Sedimentological study of the reservoir of the Manduriacu hydroelectric project, northern Ecuador

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Abstract. The first years of operation of a project, especially of hydroelectric plants, requires the permanent monitoring of the critical parameters that determine the normal operation of the project, verifying or adjusting the conditions that have been established in the design and construction of the work. For the Manduriacu Project in Ecuador the critical parameter has been the volume of sediments that the Guayllabamba River carries and that reduces the useful volume of the reservoir. This study presents the evaluation of sedimentation of the reservoir for the spring 2016 to spring 2017, conducted with a variety of tools such as the marine drone Z-BOAT 1800 HS (USV), the dual frequency echo sounder ECHOTRAC CV100 DUAL, the Long Range Radio HYDROLINK, the equipment for reception of position data GNSS TRIMBLE R10, the Echosounder control software and eChart connections as well as the Hypack MAX device manager software and other technical support. From the comparative analysis of bathymetries before and after washing, it has been determined that the volume of sediment accumulated in the year has been of 4'899.263 m³ corresponding to 59.1% of the total volume of the reservoir.

1. Introduction
The present sedimentology study corresponds to the reservoir of the Manduriacu hydroelectric project, which is located between the provinces of Pichincha and Imbabura, in one of the sub-basins of the Guayllabamba River (figure 1). The drainage area of the basin comprises approximately 6980 km² and the reservoir has been conformed to the construction of a concrete dam, mostly roller compacted, being 40 m high above the level of the channel [1].

The dam is located at the level 458.2 meters above sea level (m.a.s.l.). It includes five overflow dumps, with the lip at level 482.5, which allows evacuating a flow of 3475 m³/s, and two bottom drains for the washing of sediments from the reservoir for a flow of 1230 m³/s. The capacity of the reservoir is of about 10.3 hm³, having a length of about 4.6 km and a surface of around 80 ha. The main levels in the reservoir are being at a Minimum Operating Water Level of 489.4 m.a.s.l., the Maximum Operating Water Level at 492.5 m.a.s.l., and the Maximum Extraordinary Water Level at an altitude of about 492.9 m.a.s.l. The climatic conditions of the project area characterized by a very humid climate and register a marked period of rain from January to May and a lower rainy period between October and November. The average rainfall considered in the project is of about 1500 mm (CELEC, 2012). It has been estimated that the volume of sediments of the project is around 3.4 million m³/year [2]. A further study has been carried out for the design of the sediment deflector for the area.
close to the intake work of the hydroelectric power plant. The volume considered to be variable, yielding between 4.59 hm³/year and a maximum of 7.58 hm³/year, depending on the flow of the river in the closure area [3].

![Figure 1. Location of the Manduariacu project.](image)

We consider that there is a fault in the design of the sediment washing system. This may be noted since in order to execute this process, the total water withdrawal from the dam is required for repeated occasions for a time period of a week. This generates losses in the production of electrical energy and a hyper-concentration of sediments in the flow in the washout period, with the consequent death of the aquatic species from the area downstream of the dam. An optimal design is when continuous washes can be carried out, that do not allow the sediment to accumulate in large volumes, and according to the degree of accumulation of these. The current study is part of the monitoring of sediment volumes in order to establish future policies for the washing of the reservoir. Therefore, this work determines the accumulated sediment volume in the period between May 5, 2016 and April 25, 2017 and updates the contour vs. capacity curves of the reservoir, which allows the comparison with the parameters estimated in the design of the Manduriacu project. This time period has been chosen, as there is a level of precipitation that allows replenishing the volume of water quickly. The other hydroelectric plants in this period are operational and the operation of this plant is not essential.

2. Methodology

The recent years have been characterized by the use of cutting-edge technologies such as acoustics, laser, optics, thermal, drones and satellites in different fields of engineering and especially in hydraulics [4-8]. This confirms the need for the use of technology to ensure the results of field research, since the study of reservoir sedimentology has a great global interest [9-14]. Hydrographic surveys require optimal quality control and assurance. Therefore, precise technical specifications need to be considered, which regulate the proper use of single-beam or multiple-beam acoustic inspection systems. In this context, the present study applies the regulations of the manual of good practices for hydrographic surveys EM 1110-2-1003- Hydrographic Surveying [15], which allows to guarantee the general confidence of this study, the use of the techniques appropriate, the veracity of underwater measurements and also underwater structural surveys.

2.1. Geodetic control

The reference geodetic system used in this study has been the TM Local Manduríacu (Local Network CHM), whose horizontal and vertical datum has been based on the geodesic reference frame WGS 84.
Vertically the drill holes are referenced to the sea level, reducing the vertical uncertainty of the measured depths. The parameters of the Local Coordinate System of the baseline are presented in Table 1 and the geometric parameters in Table 2.

