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A Space–Air–Earth–Water Sensor Network Used to Determine the Impact of Overexploitation of Water Resources (Ecuador) †

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Abstract: This study analyzes repercussions for the morphology, talweg, riverbanks and surrounding structures of several aquatic systems transformed by multipurpose reservoirs located within the Ecuadorian territory of South America. For this purpose, several geomatics techniques were used simultaneously, minimizing the temporal error in the reservoir water level in order to measure the impact of partial or total emptying operations on these reservoirs. High precision geodetic networks were designed to synchronously use geospatial data-capturing equipment, namely UASs/drones with INS/GNSS systems, LiDAR sensors, RGB optical sensors, USVs/aquatic drones equipped with GNSS systems, and single-beam sensors. Photogrammetric, LiDAR and underwater results were contrasted with topographic techniques used in the monitoring and control of structures. Environmental changes in the surroundings, soil movements due to sedimentary and erosive effects, and possible displacements in existing structures were analyzed.

Keywords: UASs/USVs/drones; hydrotechnical structures; echo sounders; LiDAR

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1. Introduction

Although technological advances and the current use of airborne LiDAR–bathymetric (ALB) or hydrographic LiDAR (ALH) data acquisition methods allow for high scanning speeds and simultaneous data mixing on dry and wet surfaces, they also bring accuracy disadvantages for high-altitude rivers, due to problems with water clarity and turbidity [1], which are closely linked to suspended particles; in this context, an echo sounder will produce better results.

From existing techniques, RGB photogrammetric methodologies are adopted to capture the limits of the hydro-technical works, corroborate the water mirrors and shorelines of the reservoirs, and provide a complete interpretation of all the surveyed data.

From this multidisciplinary process results the geometric characterization of the dry and underwater areas of the environment as a main source for understanding changes in geomorphological and morphodynamic processes [2,3] that mainly influence adjacent structures, erosion risk, sedimentation, and potential river restoration [4].

2. Materials and Methods

2.1. Study Area

The study took place in 4 reservoirs (Figure 1) within the continental waters of Ecuador. These reservoirs have multiple purposes whose common axis is to provide hydroelectricity; they are differentiated by their storage volume, regulation (daily, monthly and annual), and by their geographic location, which has a substantial influence on climatic elements; in Ecuador, these locations are defined by three well individualized continental regions: the Coast, Highlands and Amazon.

