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Combining Optical and Lidar Satellite Observations for Water Level Assessment in Reservoirs

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Summary
Reliable monitoring of standing water bodies, and in particular their water level, is of critical importance for water resource management, hydropower operations, climate change adaptation, and, not least, the prevention of anthropogenic hazards. Remote sensing provides a robust alternative to traditional in situ measurements, offering large-scale and regular coverage of the areas of interest. This study presents the application of a combined approach for water level assessment based on the integrated use of optical data from the MSI sensor onboard Sentinel-2 (ESA, 2025) and LiDAR measurements from the GEDI (Global Ecosystem Dynamics Investigation) mission (UMD, 2025). The method involves delineating the water surface from Sentinel-2 (S-2) imagery using spectral indices (NDWI, MNDWI) and deriving the elevation of the water surface from GEDI profiles. The integration of these two data sources enables simultaneous spatial and vertical characterization of the water body. The case study focuses on the "Kardzhali" Reservoir, located in the Eastern Rhodope Mountains, with analyses performed for the summer months of 2023. The spatial masks of water extent were generated through morphological processing of MSI data and revealed a water surface area of approximately 10 km². S-2 scenes were carefully selected to coincide with GEDI ground tracks crossing the water surface, thereby providing 115 elevation points with an average level of 351.80 m a.s.l. and a variation below 0.20 m. The obtained results confirm the applicability of the proposed method for the joint use of S-2 and GEDI data and demonstrate the potential of the integrated approach for reliable monitoring of standing water bodies. Despite limitations related to the discrete coverage of GEDI and the dependence of S-2 on cloud-free conditions, the method proves suitable for reservoirs with well-defined shoreline boundaries.

Introduction

Reliable monitoring of water bodies is of key importance for water resource management, hydropower operations, and climate change adaptation. Remote sensing provides an alternative to traditional ground-based measurements by offering large-scale and regular coverage.

Optical sensors onboard satellites, such as S-2 and the Landsat series, enable the delineation of water-covered areas through the application of spectral indices (e.g., NDWI, MNDWI) (Gao, 1996), while radar-based satellite systems (e.g., Sentinel-1) allow for data acquisition independent of cloud cover and external illumination. In the past decade, LiDAR technologies have increasingly advanced, including spaceborne missions such as GEDI and ICESat-2 (ICESat-2, 2025), which provide discrete measurements of the elevation of terrestrial and aquatic surfaces.

The aim of this study is to demonstrate the advantages of applying a combined approach for assessing the water level of standing water bodies by extracting water extent from S-2 data for a specific reservoir using spectral indices and incorporating LiDAR-derived measurements to determine the elevation of the water surface. The complementary use of these two data sources enables the simultaneous spatial and vertical characterization of reservoirs.

Researched Object

The Kardzhali Reservoir, located in southern Bulgaria, is one of the three major reservoirs—together with the Studen Kladenets and Ivaylovgrad reservoirs—that utilize the waters of the Arda River as part of the Arda Cascade operated by the National Electric Company. The reservoir is constructed on the Arda River and has a catchment area of 1,882 km² (Nabatov et al., 2011). Its average annual inflow is 30.5 m³/s. The reservoir is situated within a polygon defined by the following coordinates: SW [41.61445835262785, 25.147239073514072] and NE [41.71832939138223, 25.340873106717197].

The dam wall is a concrete arch-gravity structure—the only one of this kind in Bulgaria. Its maximum height from the foundation is 103.50 m, and the crest length is 344 m (Nabatov et al., 2011). The crest elevation is 331.45 m a.s.l., ranking the dam as the third highest in Bulgaria. The wall consists of 25 blocks, with its upstream face designed as a vertical circular cylinder with a radius of 150 m, while the downstream face is formed by circular arcs of varying radii (Nabatov et al., 2011).
This reservoir is particularly suitable for demonstrating the proposed research method due to its clearly defined shoreline and the availability of a sufficient number of GEDI profile points covering the water body area.

Data

Optical sensors, such as those onboard the S-2 and Landsat satellites are widely used for delineating the extent of water surfaces, and spectral indices derived from them have been applied by Pipitone et al. (2018) in their study. The used spectral bands from S-2 optical imagery have spatial resolutions of 10 and 20 m. For extracting the water surface, the spectral indices NDWI and MNDWI were calculated using combinations of the green, near-infrared, and shortwave infrared regions of the electromagnetic spectrum (Gao, 1996). S-2 scenes were selected under the following conditions: complete coverage of the study area and less than 10% cloud cover for the summer period of 2023.
GEDI is a LiDAR instrument onboard the International Space Station delivering profiles with elevation and beam quality information following the ground orbital trace of the station. The data consist of point-based measurements distributed along orbital tracks and do not provide continuous spatial coverage, yet they allow highly accurate elevation measurements. For this study GEDI data products (granules) within ±5 days of the S-2 acquisition dates were selected under the assumption that the water level didn't undergo substantial variation during that 10 days period.

