Integration of Topo-bathymetry Mapping Techniques for Siltation Monitoring in the Reservoir

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Abstract **:** *Topographic and bathymetric surveying technologies provide critical data support and decision-making references for the reservoir management. This paper integrates various advanced topographic and bathymetric mapping technologies to survey terrain and sedimentation around reservoirs. As surveying technologies advance, equipment such as LiDAR and Multibeam Echo Sounders (MBES) have significantly improved mapping accuracy in both terrestrial and underwater environments. LiDAR achieves 3-5 mm accuracy for terrain measurements, while MBES provides wide 150° swath coverage with up to 6 mm resolution for bathymetric mapping. However, an efficient and feasible integration is needed in shallow water and surrounding dense forests area. Data fusion approaches combine multiple systems to compensate for individual limitations in this work. In shallow or hard-to-reach areas, Unmanned Surface Vehicles (USVs) equipped with Single Beam Echo Sounders (SBES) and a mobile SLAM LiDAR system is utilized to enhance mapping completeness. Case studies include the Mingde Reservoir siltation monitoring, and the Hushan Reservoir inter-basin water diversion project. It is worth noting that SBES-equipped USVs conducted three rounds of surveys, also yielding 0.05 m RMSE. These results indicate that the technologies used in this case achieve high precision, comparable to MBES-grade performance, especially for shallow water and land-water interface mapping, outperforming traditional methods or SBES alone. Comparisons showed siltation of 0.3 to 2.0 m in two months at the Mingde Reservoir due to upstream river scouring, while Hushan Reservoir experienced the trans-basin diversion caused up to -5.8 m of erosion and 0.4 to 2.5 m of downstream siltation. Temporal terrain model comparisons revealed two-month siltation rates of 0.03 to 0.208 m in reservoirs. The annualized siltation rate is at least 0.18 m/year, which is too high and needs regular attention. As for the more than 1 meter/year, it is common after landslides or heavy rainfall events, where a large amount of sedimentation occurs in a short time. These findings highlight the importance of integrating diverse technologies for effective topographic and bathymetric mapping, particularly in shallow water environments.*

Keywords: Data Fusion, LiDAR, Echo Sounder, Topobathymetric, Siltation and Sedimentation

Introduction

Siltation is a process of sedimentation of fine particles like silt, mud and other fine material that have been accumulating in the body of water, due to nature of the water itself settling on the lowest elevation it can flow, this process can have effect of decrease in water capacity of a both natural landscape and manmade structure and other environmental issue. In other words, siltation is a form of water pollution caused by sedimentation (Jain & Singh, 2003). The importance of siltation monitoring in reservoir management are prolong reservoir lifespan and maintain storage capacity, flood and Debris Flow prevention, Ecological and water quality protection, scientific decision-making, support for Land management and Erosion control, responding to extreme rainfall from climate change, and enhancing sustainable water resource management (Walling, 2006).

The methods of siltation monitoring vary from the requirement and cost or manpower required to perform such task, up until this day some of the countries still be using manual recording by sending personnel down to water to measure the depth from the surface water to the bottom of the water, while that is the simplest form of data collection, it is still requiring huge manpower and time if the amount of reservoirs needed to monitor are in abysmal numbers (Lopes & de Araújo, 2019). Which they purpose another approach to this dilemma, using another simplified method by using satellite imagery or remote sensing is more palpable to perform to measure reservoir in such numbers over a large area. Albeit the accuracy itself cannot be compared to on field data gathering, another method can also be using machinery such as Echo sounder, Echo sounder can be separated as SBES and MBES both have uses depending on how wide area that need to be scanned, however echo sounder alone cannot be operated, it will still need GNSS acting as Real-Time Kinematic to accurately record the coordinate, while some research also using several another tools such as manual GNSS recording, UAV and using LiDAR, that alone just to map the depth of the area under the water (Gesch et al., 2016; Collin et al., 2018; Genchi et al., 2020; Martellotta et al., 2024).

This paper integrates various advanced topographic and bathymetric mapping technologies to survey terrain and sedimentation around reservoirs. Data fusion approaches combine multiple systems to compensate for individual limitations are performed in following two experimental areas: the Mingde Reservoir siltation monitoring, and the Hushan Reservoir inter-basin water diversion project.

Methodology

a. Study Area and Used Instruments

Mingde Reservoir, formerly known as Houlong Reservoir, was completed in May 1960. The full water level is EL.61 meters, and the maximum water storage area is about 162 hectares (figure 1). The original design total water storage capacity was 17.7 million cubic meters, and the results of the siltation measurement in 2022 show that the total capacity of the reservoir is 12.4173 million cubic meters, meaning that the siltation has been thickening so much over the course of 62 years.

In order to continuously monitor the impact of reservoir siltation on reservoir capacity and grasp the distribution of silt movement and siltation in the reservoir, so as to avoid adverse effects on the life and operation of the reservoir, this reservoir regularly conducts siltation measurement business and compiles relevant measurement results into reports, in order to grasp the siltation situation of the main control sections of the water storage area and the changes in the overall H-A-V curve of the reservoir over the years. The equipment that is used in this project is the GEOMATE Model 1 USV, MBES, Backpack LiDAR RIEGL VUX1UAV, stationary LiDAR RIEGL VZ400i and UAV.

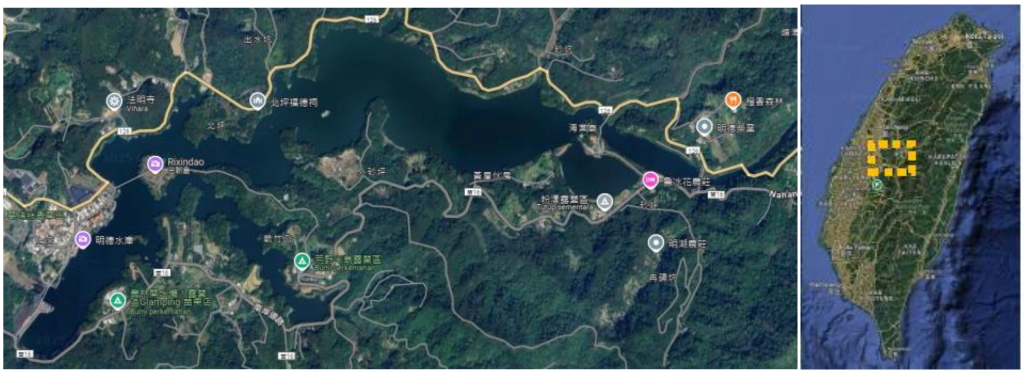


Figure 1: The Location of Mingde Reservoir.