### Table 1. Local Coordinate System of the baseline.

| Control point | North     | East       | Level (m, a.s.l.) |
|---------------|-----------|------------|------------------|
| PF-01         | 23885.286 | 732504.276 | 501.673          |
| PF-02         | 23569.048 | 732268.178 | 503.628          |

### Table 2. Geometric parameters.

| Parameter                   | Value / Unit |
|-----------------------------|--------------|
| Central meridian            | 78°54‘39.57884” W |
| Central parallel            | 00°12‘57.43109” N |
| Ellipsoidal height (h)      | 825 m        |
| Scale factor (k)            | 1.00012935   |
| Eastern origin of projection | 732504.276 m |
| Northern origin of projection| 23885.286 m |

For the complete monitoring of the position of the vessel (Zboat - Dual Echosounder - GNSS), some double frequency receivers and a radio transmitter installed on a control point of the Local CHM Network named P001 (North coordinates: 23787.366 m; East: 732512.051 m; elevation: 507.093 m, a.s.l.), have been used to continuously and timely monitor the quality of the GNSS differential signal from the bathymetric survey control center, which has been located strategically within the study area.

### 2.2. Digital information gathering system

The systems used for the bathymetric survey of the Manduriacu reservoir are the following:

- Z-BOAT 1800 HS: Marine drone, unmanned ship or USV (Unmanned Surface Vehicle). Definitions for a surface autonomous vehicle, where the surface refers to the water-sheet.
- ECOSOUNDER ECHOTRAC CV100 DUAL: Dual frequency echo sounder that includes Ethernet communications, motion sensors, speed, storage based on the data acquisition system in favor of digital image, its depth range is from 30 cm to 600 m, operates at two frequency bands: High of 100 -340 Khz and Low of 24 -50 Khz and accuracy of 0.01 m corrected with the speed of sound, among the main features.
- HYDROLINK: Long range radio (greater than 2 km) that includes high power antennas for synchronized telemetric data control between GNSS-Echosounder.
- GNSS TRIMBLE R10: Equipment for the reception of position data, with internal tilt compensation, RTK or VRS correction (xFILL), advanced processing engine (HD GNSS), electronic bubble for verticality control (SurePoint). A mobile GNNS (Rover) synchronized with the Echosounder and a base GNSS located on the ground with radio-antenna for long range.
- eChart: Echosounder control software and connections.
- Hypack MAX: Device management software, hydrographic data collection and final product processing.
- Civil 3D: Software for managing topographic databases required by the contractor.

### 3. Bathymetry

Two bathymetric survey processes were planned, being before and after the operation of washing the reservoir vessel (Reservoir Drainage). For the bathymetric process, we projected probing lines
established with a North - South direction, being perpendicular to the margins of the Guayllabamba River, and the spacing between the sounding lines has been configured (figure 2), according to the following detail:

- Every 10 m inside the structure called Deflector.
- Every 15 m after the deflector until reaching the 2.5 km length of the reservoir
- Every 25 m until reaching the tail of the reservoir at 5.1 km in length.

![Figure 2. Navigation lines of the bathymetry. Grid is of about one meter.](image)

The surveys have been conducted through 10 captures of data from the underwater bottom within 1 second, meaning every 10 deci-seconds along each line of sounding. Because the separation between drillholes and the depths obtained do not exceed 40m between the keel of the boat (Z-boat) and the underwater bottom, the current bathymetric survey is defined as a special order, according to what is regulated by the Department of the Army, US Army Corps of Engineers [15] which states that "... for surveys that require a thorough search of the background and the size of the traits to be detected by this search, it is deliberately kept small ..."

The average speed of the survey was set at 5 km/h, controlled by the speed sensor and trying to keep it constant throughout the navigation, avoiding inaccuracies that do not represent the real underwater bottom. During the capture of bathymetric data, it has been necessary to keep the level of the reservoir as stable as possible, without detriment to energy production, which allowed corrections due to variation of the level of the reservoir to be minimal, avoiding the introduction of systematic errors. In order to entirely complete the section of the studied river, surface topographic surveys have been conducted on the left and right banks of the reservoir, using the transversal profiles method orthogonal to the polygon, which give continuity to the bathymetric drilling. When arriving at the tail of the reservoir the transition between the end of the reservoir and the beginning of the turbulent flow of the Guayllabamba River has been observed, due to the tendency of the disturbance (wave) that goes from being a stable to unstable flow, behavior inherent to the hydrological characteristics of this river.

