Assessing Water Loss and Sediment Deposition at Mavrokolympos Dam Using Multimodal Methods: TLS, UAV, and Satellite Imagery

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ABSTRACT

The climate zone of Cyprus is characterized as semi-arid climate followed by hot, dry summers and mild winters with low rainfall. For addressing water scarcity during the dry summer months, the Cypriot government implemented a policy of constructing reservoir dams across the island. Most of these dams were built after 1960 and are now ageing. The sudden water evacuation of the Mavrokolympos Dam in Paphos, Cyprus, due to a ventilating system failure provided a rare opportunity to assess rapid water loss and sediment transport within the reservoir over time and the outflow sentiment volume during the water loss event. This study integrates terrestrial laser scanning (TLS), unmanned autonomous vehicles (UAVs), and a time series of PlanetScope satellite images to analyze pre- and post-evacuation conditions focusing on the initial water body mass just before and immediately after the event occurred. The satellite images were used to delineate the waterbody's extent before and after drainage, enabling volume estimation of the water loss. TLS and UAV surveys captured high-resolution topographic data of the emptied reservoir, validating satellite-derived volume estimations through a Digital Elevation Model (DEM). Additionally, the sediment layer deposition in the reservoir was quantified providing insights into the waterbody mass of the dam at full capacity in recent years, also allowing for an assessment of sediment displacement towards the river mouth. This multimodal approach enhances our understanding of reservoir dynamics, water resource management, and sediment transport processes following abrupt drainage events.

Keywords: Dam, water, Remote Sensing, TLS, UAV, PlanetScope, Cyprus

INTRODUCTION

Water not only affects third-world communities; it is also a significant issue for the small eastern Mediterranean island of Cyprus. It is an example of how water is managed and accessed in Europe and generally to highlight water problems impacting in larger cities and regions globally in the forthcoming future [1]. Cyprus initiated a program back in the 60's which created water dams across the island on nearly all main rivers to address its high-water stress, driven by rainfall variability and increasing water demand [2].

Globally the dams face the sedimentation process which accumulates in dams and undermines their capacity storage. This has a direct impact on their ability to deliver the initial supply that the dam was designed for, such as potable use and agricultural demands [3]. This process taking place in the dams behavior regarding storing water is globally an issue that is under research and development for solutions, as maintaining a dam is quite a challenge. Sedimentation can obstruct dam operations and cause possible failures by affecting intake and outlet functions [4]. The Mavrokolympos Dam, located in the region Paphos, Cyprus, exemplifies in all above-mentioned concerns. Built in 1966 as an earthfill dam with a design capacity of ~2.2×10^6 m^3 and surface area ~0.175 km^2 at full supply, it has been playing a key role in local irrigation. In January 2025, a failure in the dam's discharge tunnel ventilation system led to

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an abrupt and complete reservoir drainage. This unprecedented event provided a unique opportunity to assess both the immediate water loss due to the failure and the long-term sediment deposition in the reservoir. Traditional approaches to evaluating reservoir capacity (e.g. periodic bathymetric surveys, turbidity, trophic state) are labor-intensive and infrequent [5], potentially missing rapid changes during such extreme events. In contrast, modern geospatial techniques can capture high-resolution data quickly and repeatedly.

The research combines terrestrial laser scanning (TLS) with unmanned aerial vehicle (UAV) photogrammetry and satellite remote sensing images to study Mavrokolympos Reservoir before and after drainage operations. The combination of data from different sources enables the best features of each method to be used because TLS delivers precise topographic mapping at the millimetre level, while UAV photogrammetry generates detailed digital elevation models and orthophotos quickly, and satellite imagery provides extensive spatial reach and frequent observations of surface water changes. The integrated approach has proven successful in environmental monitoring applications by producing more detailed and reliable results than using individual methods separately. Research has demonstrated that combining UAV and TLS data enhances the accuracy of change detection operations on difficult terrain areas [6]. The high-temporal resolution offered from PlanetScope satellites have demonstrated their value in monitoring reservoir surface changes and volume variations at a previously unattainable time scale [7]. The integration of these data sources enables us to measure the water volume reduction during the January 2025 failure and determine the accumulated sediment volume in the reservoir since its initial construction.