Hushan Reservoir is an off-stream reservoir that is built upstream of Meilin River in Yunlin County, the catchment area covers Douliou City and Gukeng Township in Yinlin County also Jhushan Township in Nantou County. Source of silt deposition is not only coming from its own drainage and rain washout, but also from other stream that have been caused by trans basin diversion into Qingshui River which from the upstream Xin Xing Zheng bridge of the Tong tou weir to the downstream groundsill works of Tong tou bridge interval (Figure 2). Which is why it is necessary to monitor reservoir sedimentation measurements regularly on both reservoir and the river since the sudden change of flow of water might causing unintended effect on the silting and service life of reservoir.

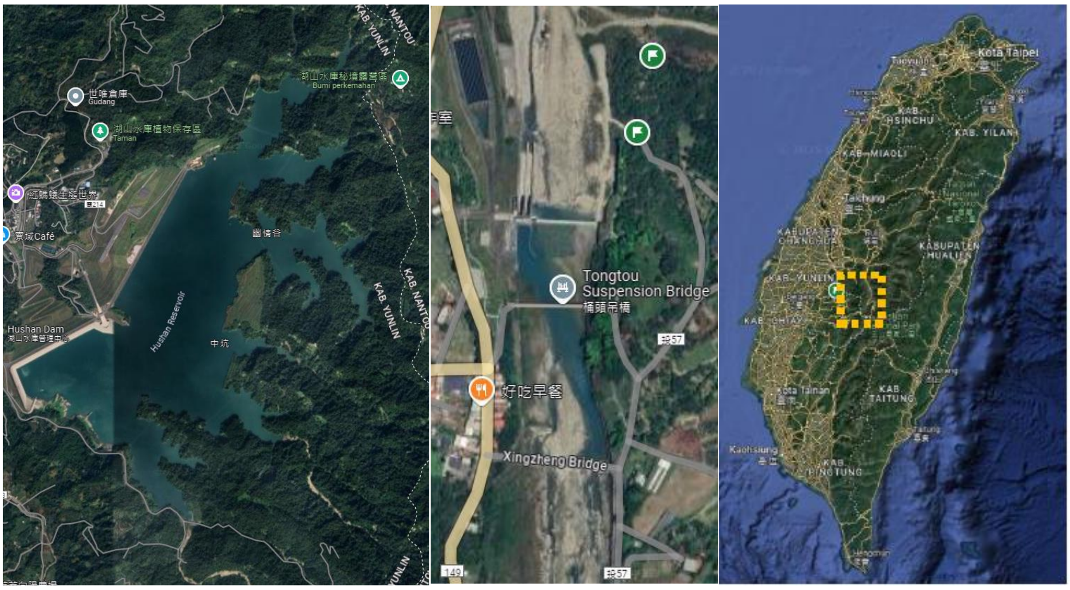


Figure 2: The Hushan Reservoir (left) and Tongtou Weir (middle).

There are several tasks that need to be done to monitor the areas, which are:

a) Reservoir sedimentation surveying for the area below the highest water level

b) Mobile-LiDAR surveying for scanning area above the highest water level both reservoir and the river

c) SBES UAV and MBES for scanning area under the water in reservoir and only SBES UAV scanning for the river area.

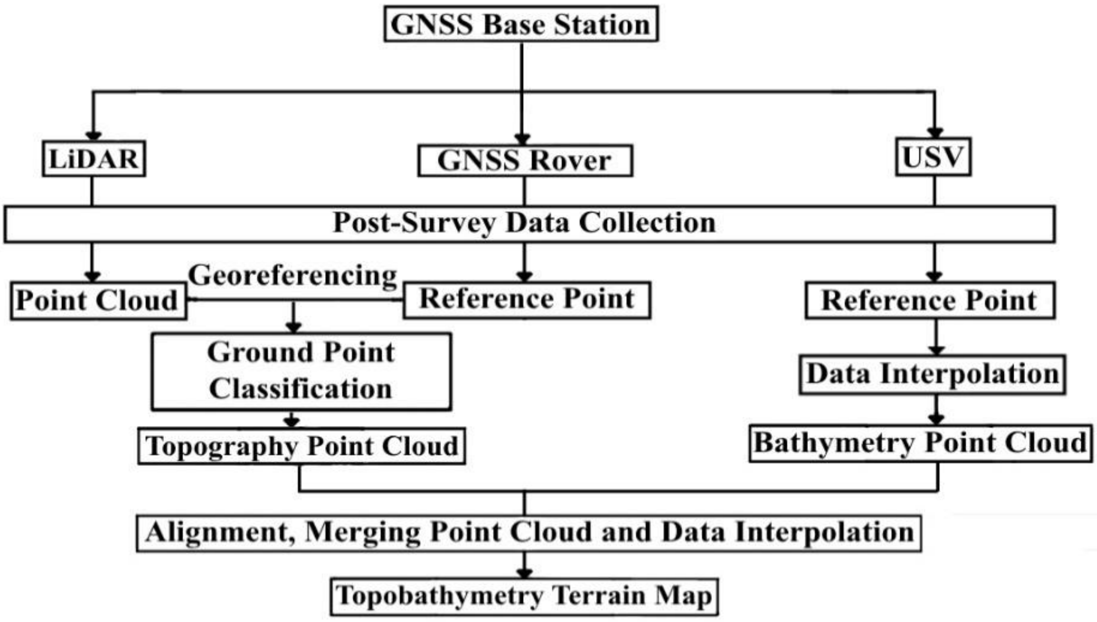
d) Using the recorded data to draw topographic maps.

e) Calculating reservoir volume using topographic maps.