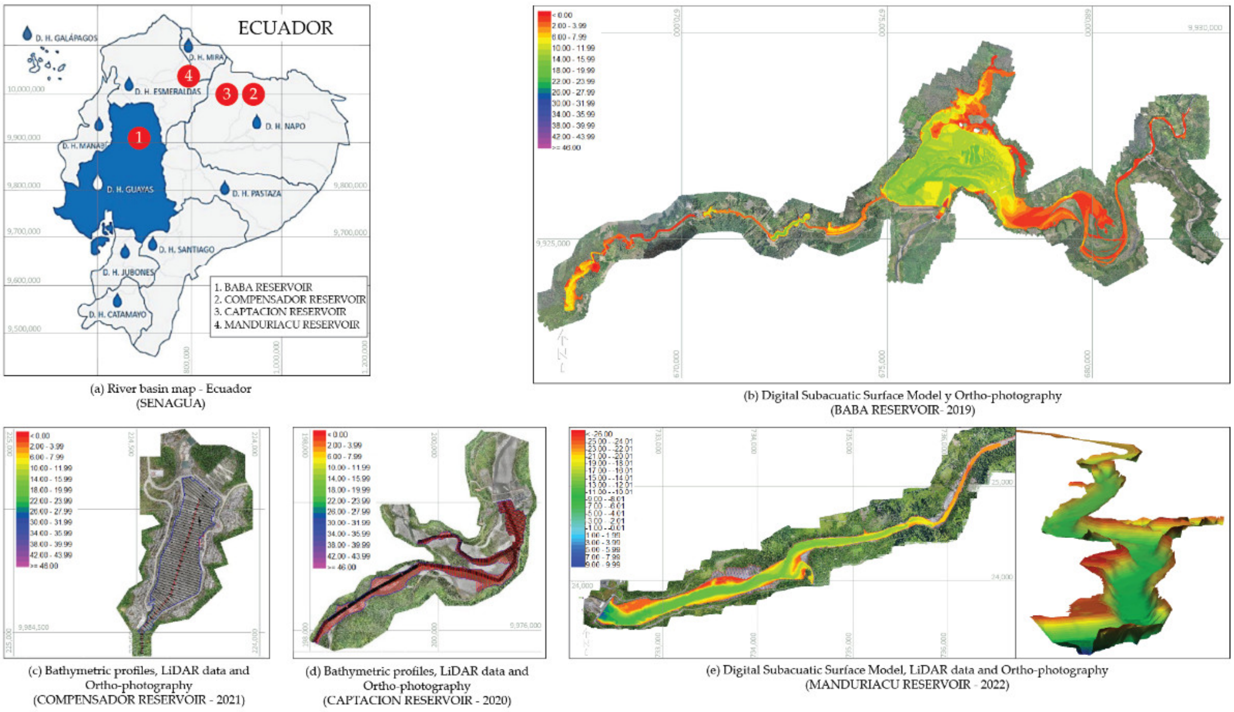


Figure 1. Geographical location of the four case studies, which are located in different types of relief and climatic zones within Ecuador.

In general terms, relief modifies rainfall. the higher the altitude, the lower the atmospheric pressure. The higher the solar radiation, the greater the change in wind trajectory, and the air forced to rise tends to cool down. The data to be taken into account for the analysis of the accuracy of the measurements were obtained with sensors onboard UASs/drones.

Figure 1a shows the hydrographic demarcation of Ecuador with the 4 reservoirs studied. The Baba reservoir (Figure 2b), with a flooded area of 1032 hectares, generates 42 MW. The Compensador reservoir (Figure 1c), with a volume of 800,000 m^3, and the intake reservoir (Figure 1d) belong to the Coca Codo Sinclair project, which generates 1500 MW. And the Manduriacu reservoir (Figure 1e), with a reservoir area of 70.50 hectares, generates 65 MW.

(**a**) (**b**)

Figure 2. Hydrographic system: (**a**) shore control base; (**b**) echo sounder connections.

2.2. Materials

2.2.1. USV/Drone Echo Sounder System

For the underwater data survey [5–7], a Z-BOAT 1800 HS marine drone was used with an ECHOTRAC CV100 DUAL dual-frequency (100–340 Khz and low 24–50 Khz) echosounder, ethernet communications, GNSS-RTK, motion and velocity sensors, a depth range from 30 cm to 60 0m, and accuracy of 0.01 m ± 0.1%. A land control center with a device manager computer and hydrographic data collector + GNSS RTK (Figure 2) was installed for real-time visualization of survey status.

2.2.2. LiDAR and RGB UAS/Drone System

The UAS/drone system (Figure 3) is composed of two main components: one on-board and one on the ground. The on-board components of the Matrice 600 Pro aircraft (DJI, Shenzhen, China) are a Riegl miniVUX-1UAV sensor (RIEGL, Horn, Austria), which is a 5-pulse ALS (airborne laser scanner) [8,9] (@ 100 kHz PRR & 360° FOV); an INS/GNSS inertial system with a heading RMS accuracy of 0.009°/0.019°, operating in RTK, PPP and PPK modes; and a 42.4 MP Sony Alpha A7RII RGB camera (Sony Corporation, Minato, Japan). On the other hand, the ground components are a computer synchronized with onboard components that manages the flight and displays the collected data in real time, and a GNSS receiver as a ground base.

(**a**) (**b**)

Figure 3. Aerial system: (**a**) ground control; (**b**) INS/GNSS LiDAR/RGB system on Matrice 600ProRTK.

2.3. Survey Methodology

Due to the inherent conditions of each reservoir, High precision geodetic networks were designed to allow the possibility of linking all the sensors together for the survey processes, allowing continuous monitoring of the water levels of each reservoir and avoiding corrections that we coined pseudotides.

In general, for each reservoir, navigation was planned with the help of satellite of 1:5000 cartography images from the Military Geographic Institute of Ecuador (IGM). The bathymetric survey [5,10] at 5 km/h and the photogrammetric and LiDAR survey at 25 km/h were performed simultaneously, and to reduce the drift error, the distance was limited to 5 km.

Finally, once the data were post-processed and the digital fusion models of all bathymetric and laser data combined with photogrammetric data [11] were generated, monitoring and topographic control measurements were performed to verify the accuracies achieved in all survey processes and products.