The research presents the multimodal survey methodology together with its obtained results. The introduction section provides background information and explains the research goals. The Materials and Methods section explains the methods used to obtain data from TLS, UAV and satellites as well as the procedures for DEM creation and water boundary definition. Eventually, the discussion section shows the calculated water loss and sediment deposition amounts and evaluates remote-sensing measurements against field observations before discussing their effects on reservoir storage capacity and operational management. The conclusions section demonstrates how this combined methodology serves water resource management and future dam monitoring needs.

MATERIALS AND METHODS

Study Area and Event

Mavrokolympos Dam is a 45 m tall earthfill dam in western Cyprus, impounding a small catchment in a semi-arid climate. Prior to the January 2025 incident, on the 17th of January the reservoir's capacity was calculated $\sim 1.25\times10^6$ m^3 of water stored, corresponding to a water surface elevation of 105m above mean sea level, in regard with the WDD (Water Development Department) claim at a capacity of $\sim 1.19\times10^6$ m^3.The designed maximum capacity is 2.218×10^6 m^3 at 109,5m above mean sea level. Immediately after the discharge tunnel vent failure, the reservoir rapidly drained, leaving behind exposed reservoir bed surfaces. This created ideal conditions for high-resolution surveying of the reservoir bathymetry and sediment. All survey work was conducted in the weeks following the drainage, under permits from the Water Development Department.

Figure 1: Area of Interest and Vent Outlet -Reservoir bed, Mavrokolympos Dam

Terrestrial Laser Scanning (TLS)

Terrestrial laser scanners (TLS) are advanced instruments utilized to capture high-density 3D point clouds with exceptional accuracy. These devices play a crucial role across various industries, including surveying, construction, and engineering. Their effectiveness is particularly notable in applications such as topographic mapping, heritage preservation, and construction monitoring, thereby underscoring their versatility and importance in contemporary practices[8].

The 3D geometry of the drained reservoir basin was collected with a Trimble X9 terrestrial laser scanner. Established a network of 90 TLS scan stations around the reservoir perimeter and along the exposed reservoir floor where access allowed. Individuals' station recorded approximately 25–30 million points, and there was a very high-resolution point cloud of the reservoir topography. Neighbouring scans had a ~40% overlap to cover the entire region and for point cloud registration. The TLS data referenced into CGRS93, the Cyprus Geodetic Reference System (Cyprus Local Transverse Mercator projection), with Real-Time Kinematic GPS (RTK-GPS) on a subset of control points via post-processing using the R980 receiver (Trimble). Registration was based on the coordinated information with horizontal accuracy of ±0.02 m and vertical accuracy of ±0.035 m (enabling centimetre-level accuracy), which was supported through the RTK-GPS receiver by connecting with the national CYPOS network. Co-registration of the TLS point clouds from all stations was accomplished to a common coordinate system using an iterative closest point algorithm with a mean cloud-to-cloud registration error of 4.45 mm rmse (root-mean square error) for the entire dataset. This millimetre-scale alignment error is evidence for an internal consistency of the TLS model, which is commensurate with the nominal range accuracy of the scanner of ~4 mm at the corresponding range of 100 to 150 m from the scanner. The point cloud was georeferenced, filtered from any spurious points (i.e. stray returns from vegetation or moving objects), and interpolated to allow the production of a high-resolution DEM of the reservoir bottom and slopes. The TLS-based DEM was computed with a cell size of 0.5 m and is considered here as the ground truth data for elevation when quantifying the volume of the drained reservoir, by means of TLS, due to the ability of that method to monitor detailed topographic variations and provide topography results.

