatter intensity values of the scene objects (Figure 7.).

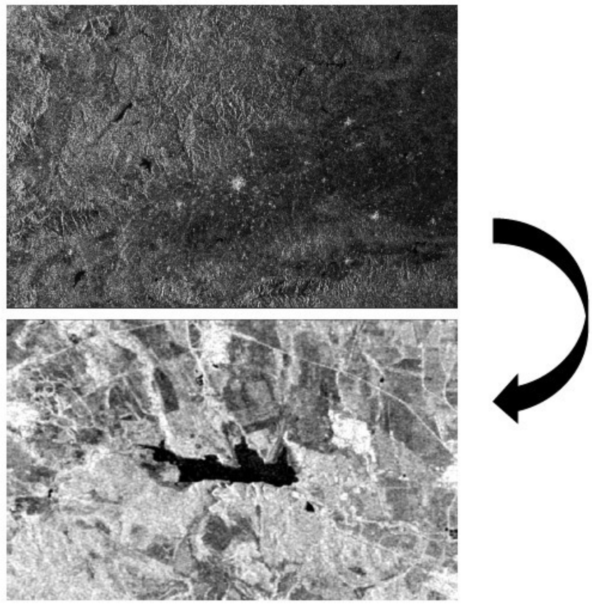

Figure 7. Original and geometrically and radiometrically corrected radar image

By histogram we analyse the characteristics of the distribution, such as symmetry or asymmetry, unimodality or bimodality, presence of outliers, and others.
To determine the water areas from the radar image, an analysis of the backscatter histogram is performed (Figure 8.). The histogram is a visual representation of the empirical distribution of a continuous quantitative variable. This is obtained from observations on a variable that can take values on a continuous scale. It is an approximation of the density function of the distribution of a random variable that is a model of the observed variable.

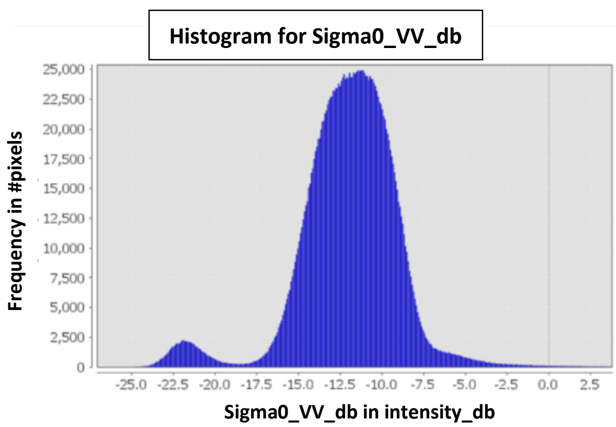

Figure 8. Histogram of radar image scatter values

For each image, a histogram of the channel σ0 is formed. In order to create a binary image, it is necessary to define an interval in which the backscatter intensity from the water areas is reflected. For this purpose, randomly distributed points are placed along the water body (Figure 9.) and a profile is created (Figure 10.)