2.4. Obtaining Wet and Dry Digital Surface Models

The trajectories (Figure 4) were processed with two computing algorithms: tightly coupled (tC) and loosely coupled (lC), with the TC method being more efficient, with accuracies below the maximum permissible ±2 cm in position and ±2 arcmin in attitude.

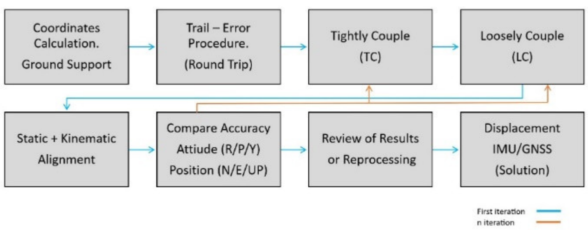


Figure 4. Sequence chain of the trajectory adjustment procedure.

The adjusted and refined LiDAR and photogram data were classified and orthorectified, respectively, while the refined bathymetric data were finally reduced and merged to generate a single underwater and dry surface model.

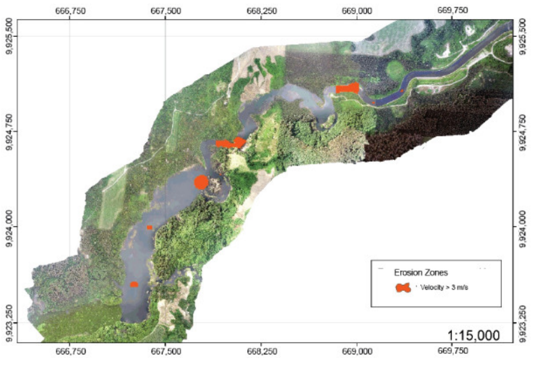
3. Results

The post-processing accuracies of trajectories did not exceed 0.2 arcmin for attitude values and 0.002 m for positional displacements.

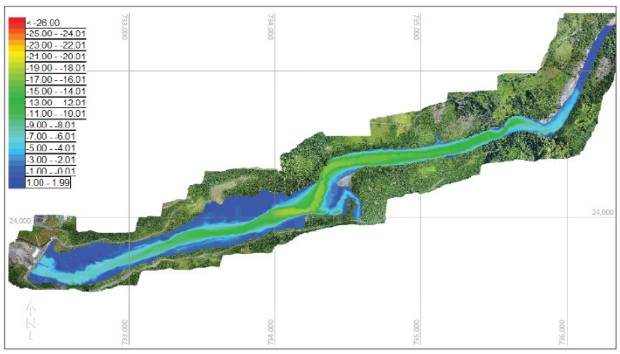
With the on-the-ground topographic control campaigns of the structures and surrounding slopes, several monitoring areas were quantified for quality control within the digital terrain models, obtaining results with accuracies of 2 cm horizontally and 2.5 cm vertically.

For the bathymetric surveys, the position and depth data gave a confidence level of 95%, i.e., a special order survey according to the standards established in the IHO. The final accuracy of the residual analysis was 0.03 m ± 0.1%, checked with control topography along the concrete structure referred to as a deflector.

This procedure resulted in calculations of accumulated water volumes; three-dimensional models of sediment outflow and transport; and one-dimensional hydraulic models for water transfers, localized sediment volumetry, and erosive processes (Figure 5).



(**a**)



(**b**)

Figure 5. Impact on the reservoirs: (**a**) erosion zones of the BABA reservoir; (**b**) three-dimensional model of sediment accumulation and sediment removal in the Manduriacu reservoir.

4. Conclusions

There is a considerable difference between the volumes of water designed and those verified in the field (−30% on average), so there is a high level of sedimentation in these reservoirs, reducing their life span considerably.

Submeter movements in subsea structures (e.g., displacement found in baffle slabs) can be monitored to control thrust forces caused by reservoir operation.

For reservoirs located on mountain rivers, it is necessary to generate water level control models that monitor changes in height and pseudotides and incorporate them into transect adjustment calculations to avoid deviations in bathymetric data.

The increase in turbidity downstream of dams is a harmful effect that is directly proportional to the amount of sediment removal through the floodgates required to maintain a useful volume in reservoirs; therefore, the design of hydro-technical works must integrate sediment and slope-monitoring manuals upstream, within, and downstream of reservoirs.

The indiscriminate increase in the operating velocities of reservoirs in high-altitude rivers aggressively and progressively erodes inland slopes, directly affecting their structural integrity and the adjacent aquatic and environmental surroundings.

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