3.1. Echosounder

The used echosounder has been the ECHOTRAC CV100 DUAL dual frequency, whose bandwidths for high frequencies are between 100 and 340 kHz and for low frequencies between 24 and 50 kHz. The depth range of this echo sounder is from 30 cm to 600 m, with a precision of 0.01 m (+/- 0.1%)
corrected with the speed of sound. Due to the specific mounting characteristics of the echosounder inside the boat (Zboat), the beam is directed without inclinations, and since the GNSS equipment is located on the center of the echosounder axis, no offset control is required, which consequently eliminates factors of vertical and horizontal uncertainty caused by incorrect knowledge of the orientation of the boat with respect to the equipment installed during the lifting process. The clocks of the GNSS equipment and the echo sounder were synchronized to obtain unique position and depth data eliminating the combined latency between these equipment and for the transfer of the bathymetric data, in real time, a telemetry system was used that synchronizes the transmission time and the reception of sonar echoes. Additionally, prior to the start of activities, the respective adjustments and calibration of the equipment have been conducted. The frequencies used during the surveys were 33 kHz and 210 kHz and no correction has been required due to the effects of the tidal currents due to the fact that the reservoir has a stable, almost laminar flow.

3.2. Texture of the subaquatic floor

Two bathymetric surveys have been conducted at different times indicated as: Pre-Wash and Post-Wash, which allow evaluating the volume of sediment existing and evacuated in the washing operation of the reservoir vessel. The first bathymetric process, Pre-Wash, began with the level of the reservoir located at the elevation of 492.80 m.a.s.l. and, the underwater bottom could be examined completely in accordance with the planned survey lines, appreciating the sediment deposit areas accumulated along the reservoir, which are mainly located on the natural course of the Guayllabamba River and in the areas marked with color red, as illustrated in figure 3. In the first sounding lines, parallel to the axis of the dam, we observed the sediment levels that have been close to the water intakes of the hydroelectric power station.

![Figure 3. Pre-washed sediment level.](image-url)

The navigation and data capture ended at the time when the boat (Z-boat) marked 50 cm between the keel and the underwater bottom and / or at the time the boat was next to the vertical slope of the shore, allowing to reach the navigation lines to the ends of the left and right banks of the reservoir, and with this the areas of reduced access and islets within the reservoir were determined. Once the level of the reservoir stabilized, as a result of the ascent after the washing process, the second bathymetric
process was started, Post-Wash, with the level of the reservoir located at a height of 492.80 m.a.s.l. and ratified by the operating personnel that was in the hydroelectric power station. This condition gave place to the underwater bottom to be fully examined and in accordance with the planned survey lines and in this way the sectors where the sediment was washed throughout the reservoir were determined (figure 4). Within the area of Bathymetric baffle survey was decided to reduce the interval, from 15m to 10 m, between the sounding lines, in order to determine its geometry with better detail with emphasis on the location of the slabs that are part of its structure (figure 5).

![Figure 4. Post-Wash sediment level.](image)

![Figure 5. Deflector echogram - Inspection of slabs.](image)

Navigation and data capture has been performed without access problems reduced by high levels of sediment and, the detection of concrete structures (deflector and submerged bridge) existing in the
depths of low depth to monitor their location had successful results, which show the position of these structures without significant changes with reference to previous studies. For the two bathymetric survey processes, the probing lines in the Guaycuyacu sector have been extended, from the reservoir area to the carriage bridge of the same name, due to the erosion evidenced and that is occurring on the banks of that sector, in such a way that it forms part of the sediment analysis of the washing operation.

4. Coast line and topography
The coast lines (edge of the reservoir) have been determined through topographic surveys linked to the Manduriacu Local Network of precision, after the works of marking, measuring and adjusting the closed polygonal that covers the study area. The topographic equipment (technical staff, total station and prisms) measured the edge of the terrain, left and right margin at the level of the water mirror or reaching the banks of the reservoir margins in case of gorges. To obtain the complete section of the course of the Guayllabamba river, detailed topographic surveys have been conducted, highlighting the encountered geographical features and that thanks to the used profile method, these surveys have been aligned with the bathymetric drilling, in order to fully monitor the surface and underwater condition of the slopes of the reservoir margins (figure 6). In addition to the foregoing, and based to the photographic capture in situ, in real time and georeferenced to the TM Local Manduriacu coordinate system, during the whole navigation of the vessel, the various points of interest for the control of landslides have been determined (figure 7).