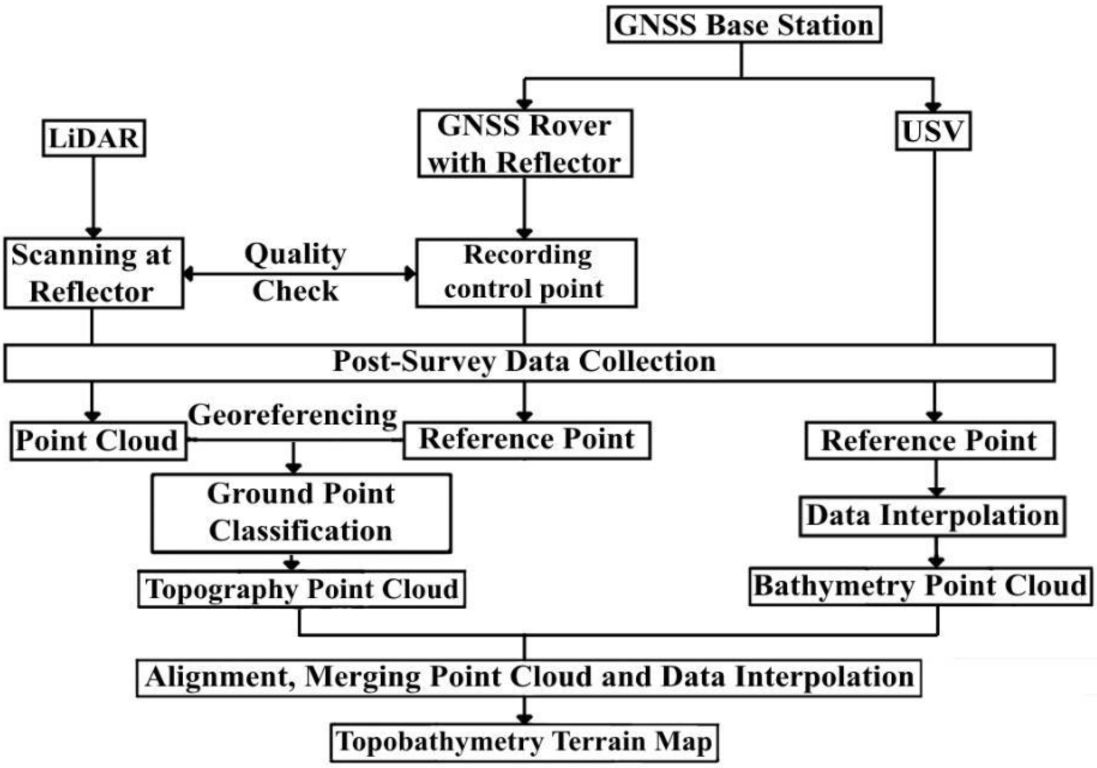
Control survey tasks were performed in September and October 2023 and as for the Reservoir sedimentation survey using MBES, SBES USV and Mobile-LiDAR using RIEGL VUX1UAV are performed in October 2022.

b. Methodology

The methodology proposed to scan shallow water area like shoreline or coastal zone towards the sea, and any other inland water body that is full or partial vegetation in the area like lake, mangrove, swamp or reservoir, as GNSS control point and samples taken will become anchor for both types of LiDAR, that is stationary LiDAR and SLAM LiDAR to be compared of, thus become a reliable data for comparison which is better to be used on such area, however as far as data availability, Budai Port shall be the main subject for this methodology for mapping topobatymetry of the area, next figure are methods purposed for a stationary LiDAR and SLAM LiDAR (Figure 3).



(a) Stationary LiDAR (VZ400i)

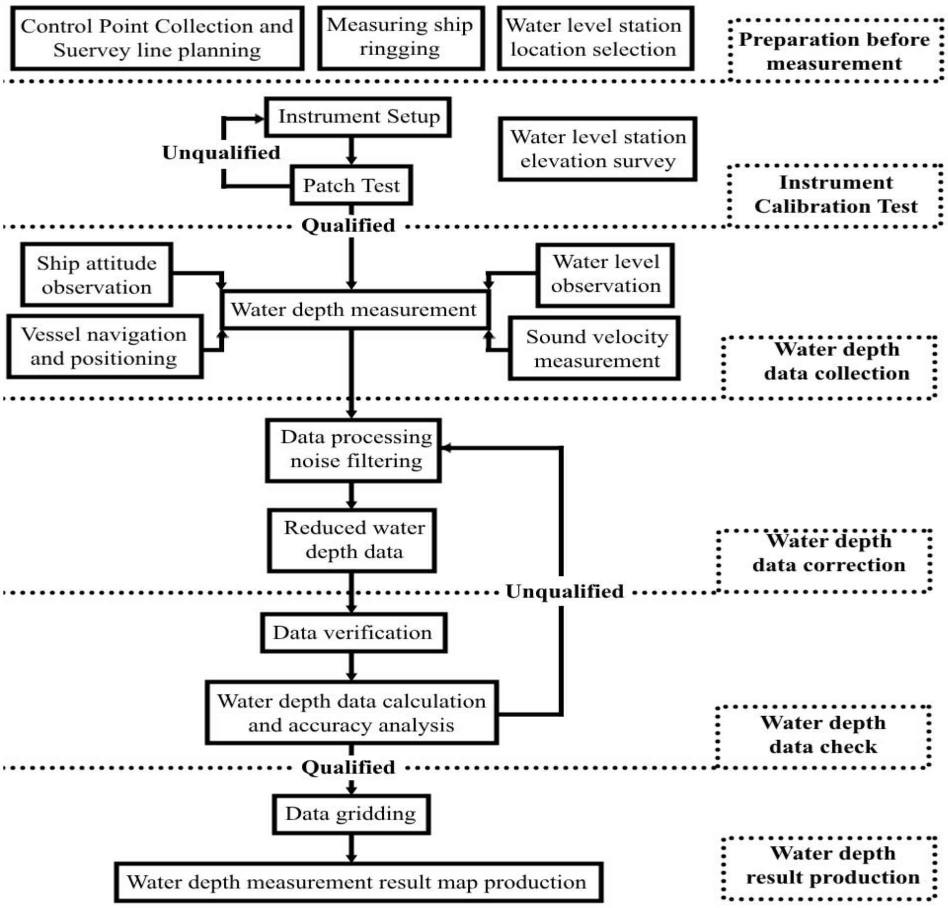


(b) SLAM LiDAR (RIEGL VUX1UAV)