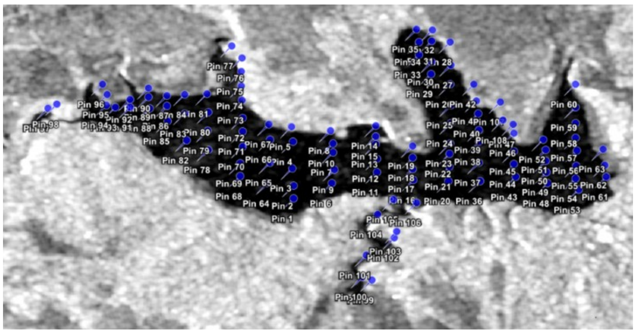

Figure 9. 100 randomly distributed points along the water body

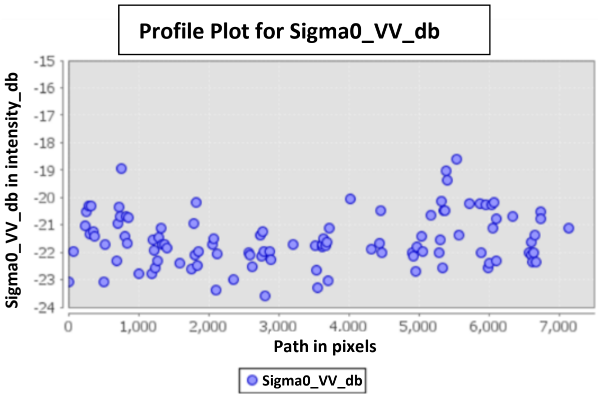

Figure 10. Create a profile

The backscatter intensity values are located along the ordinate of the profile. It can be seen from the figure that all pins placed on the water areas fall in the interval [-18; -24] dB. This interval is used when creating a mask of the water areas, or more precisely, a binary image. It is important to note that this interval is not constant and varies for each individual image.
After further analysis of the histograms of all images, it was concluded that 15 of the 18 images have a strong bimodal structure. For the remaining 3 images, randomly distributed points along the object were placed to determine the interval.
Once the range of values reflecting the water territories has been determined, we move on to creating a binary image using the BandMaths operator. The general form of the equation used is as follows:

If $\sigma^0 < i$ then 1 else 0 (6)

where σ^0 = backscatter channel
i = larger value of the specified interval

This equation results in binary representations in which water areas are given a value of 1 and all other areas are given a value of 0. These images were imported into QGIS where the areas of the water bodies of the scene were determined.

3.3 Integration of Results in GIS

Using vector layers, a web map of the Koprinka dam was created, containing all layers, a cadastral map overlay and an Open Street Map overlay. The web map was created using the "qgis2web" add-on to the QGIS software. The plug-in allows to perform various settings on the web map, such as displaying different information from the attribute table of a selected layer, performing different measurements, displaying coordinates, searching by address or coordinates, etc. From the 36 images, 18 mapcharts were created, presenting graphical and tabular information about the images. The coordinate system used for the web map and the cartograms is BGS2005 - Cadastral.
The interactive web map enables the visualisation of characteristics of a selected object once it is clicked.
The web map can be visited via the following link: https://nikolaymitev17.github.io/koprinka

4. Results and Analyses

Figure 11 graphically presents the changes in the water surface area for the period from the beginning of 2022 to the end of 2023.

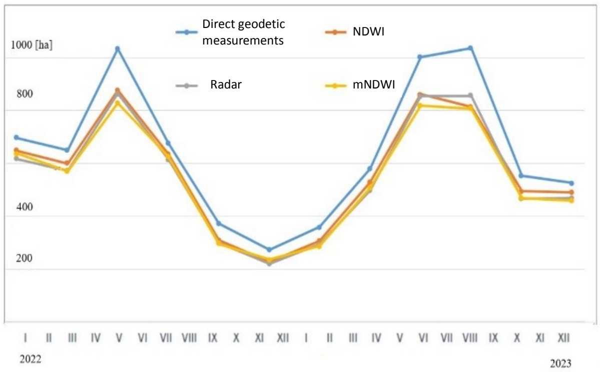

Figure 11. Changes in the water surface area

Table 1. presents a comparison of surface water areas obtained from different types of imagery for 2 years (2022-2023)

Type of image	Surface water area differences [%]	
	min	max
mNDWI / NDWI	0.9%	6%
NDWI / Radar	0.9%	7%
Radar / mNDWI	0.2%	6%

Table 1. Surface water area differences

Table 2. Presents a comparison of surface water areas obtained from different types of imagery and direct geodetic measurements for 2 years (2022-2023)

Other data	Type of image	Surface water area differences [%]	
		min	max
Calculated water surface area from direct geodetic measurements	mNDWI	9%	19%
	NDWI	6%	21%
	Radar	8%	22%

Table 2. Comparison of results with direct geodetic measurements

The comparisons between the obtained results and the direct geodetic measurements indicate that the smallest differences are

observed in the water surface areas derived from the Normalized Difference Water Index (NDWI).
Larger discrepancies are found in the water surface areas obtained from radar imagery and the Modified Normalized Difference Water Index (mNDWI).