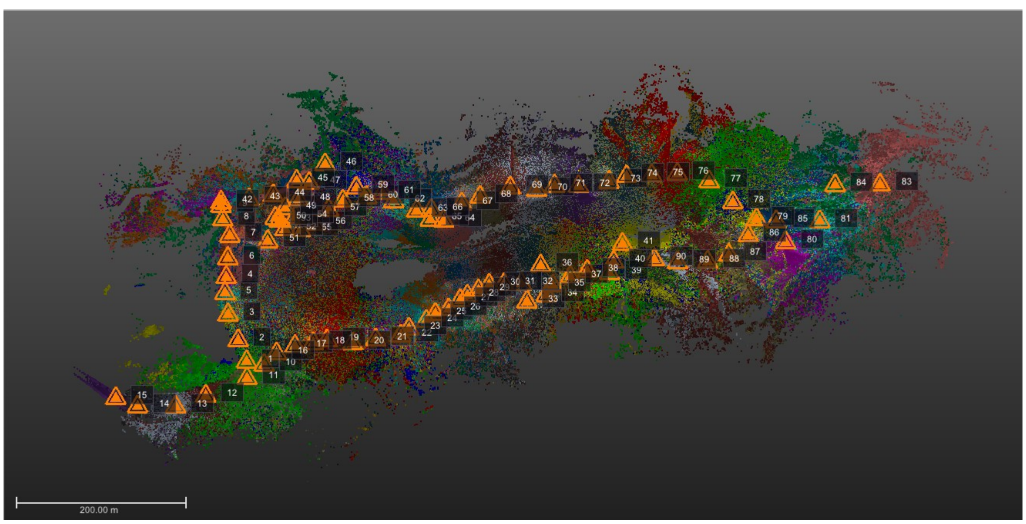

Figure 2: TLS scan stations imprinting the empty Dam

UAV Aerial Survey

In addition to the TLS, we completed an unmanned aerial vehicle (UAV) photogrammetry survey to quickly map the exposed reservoir area and the beach surface overhead. A DJI Phantom 4 quadcopter (DJI, SZ DJI Technology Co. LTD, China) with a 12 MP camera was flown in a pre-determined grid flight pattern plan at an altitude of approximately 100 m above ground level (AGL) which covered the reservoir footprint and surrounding area. Acquisition and processing of data occurred from 206 pictures taken at nadir, with a ~70% overlap to guarantee stereoscopic viewing of the site. Five artificial ground control point (GCP) targets visible in the images were positioned at the study site and surveyed with an RTK-GPS to ±3 cm accuracy to georeference the photogrammetric models. The images were photogrammetrically processed with Structure-from-Motion (SfM) techniques (software Agisoft Metashape). Tie points were detected and matched automatically between images, and a bundle adjustment was conducted with GCP constraints to estimate camera poses and a sparse 3D point cloud. A dense point cloud was processed (with ~40 million points over the reservoir area) and interpolated to a DEM and orthomosaic image. The UAV-based DEM resolution was 0.2 m, enabling the representation of small spatial details of the reservoir bed. We observed that the vertical accuracy of the UAV DEM was in the scale of a few cm in comparison with the GCPs, which were consistent with the results from other studies that compared the UAV SfM DEMs with those constructed by high-precision LiDAR. For quality assessment of the DEM, a range of spot elevations were compared with the TLS point cloud; a good agreement was obtained between the two (with differences being typically <0.1–0.2 m). The high-resolution orthomosaic (pixel resolution of ~5 cm^2) provided a fine visual record of the sediment surfaces (such as sediment texture and color) that facilitated the interpretation of sediment distribution.