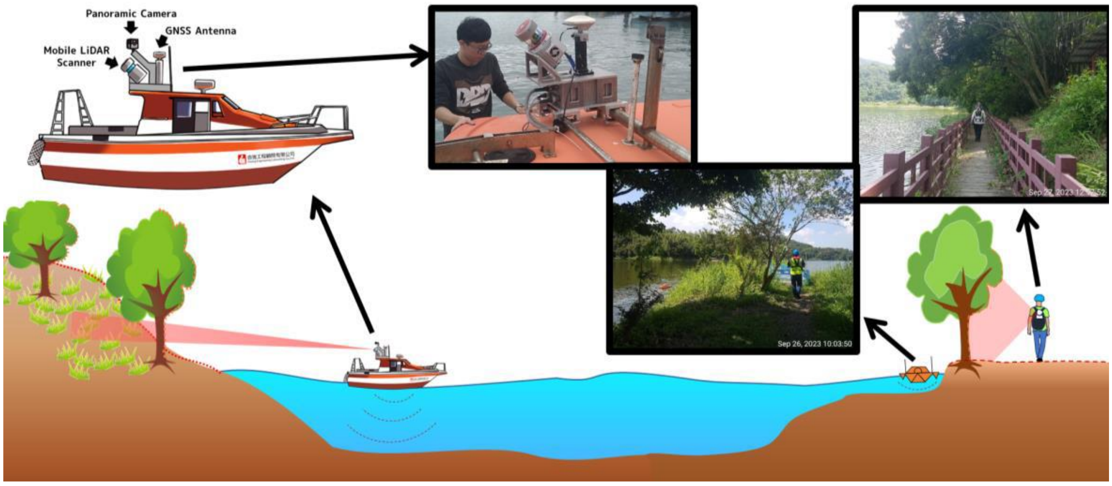
Figure 3: Surveying methods via LiDAR.

When comparing operating between RIEGL VZ400i or RIEGL VUX1UAV, it boils down to thinking about using stationary LiDAR with SLAM LiDAR with its own ups and downs, while stationary LiDAR provides higher accuracy due to SLAM LiDAR have little sway no matter how stabile the stride is, lower confidence level which is the lower the level the higher the precision of the point cloud it provides and lastly able to scan on longer distances than SLAM LiDAR. The SLAM LiDAR provides faster scanning time which the difference could make more than one hour depending on the size of the area, can be operated along with other tools at the same time and provides closer scanning towards the corners of the object of observation.

Surveying Reservoir areas require another method that able to scan the terrain under the depth of water, by using MBES open to wider scan area and faster operation compared to using UAV SBES alone, the USV itself still be able to be used for covering small parts that MBES cannot cover and another equipment like SLAM LiDAR can also help to cover Land area more closely (Figure 4(b)). The schematic diagram below (Figure 4(a)) shows detailed progress of MBES surveying methods.