5. Conclusion

The integration of multispectral and radar imagery, combined with advanced image processing methods, enables a detailed understanding of the dynamics of water bodies. This study demonstrates the potential for integrating remote sensing technologies and Geographic Information Systems (GIS). Their combination supports strategies for water resource management. Through the use of multispectral and radar imagery, water surfaces can be effectively mapped and analyzed. The integration of obtained results within a GIS environment facilitates efficient data storage, management, and visualization, allowing decision-makers and specialists to make informed management decisions based on reliable and up-to-date information.
In the future, this study could be further expanded by analyzing soil moisture and vegetation surrounding the dam, which is possible through the use of the Normalized Difference Moisture Index (NDMI). Such analyses may reveal relationships between moisture levels and variations observed across different indices and image types, contributing to achieving more precise and reliable results in future studies.
Utilizing Sentinel-1 and Sentinel-2 imagery enables a broader range of analyses. For example, optical images from Sentinel-2 can be used for bathymetric analysis of the reservoir bed or for assessing water quality (e.g., determining chlorophyll levels, phytoplankton concentration, turbidity, etc.). Meanwhile, radar imagery can be applied to quantify volume differences between multiple acquisitions by generating digital elevation models through InSAR (Interferometric Synthetic Aperture Radar) processing.

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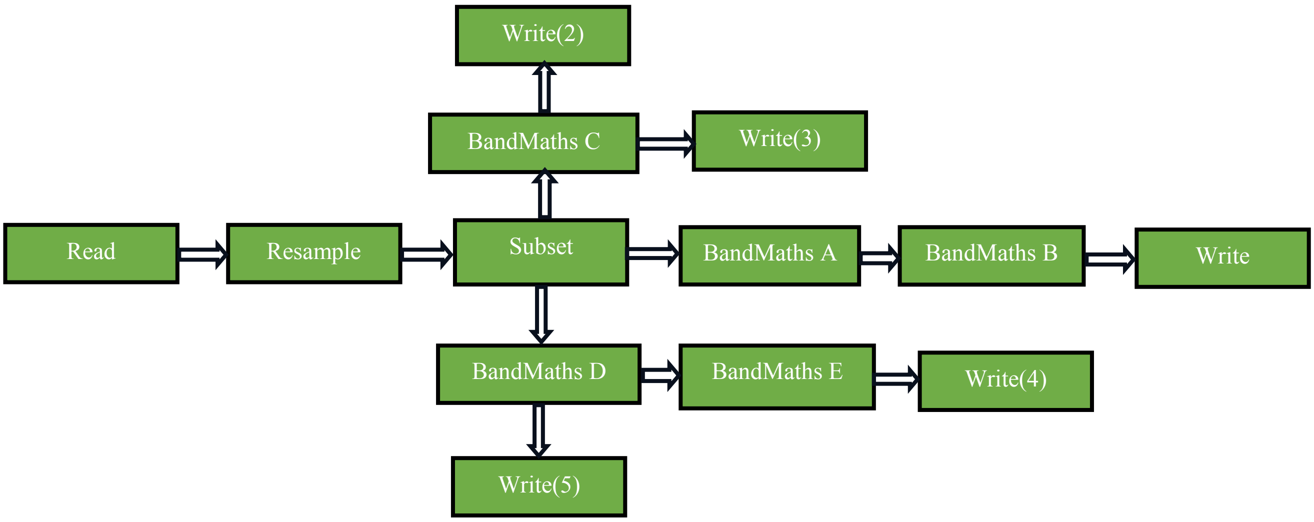
Appendix

Appendix 1 Automatic optical satellite image processing in SNAP



Appendix 2 Automatic radar satellite image processing in SNAP