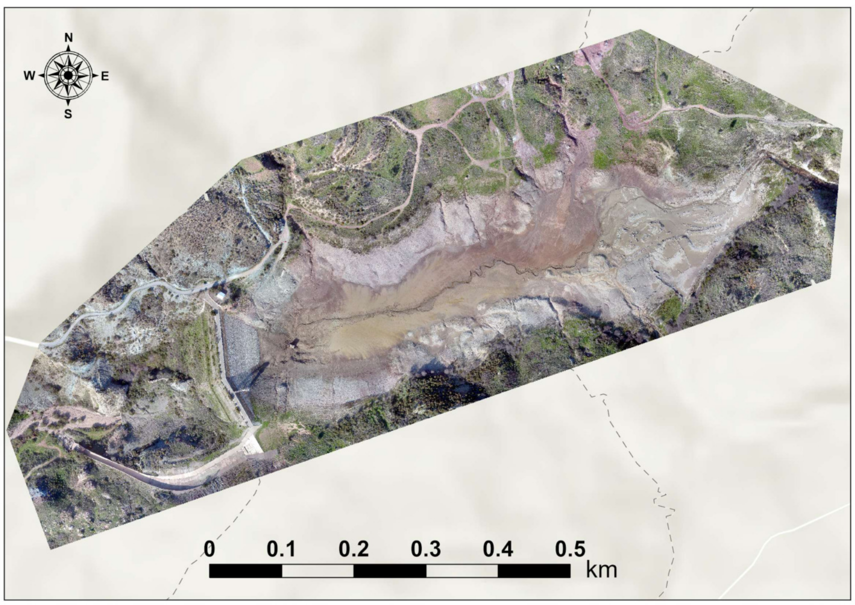

Figure 3: UAV Produced Orthomosaic

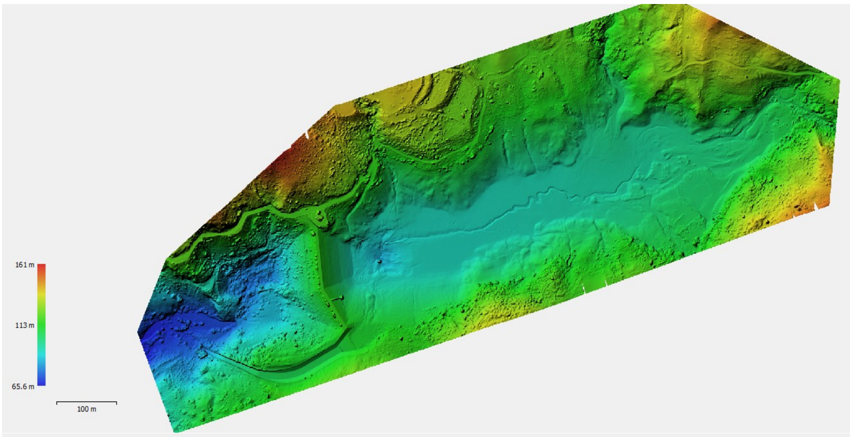

Figure 4: Dem created from (SFM) UAV point Cloud

Satellite Remote Sensing

In our investigation of the water extent prior (17 January 2025) to and during the failure event (20 January 2025) , we employed imagery from PlanetScope satellite platforms. This approach allowed for a comprehensive analysis of the spatial and temporal changes in water coverage, providing critical insights into the dynamics of the failure event. PlanetScope is a constellation of nano-satellites operated by Planet Labs, offering daily imagery at ~3 m resolution for RGB and NIR bands. Images from 17 January 2025, just before the drainage event, when the reservoir was retaining water, and a PlanetScope scene from 20 January 2025, immediately after the major drainage, to capture the change in water coverage. The images were processed to delineate water bodies. We applied the Normalised Difference Water Index (NDWI) to enhance open water features in the imagery[9].

The formula of NDWI:

$$NDWI = (\text{Band 2 (Green)} + \text{Band 4 (NIR)}) / (\text{Band 2 (Green)} - \text{Band 4 (NIR)}) \quad (1)$$

NDWI gives positive values for water, as water has higher reflectance in green light and absorption in near infrared. We chose NDWI as it is a widely used index for water mapping in satellite images. NDWI thresholding cleanly separated the water pixels from land in both dates. The water classification was refined by minor manual editing (removing a few false positives like shadowed areas classified as water). The water surface area on each date was calculated from the NDWI mask.