Methods

Extraction of Water Surface Area from S-2 Data

To generate the water mask S-2 images were processed to calculate the NDWI and MNDWI spectral indices, from which binary raster layers were created. Following the initial binarization of water pixels morphological operators were applied to remove single and noisy pixels as well as small scattered objects. Specifically, erosion and closing operators were used as part of the subsequent image processing. In addition, a *focal_min* operator was applied to generate an inward offset of one pixel from the shoreline, thereby eliminating mixed pixels in coastal zones and ensuring a more accurate and reliable separation of the water surface from other land-cover classes.

Processing of GEDI Data

The LiDAR data from GEDI can be processed both on personal workstations using specialized software and in cloud-based environments such as Google Earth Engine (Hamoudzadeh et al., 2025), which enable similar analyses. The selected GEDI data products, made available from the online archive (NASA, 2025), were processed on high performance workstation starting with filtering according to the geometry of the study area, and only those points falling within the water mask derived from S-2 were extracted. This was achieved through spatial intersection of the GEDI vector data with the vectorized water mask obtained from S-2 raster. During the analysis, the attributes *elevation* and *beam quality* were used, with low-quality measurement points excluded (see Figure 1).

Results

The results presented below confirm the potential of GEDI data for monitoring the dynamics of standing water bodies. The water mask derived from S-2 data delineates a clearly defined water surface with an area of 10.1 km² for the selected dates. The morphologically refined mask effectively eliminated isolated noisy pixels and minimized boundary inconsistencies along the shoreline, thereby providing a reliable spatial representation of the water surface.
After spatial filtering, the GEDI points falling within the water mask provided discrete measurements of the water surface elevation. For the specific scene analyzed over the reservoir, 115 valid points were identified, corresponding to an average density of 11 points/km². The mean water level for the observed period was 351.80 m, with a variation of approximately 0.18 m among individual measurements. The minimum value was 351.21 m, while the maximum reached 352.41 m, with the highest values likely resulting from surface reflections or minor wave effects. This represents a highly stable result, as the variation remained below 20 cm, thereby

confirming the reliability of GEDI measurements over water surfaces. On figure 2 illustrated is the distribution of water surface elevations relative to their frequency within the produced GEDI data set.