(a) MBES schematic method



(b) Illustration of Method working with MBES, USV and SLAM LiDAR

Figure 4: Combination of Equipment Used for Reservoir Surveying

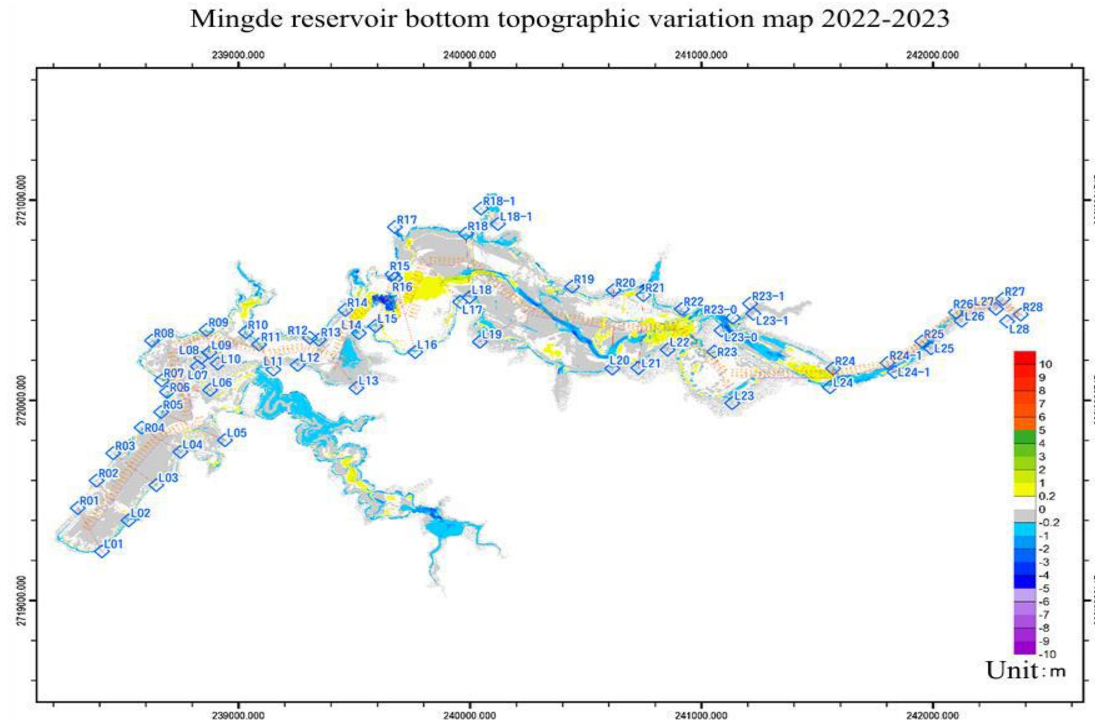
Results and Discussion

a. Data Processing and Integration

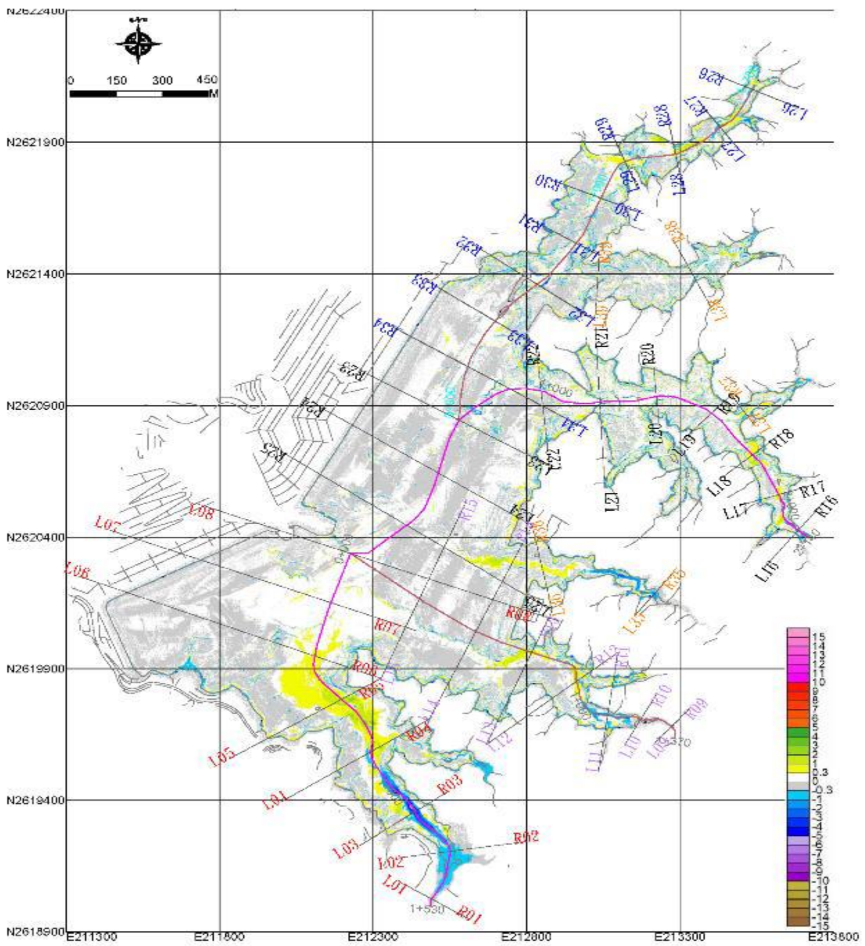
Field survey data were acquired using multiple platforms, including **Multibeam Echo Sounders (MBES)**, **USVs**, **stationary and SLAM LiDAR systems**, and **Unmanned Aerial Vehicles (UAVs)**. Before these datasets could be analyzed, they underwent calibration and preprocessing to ensure accuracy and consistency.

The first step was **data conversion**, in which all datasets were standardized into a single compatible format for integration into a Digital Elevation Model (DEM). USV-collected bathymetric data, initially recorded in CSV format, were converted into *.las files to match the LiDAR point cloud format. Once both LiDAR and echo sounder datasets shared the same file type, the **topobathymetric mapping** process was carried out.

The final topographic maps were presented as coordinate grids and contour lines. Depending on analytical needs, projection lines were added at fixed intervals or aligned with prominent geomorphological features. Contour lines were also color-coded to highlight changes between survey periods—blue representing **siltation** and yellow representing **sedimentation**—when comparing DEMs from different years. For instance, siltation and sedimentation patterns from 2022 to 2023 are illustrated in **Figure 5(a)** for Mingde Reservoir and **Figure 5(b)** for Hushan Reservoir.



(a) A Siltation Map in the Mingde reservoir



(b) A Siltation Map in the Hushan reservoir and Tongtou Weir

Figure 5: Siltation Map from 2022 to 2023 for two Reservoirs.

b. Height-Area-Volume (HAV) Analysis

From the processed DEM data, Height-Area-Volume (HAV) curves were derived to evaluate historical changes in storage capacity at Mingde and Hushan Reservoir, shown as Figures 6 and 7, respectively. The H-V curve (solid line) represents storage volume at given elevations: a downward shift indicates increased capacity, while an upward shift reflects reduced capacity. The H-A curve (dashed line) represents surface area: an upward shift indicates an increase in area, while a downward shift shows a decrease.