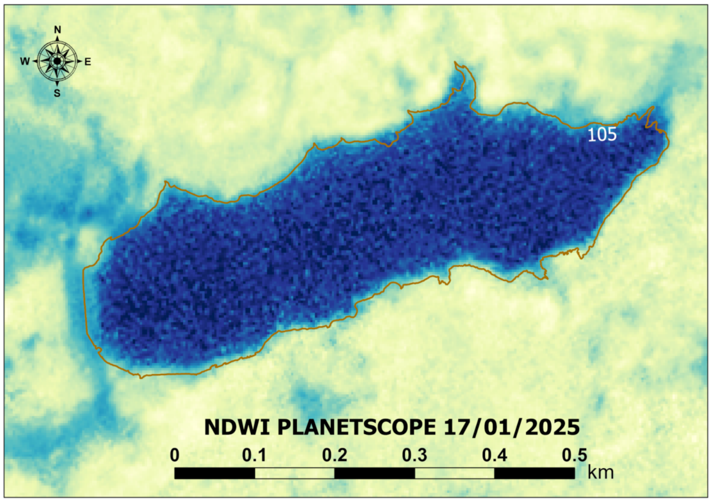

Figure 5: Planetscope Satellite Imagery -NDWI before failure-water loss

Volume and Sediment Calculations

We employed GIS analyses to derive water volumes corresponding to the satellite-observed water extents and to estimate sediment deposition volume. First, using the high-resolution DEM of the reservoir (TLS-derived), we generated an elevation–area–volume curve for the reservoir by progressively flooding the DEM to various water levels. This curve allowed us to translate a mapped water surface area (with an inferred water elevation) into a stored water volume. For 17 January 2025, the NDWI-derived water polygon covered an area of approximately 0.172 km^2, which corresponded (based on the DEM) to a water elevation of \~105m and a volume of about 1.19×10^6 m^3. This aligns well with the dam's managing authority WDD claim (1.25×10^6 m^3), considering the reservoir was near but not quite overflowing. These two dates indicates that roughly 1.19×10^6 m^3 of water were lost from the reservoir during the failure in the span of only three days. Field observations confirmed that by the end of January 2025 the reservoir was effectively empty, with only minor puddles remaining in the deepest sections of the river channel. We estimate the total water evacuated by the failure event to be on the order of 1.19×10^6 m^3.

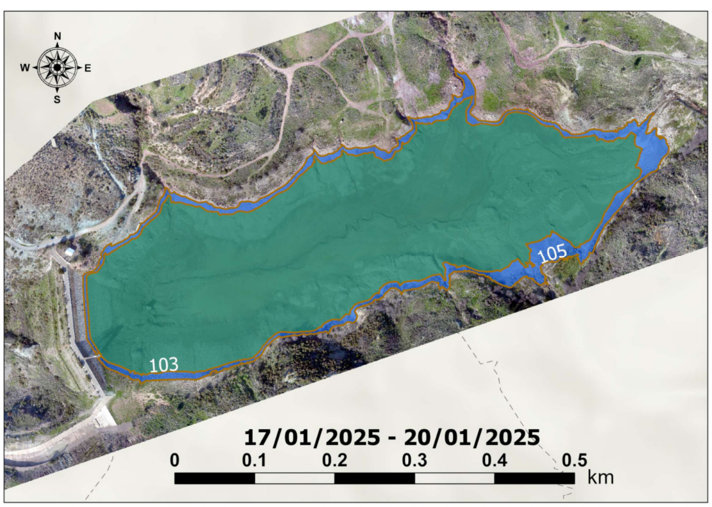

Figure 6: Water Delineation-Boundaries from 17/01/2025-20/01/2025

To quantify sediment deposition, we compared the current reservoir capacity (as measured by our DEM) to the original design capacity. Using the elevation–volume curve derived from the DEM, we found that filling the reservoir to the historical full supply level (spillway elevation) would now store a maximum of ~1.87×10^6 m^3, rather than the 2.20×10^6 m^3 originally intended. This indicates that approximately 0.33×10^6 m^3 of capacity has been lost due to sediment accumulation since 1966, equivalent to about 15% of the original volume. Essentially, sediments eroded from the watershed have occupied part of the reservoir's volume. The spatial distribution of these sediments was inferred from the DEM: the difference between the current bathymetric surface and the likely original bottom (the latter reconstructed from design documents and assuming the dam has not subsided significantly) shows that most sediment has deposited in the upper reaches of the reservoir (near the river inflow) and in several delta-like wedges. This pattern is typical, as coarse sediments drop out first at the head of the reservoir, forming a delta, and finer materials travel further towards the dam. The sediment deposits were observed to be several meters thick at the reservoir's inlet zone, tapering off toward the dam[10]. Some sediments were also transported out during the sudden drainage; evidence of a sediment plume exiting the dam was noted downstream, though quantifying that outflow sediment volume was beyond the scope of this study. All GIS analyses for volume calculations were performed in ArcGIS Pro and cross-checked with CloudCompare for 3D volume differencing. The uncertainties in the volume estimates stem from DEM accuracy (estimated ±5–10 cm vertically) and the unknown exact pre-impoundment topography; however, given that the dam was near empty during our survey, our DEM effectively captures the current reservoir bottom directly.