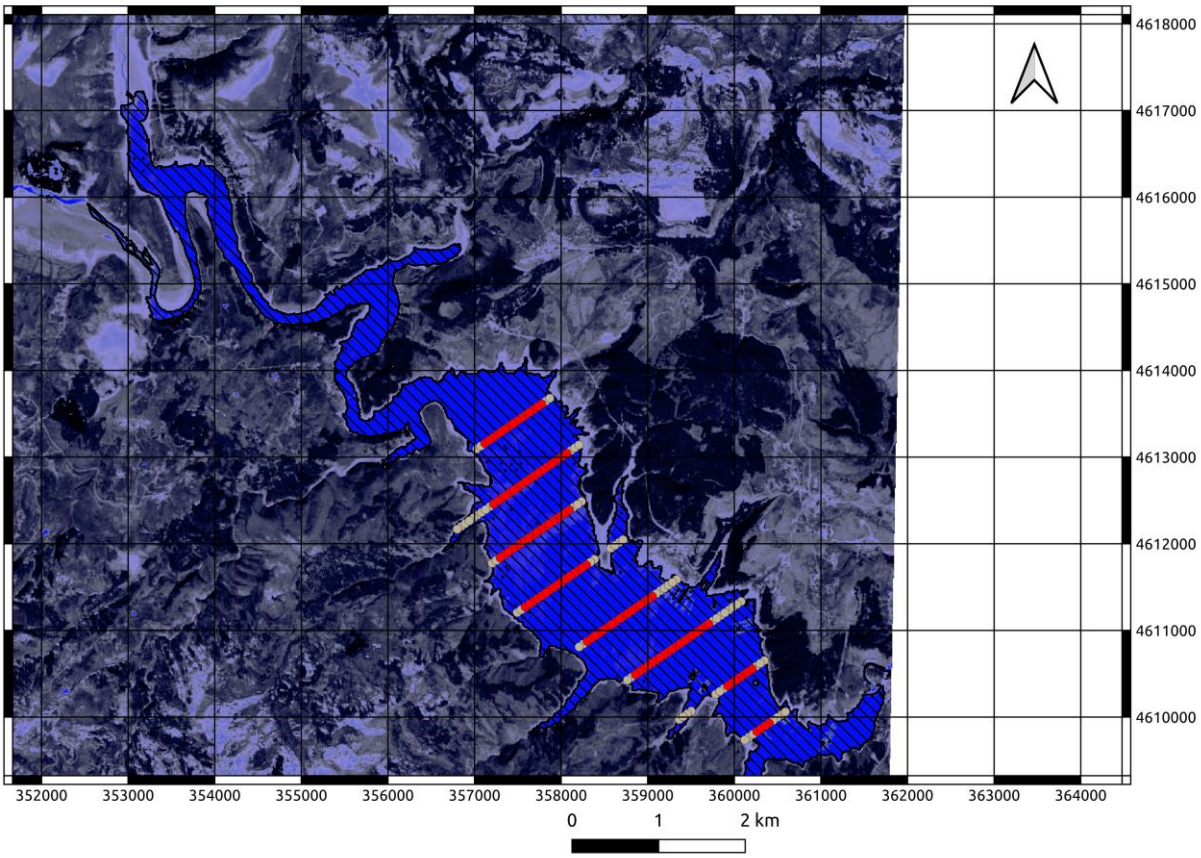


Figure 1. Calculated NDWI index. Generated spatial–vector mask. GEDI data filtered and intersected with the mask.

Discussion

The proposed combined approach demonstrates the advantages of integrating optical and LiDAR data for monitoring water levels in surface standing water bodies (e.g., lakes and reservoirs). S-2 data provided reliable spatial information on the extent of the water surface, while GEDI delivered direct elevation measurements at discrete points within the study area.

The method also has limitations, such as the moderate spatial resolution of S-2 imagery and its dependence on cloud-free conditions, as well as the track-based nature of GEDI measurements, which cover only strips across the water surface rather than producing continuous imagery. Despite these constraints, the spatial–elevational integration of the two data types enabled a more precise assessment of water levels compared to the use of either data source alone.

It should be noted that the proposed method is suitable for monitoring standing water bodies with well-defined shorelines and available LiDAR profiles, and it may potentially be extended through the inclusion of additional satellite missions (e.g., ICESat-2) or radar-based observations for periods with cloud cover.

The visualization of GEDI profiles overlaid on the water mask confirms the correspondence between the area delineated from S-2 data and the elevations derived from GEDI measurements. The combination of the two data sources enables a reliable assessment of both the water level and the spatial distribution of the water mass within the reservoir. The method demonstrates significant potential for application in the monitoring of other water bodies of this type.

Conclusions

This study presented proof for a concept concerning the combined method for assessing reservoir water levels integrating remotely sensed data from passive (S-2) and active (GEDI) satellite instruments. The joint use of both sources enabled a reliable evaluation of water level, including mean elevation and its spatial distribution, across whole water surface. The proposed approach may be further extended through the incorporation of

additional satellite-based instruments, thereby facilitating continuous and sustainable monitoring of water resources. Future perspectives for the development of this method include the integration of data from ICESat-2 or synthetic aperture radar (SAR) sensors to provide short-term, and potentially continuous monitoring under varying atmospheric conditions.

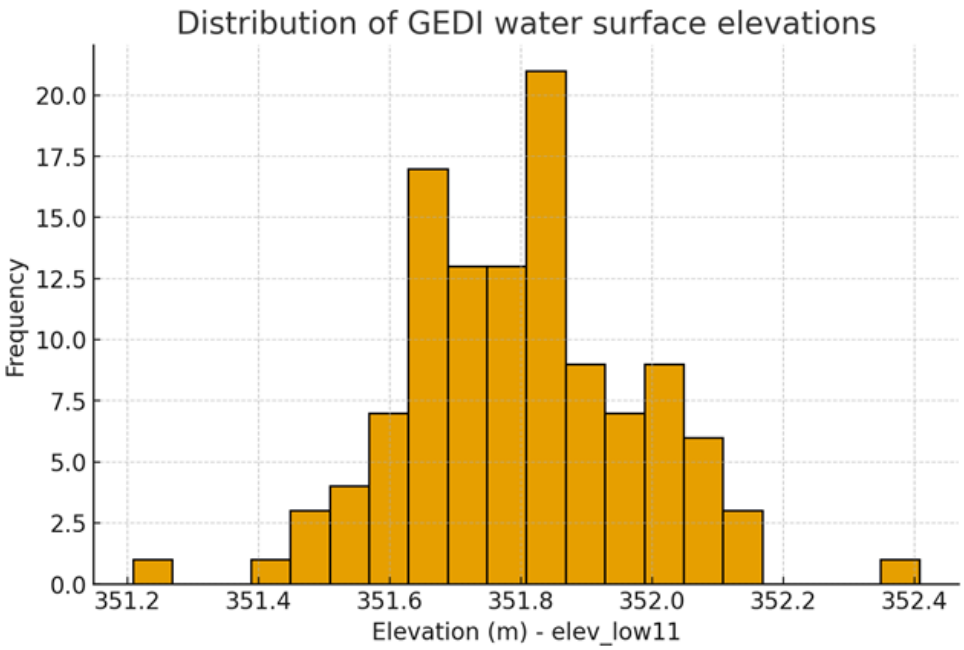


Figure 2. Distribution of water surface elevation based on GEDI data.

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