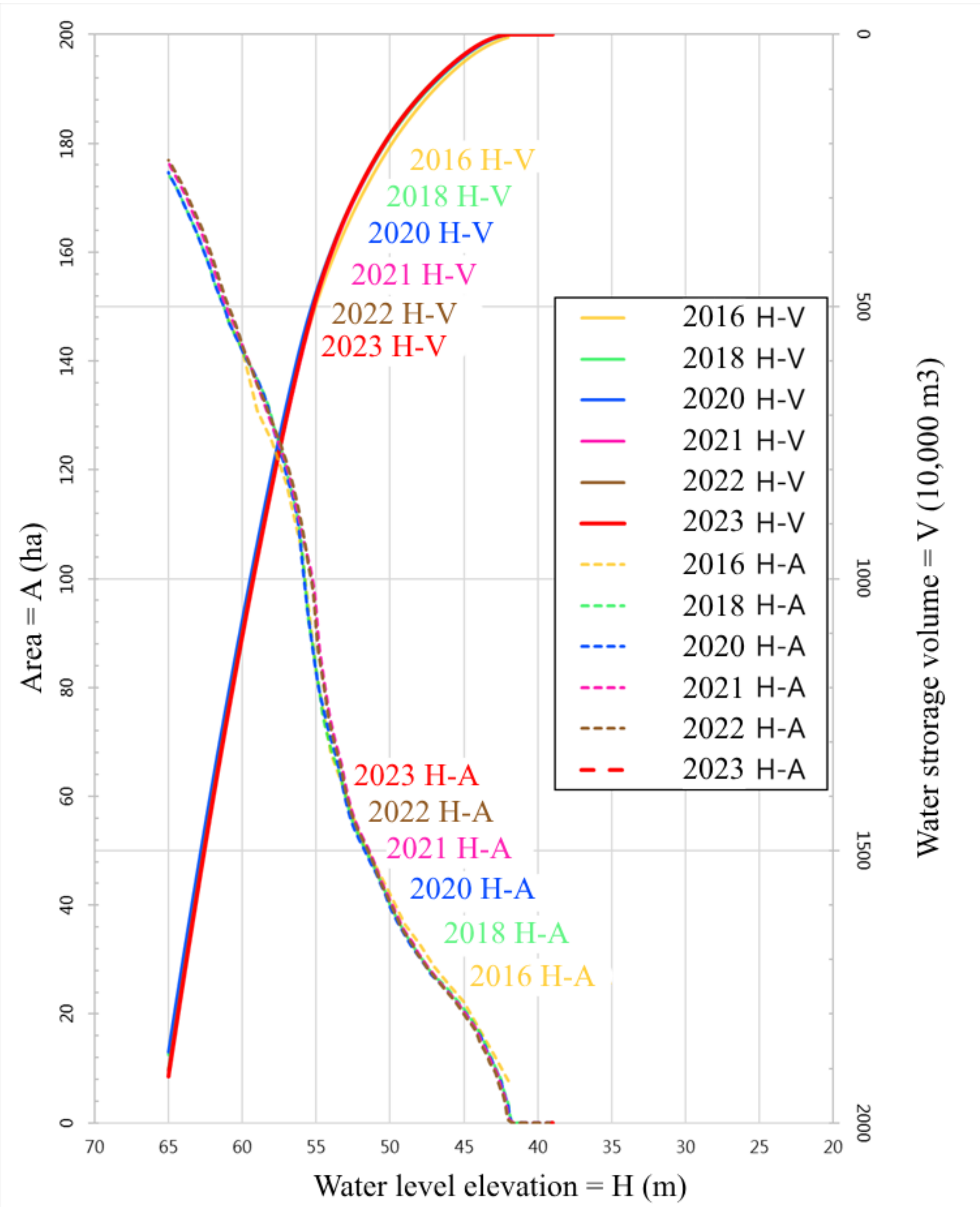


Figure 6: Height–Area–Volume (HAV) curves from 2016 to 2023 at Mingde Reservoir.

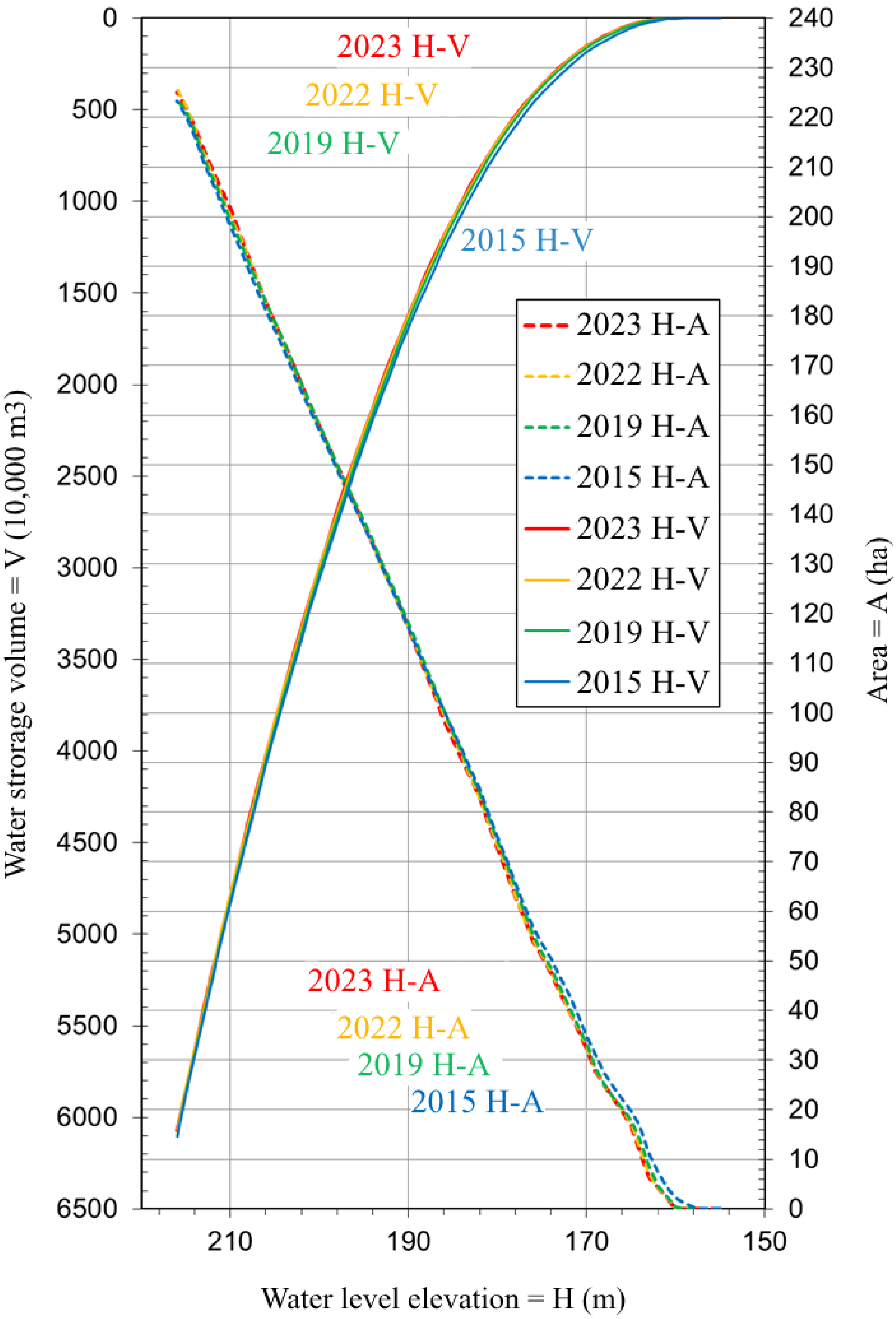


Figure 7: Height–Area–Volume (HAV) curves from 2015 to 2023 at Hushan Reservoir.

Mingde Reservoir (Figure 6) — Between 2016 and 2023, H-V curves consistently shifted downward, indicating a progressive, year-on-year decline in reservoir volume at equivalent elevation levels. This pattern suggests ongoing sediment accumulation, reducing effective storage capacity. In contrast, the H-A curves remained stable, implying that while volume decreased, the surface area did not change significantly, indicating a gradual loss of volumetric efficiency.