Data Integration and Validation

Finally, the multisource data were integrated to derive insights from the field survey. The orthomosaic and Digital Elevation Model (DEM) produced by the UAV were imported into the same GIS environment as the TLS DEM. The UAV was able to cover areas that the TLS could not scan, such as some steep inner banks and water puddle zones, allowing the UAV DEM to fill the gaps in the TLS model. Overall, the two DEMs showed strong agreement, leading to the creation of a blended DEM for final analysis. On January 17, 2025, the water extent derived from satellite data was compared with the Digital Elevation Model (DEM) to confirm that the water boundary corresponded to the approximate 105m elevation contour. This cross-validation increased our confidence that satellite remote sensing accurately captured the reservoir extent, and that our volume calculations based on the DEM for that area were correct.

Similarly, the water extent derived from PlanetScope on January 20, 2025, which represented a small remaining pool of water, aligned well with the lowest parts of the DEM. We observed that the spatial resolution of PlanetScope (3 m) did significantly impact area estimation in this case, as the reservoir is relatively large and the Normalised Difference Water Index (NDWI) thresholding effectively defined the boundaries.

Recent studies have recommended this multi-platform approach to enhance the accuracy and frequency of surface water monitoring [11]. All area and volume measurements were verified against field observations, such as visually estimated waterline recession, and were found to be consistent.

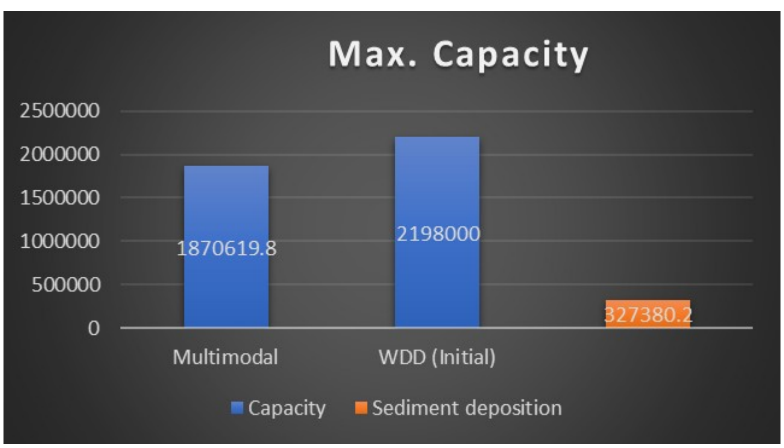

Figure 7: Dam capacity results

DISCUSSION

Following the January 2025 vent failure, the Mavrokolympos Dam experienced a significant water loss of approximately one million cubic meters within days. Remote sensing data indicated a decrease in water surface area from 0.17 km² to ~0.03 km² and a drop in water level from 105 m to about 103 m. This rapid loss due to a vent failure is unusual for Cyprus, with typical drawdowns occurring gradually. High-resolution PlanetScope imagery was critical for capturing this event quickly, and the loss represents water that could have irrigated significant agricultural plants, prompting communication with local authorities. UAV and TLS surveys mapped the exposed lakebed, revealing wet sediment areas that may affect dam capacity.

Our analysis shows sedimentation has reduced Mavrokolympos Dam's capacity by about 15% over 59 years, averaging 0.25% per year if would be divided by a mean value yearly, which is lower than the global average [12]. Currently, around one-third of a million cubic meters of sediment is trapped, potentially raising pressure on the dam during floods. The sedimentary deposition analysis suggests that the reservoir's effective capacity is now 1.87×10^{6} m^3, which can further restrict water supply during droughts. Data on sediment could guide remediation efforts like excavation or flushing for better dam management, as well as in the perspective of long-term maintenance or even a dam upgrade in functional equipment.

Utilising TLS, UAV, and satellite data in our study demonstrated a complementary approach for hydrographic and sediment surveys. Satellite imagery showed water extent changes, UAV provided detailed surface mapping, and TLS delivered accurate 3D measurements. The integration of these methods validated findings and enhanced data reliability. Rapid deployment of satellite, UAV, and TLS data collection improved efficiency compared to traditional methods.

The findings have significant implications. Documenting lost water volume aids in regional water accounting, while sediment volume assessment informs long-term reservoir planning. Given the current rate of sedimentation, managers may need to consider interventions to extend the dam's lifespan. This study also presents a method applicable to other reservoirs, suggesting routine UAV surveys combined with satellite observation for continuous storage capacity tracking, especially relevant in semi-arid areas like Cyprus.

CONCLUSIONS

This study presented a comprehensive assessment of water loss and sediment deposition at Mavrokolympos Dam following a rapid drainage event, using a fusion of TLS, UAV, and satellite remote sensing methods. The multimodal approach proved highly effective, yielding several key findings and demonstrations such as Quantification of Water Loss of Approximately 1.19×10^{6} m^3 of water was lost in the January 2025 failure. High-resolution PlanetScope satellite imagery combined with DEM analysis enabled precise volume estimation within days of the event. This rapid assessment is invaluable for emergency water management, allowing authorities to gauge the impact on supply immediately. It highlights how new satellite constellations can complement traditional monitoring and provide near real-time data during infrastructure failures.

Sediment Deposition and Capacity Reduction obtained from Terrestrial laser scanning and UAV photogrammetry mapped the exposed reservoir bed at centimetre-scale detail. Comparing the current topography to historical capacity data indicates $\sim0.33\times10^{6}$ m^3 of sediment accumulation since the dam's construction, corresponding to a 15% loss of original storage capacity. This moderate rate of sedimentation (0.25%/year) is lower than global averages but still represents a significant long-term reduction in water yield. The spatial sediment distribution, with a delta at the inflow and finer sediments toward the dam, was clearly visualized. Such information is critical for planning any sediment removal or management strategies to extend the reservoir's life.

Methodological Integration and Validation and employement of three independent data sources provided robust cross-validation. Satellite-derived water extents matched closely with UAV/TLS-derived DEM contours, and volumetric calculations from remote sensing were corroborated by ground truth. UAV photogrammetry, validated by TLS, demonstrated that low-cost drone surveys can accurately capture reservoir bathymetry when water is absent, offering a practical tool for other aging reservoirs lacking recent surveys. The combined dataset allowed a level of accuracy and confidence unachievable by any single method alone. This underscores the value of integrating remote sensing and in-situ measurements for hydrological applications. The study effectively leveraged the temporal reach of satellites, the aerial perspective of UAVs, and the precision of TLS to achieve a comprehensive assessment.

The findings have direct implications for water resource management and dam safety in Cyprus and similar contexts. Knowing the exact volume of water lost informs short-term water allocation decisions for the affected region. Understanding sedimentation extent guides maintenance decisions – for instance, whether to dredge the reservoir or adjust operational rules. More broadly, the success of this multimodal survey advocates for its adoption as a standard practice in periodic reservoir monitoring. With climate change likely to increase extreme events (droughts, intense rain) that test water infrastructure, having accurate, up-to-date knowledge of reservoir capacity and condition is increasingly important. Our approach provides a template for acquiring that knowledge efficiently.

In conclusion, the abrupt drainage of Mavrokolympos Dam, while unfortunate, provided an opportunity to demonstrate how modern geospatial techniques can rapidly and accurately assess critical parameters of a reservoir's status. The integration of TLS, UAV, and satellite imagery offered a multi-scale perspective – from millimeters to meters to kilometers and from immediate aftermath to historical context. This holistic understanding is essential for effective water resource management, dam maintenance, and hazard mitigation. Future work will focus on continued monitoring as the dam is repaired and the reservoir refills, repeating UAV and satellite surveys will allow tracking of any new sediment inflows or changes in capacity. Future plans are to explore automated change detection algorithms (potentially AI-driven) on the multi-temporal satellite data to flag sudden losses or gains in water extent. Such advancements could further enhance early warning capabilities for reservoir management. The field study contributes to the growing evidence that combining multi-modal observations is a powerful strategy in Earth resource monitoring, and it encourages dam operators and researchers to adopt these technologies for sustaining water storage in the face of both gradual and sudden changes.

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