Hushan Reservoir (Figure 7) — From 2015 to 2023, H-V curves shifted slightly upward, suggesting increased water storage volume at equivalent elevation levels. This atypical trend may be attributed to active dredging, basin restructuring, or improved hydrographic survey accuracy. The H-A curves exhibited minimal change, indicating a stable surface area. Notably, trans-basin diversions—redirecting water from other watersheds—can substantially affect hydrological patterns, potentially explaining higher storage volumes for similar elevations in certain years.

c. Erosion and Siltation Patterns

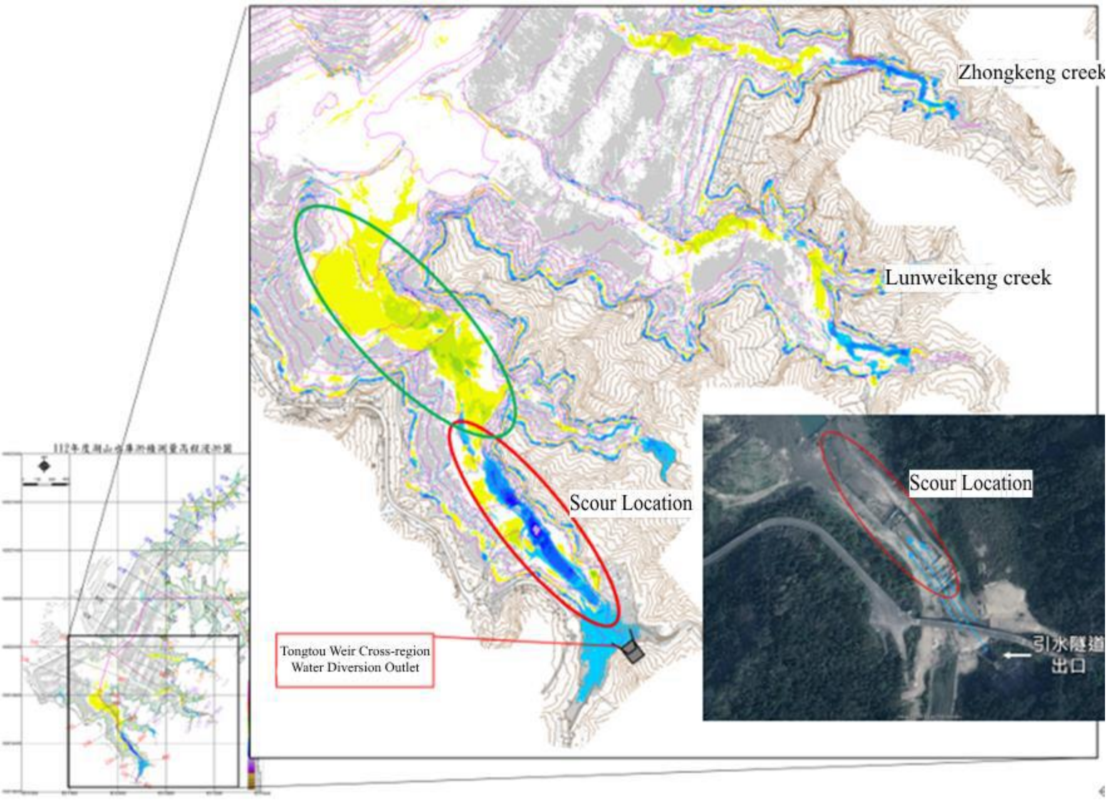
Detailed terrain change analysis at **Hushan Reservoir** (Figure 8) revealed significant geomorphic alterations along its main tributaries: Nanshikeng Creek, Lunweikeng Creek, and Zhongkeng Creek. The upper reaches of these channels exhibited **scouring**, while the mid- to downstream sections showed **siltation**.

The **Nanshikeng Creek** experienced the most severe erosion (red circle; see Figure 8(b)), with scouring depths ranging from -1 m to -4 m. Downstream of the Tongtou Weir cross-basin water diversion outlet, maximum scouring reached -5.8 m, indicating intense erosional forces. In contrast, the middle and lower reaches (green circle) accumulated sediment ranging from 0.4 m to 2.5 m in height.

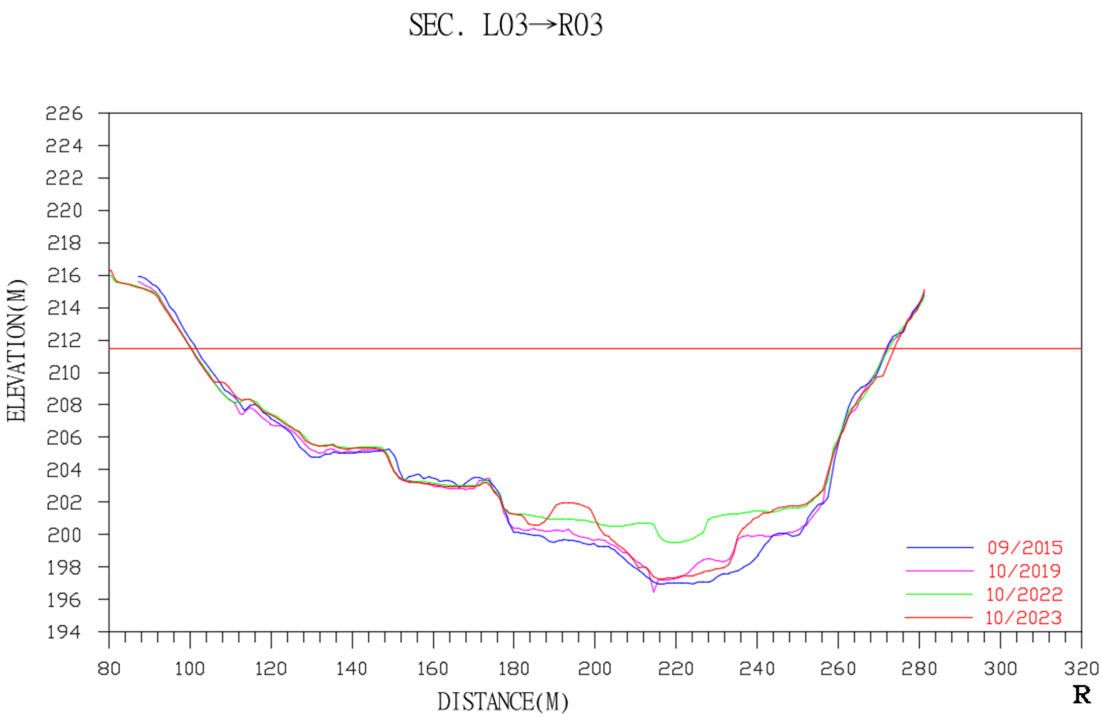
In **Lunweikeng Creek** and **Zhongkeng Creek**, upstream scouring depths ranged from -0.5 m to -2.8 m, while downstream siltation ranged from 0.5 m to 2 m. Minor sediment deposition occurred in the forebay, slightly reducing dead storage capacity.

These geomorphic changes were influenced by **Typhoon Haikui** in early September, which significantly increased rainfall and inflow rates, as shown by the red hydrograph line in Figure 8.

Reservoir comparison — Hushan Reservoir, with its active trans-basin diversion operations, exhibited the deepest scouring (-.8 m) and downstream siltation (0.4~2.5 m). In contrast, Mingde Reservoir was undergoing dredging during the September 2023 survey (Figure 5(a)), with dredging depths of -2 m to -4 m and subsequent sediment accumulation of 0.3~2 m at lower elevations. Natural scouring in Mingde Reservoir (Figure 5(a)) ranged from -1 m to -3.5 m, with downstream siltation of 0.5~2 m, likely due to upstream inflow and sediment transport processes.



(a) The area affected by scouring



(b) Cross section of L03-R03.

Figure 8: Detailed map showing erosion and siltation patterns in Hushan Reservoir.

Conclusion and Recommendation

For Topo-bathymetry Mapping**,** data fusion between LiDAR and Unmanned Surface Vehicles (USVs) can be highly advantageous when project terrain involves complex interfaces between land and water, particularly in areas heavily obstructed by vegetation, such as reservoir shorelines. In most cases, Unmanned Aerial Vehicles (UAVs) equipped with LiDAR can effectively cover the majority of the survey area. However, for sections close to the water where dense vegetation impedes aerial scanning, boat-mounted LiDAR becomes a more suitable option. When high-density point cloud capture is required, Simultaneous Localization and Mapping (SLAM) LiDAR systems can be employed. Conversely, when the primary objective is to validate accuracy, stationary terrestrial LiDAR scanners are preferable.

The accuracy of these systems can be compared through their root mean square error (RMSE) values. SLAM LiDAR typically achieves an RMSE of approximately 7 mm, whereas stationary LiDAR scanners can achieve around 5 mm (Aguilar et al., 2008), indicating a higher accuracy for the latter. This difference can be attributed to the confidence levels and spread of the resulting point clouds. Nevertheless, both methods remain efficient for topobathymetric surveys, with the main operational difference being that larger survey areas require proportionally longer acquisition times.

When topographic and bathymetric datasets are integrated, the resulting terrain model encapsulates Digital Elevation Model (DEM) data that represents not only the land surface but also the underwater morphology and the precise boundary between land and water. This level of detail allows for accurate identification of siltation and sedimentation patterns, which may result from either natural scouring or anthropogenic interventions such as dredging. Even indirect effects of dredging can influence sediment distribution, particularly in lower-elevation zones where water flow concentrates.

In projects involving trans-basin diversions, where water enters the reservoir at high velocity, significant scouring can occur near the inflow zone. For example, at Hushan Reservoir, erosion depths reached up to -5.8 m, with downstream siltation heights ranging from 0.4 m to 2.5 m. Similarly, when river flows converge into narrow sections of a reservoir, scouring intensity increases markedly. This is observed at Mingde Reservoir, where natural scouring depths of -1 m to -3.5 m approach the magnitude of erosion seen in dredging zones. The dredging project in Mingde, located in the lower-middle section of the reservoir, produced erosion of -2 m to -4 m, with sediment accumulation in lower elevations ranging from 0.3 m to 2 m.

It is important to note that in Mingde, the most substantial natural scouring occurs in the higher southern section of the reservoir, while dredging operations are concentrated in a different area. This spatial separation indicates that the two phenomena—natural scouring and dredging-related erosion—are independent events rather than directly influencing one another.

According to the above siltation analysis results for the two reservoirs, natural scouring and sediment deposition within reservoirs can be significantly greater. Recorded changes in two months range from 0.3 m to 2.0 m at Mingde Reservoir, while Hushan Reservoir experienced the trans-basin diversion caused up to -5.8 m of erosion and 0.4 to 2.5 m of downstream siltation. Temporal terrain model comparisons revealed two-month siltation rates of 0.03 to 0.208 m in reservoirs. The annualized siltation rate is at least 0.18 m/year, a rate high enough to warrant regular monitoring and management. Rates exceeding 1 meter per year are typically observed following landslides or heavy rainfall events, when large volumes of sediment are deposited over a short period.

References

Aguilar, F. J., & Mills, J. P. (2008). Accuracy assessment of LiDAR-derived digital elevation models. *The Photogrammetric Record*, *23*(122), 148–169. https://doi.org/10.1111/j.1477-9730.2008.00476.x

Collin, A., Hench, J. L., Pastol, Y., Planes, S., Thiault, L., Schmitt, R. J., Holbrook, S. J., Davies, N., & Troyer, M. (2018). High-resolution topobathymetry using a Pleiades-1 triplet: Moorea Island in 3D. *Remote Sensing of Environment*, *208*, 109–119. https://doi.org/10.1016/j.rse.2018.02.015

Genchi, S. A., Vitale, A. J., Perillo, G. M. E., Seitz, C., & Delrieux, C. A. (2020). Mapping topobathymetry in a shallow tidal environment using low-cost technology. *Remote Sensing*, *12*(9), 1394. https://doi.org/10.3390/rs12091394

Gesch, D., & Wilson, R. (2001). Development of a seamless multisource topographic/bathymetric elevation model of Tampa Bay. *Marine Technology Society Journal*, *35*(4), 58–64. https://doi.org/10.4031/002533201787433908

Lopes, J. W. B., & de Araújo, J. C. (2019). Simplified method for the assessment of siltation in semiarid reservoirs using satellite imagery. *Water*, *11*(5), 998. https://doi.org/10.3390/w11050998

Martellotta, A. M. N., Levacher, D., Gentile, F., & Piccinni, A. F. (2024). Estimation of silting evolution in the Camastra Reservoir and proposals for sediment recovery. *Journal of Marine Science and Engineering*, *12*(2), 250. https://doi.org/10.3390/jmse12020250

Walling, D. E. (2006). Human impact on land–ocean sediment transfer by the world's rivers. *Geomorphology*, *79*(3–4), 192–216. https://doi.org/10.1016/j.geomorph.2006.06.019