![Figure 6. Bathymetry and topography of the area near the dam.](image)
5. **Post process, volumes and capacity curves**

In order to process the captured bathymetric data, we performed revisions at the end of each working day, verifying the measured zones until the end of the area required for the Pre and Post-wash. The resulting echograms have been processed using HYPACK MAX software, which contains all the attributes of capture and post processing, effect by which, in each echogram resulting from each survey line, errors (jumps), have been corrected in the acoustic data observed by each ping, due to materials in suspension or fish that has been encountered along the way. This process has been conducted using the manual editor of double frequency beam data. With respect to the data files North,
East and Depth, we obtained the raw files in the first instance, after processing the echograms the edited data results, which are finally reduced (sort data) according to the norms established in the Department of the Army, US Army Corps of Engineers [15], giving the confidence level for the position and depth established by 95%. All these files (raw, edited and reduced) are kept for careful supervision and integrity monitoring due to the type of performed survey, called Special Order. Therefore, for the digital representation of the subaquatic floor by coordinates and depths, the bathymetric model has been generated, where the parameters and attributes for the generation of contour lines have been specified, forming a three-dimensional model TIN (figure 8).

Finally, the volumes of the three-dimensional models have been calculated using the TIN versus Level Method, and in turn, the three-dimensional models were exported to re-process them using the Civil 3D software for the calculation of volumes. Resulting in the evacuated sediment volume of 4'899,263 m³, which corresponds to 59.1% of the total of the reservoir since the storage capacity of water in the reservoir of the Manduriacu hydroelectric plant of about 8'287,492 m³ for the stabilized water level at an average height of 492,30 m.a.s.l and calculated due to the existing level variations during the entire bathymetric survey. These results have been demonstrated by the submitted calculation reports. Once the field and laboratory works of the detailed topographic surveys of studied river margins have been completed in conjunction with the subaquatic floor information, the data set has been modeled in order to generate the updating of the Level-Area-Volume curve of the reservoir based on table 3.

| Data | Methods | Final average area | Modified prismoidal |
|------|---------|--------------------|---------------------|
| Dam Height | Level | Area | Average area | Accumulated volume | Accumulated volume |
| m | m.a.s.l. | m² | m² | m³ | m³ |
| 0 | 459 | 245,87 | 0,00 | 0 | 0 |
| 1 | 460 | 751,64 | 498,80 | 499 | 476 |
| 2 | 461 | 1640,72 | 1196,20 | 1695 | 1643 |
| 3 | 462 | 4137,01 | 2888,90 | 4584 | 4438 |
| 4 | 463 | 13008,04 | 8572,50 | 13156 | 12598 |
| 5 | 464 | 17628,97 | 15318,50 | 28475 | 27858 |
| 6 | 465 | 29503,38 | 23566,20 | 52041 | 51171 |
| 7 | 466 | 43164,21 | 36333,80 | 88375 | 87289 |
| 8 | 467 | 61492,62 | 52328,40 | 140703 | 139348 |
| 9 | 468 | 73315,89 | 67404,30 | 208107 | 206665 |
| 10 | 469 | 88998,11 | 81157,00 | 289264 | 287696 |
| 11 | 470 | 106607,71 | 97802,90 | 387067 | 385366 |
| 12 | 471 | 125533,83 | 116070,80 | 503138 | 501308 |
| 13 | 472 | 145239,05 | 135386,40 | 638525 | 636575 |
| 14 | 473 | 163859,00 | 154549,00 | 793074 | 791031 |
| 15 | 474 | 181517,04 | 172688,00 | 965762 | 963643 |
| 16 | 475 | 201731,35 | 191624,20 | 1157386 | 1155179 |
| 17 | 476 | 225147,97 | 213439,70 | 1370825 | 1368511 |
| 18 | 477 | 249920,44 | 237534,20 | 1608360 | 1605938 |
| 19 | 478 | 271912,60 | 260916,50 | 1869276 | 1866777 |
Table 1: Level area volume curve.

| Level (m) | Area (m²) | Volume (m³) |
|----------|-----------|-------------|
| 480      | 282628.70 | 2149338    |
| 481      | 304589.60 | 2453858    |
| 482      | 348102.60 | 3128348    |
| 483      | 371005.20 | 3499289    |
| 484      | 395093.10 | 3894320    |
| 485      | 420507.00 | 4314757    |
| 486      | 449752.60 | 4764416    |
| 487      | 479969.30 | 5244314    |
| 488      | 509600.50 | 5753837    |
| 489      | 549043.70 | 6302705    |
| 490      | 589356.30 | 6891987    |
| 491      | 624361.70 | 7516255    |
| 492      | 679449.10 | 8195380    |
| 493      | 740092.70 | 8935339    |

Figure 9. Level area volume curve.

Of the two used methods, we have been able to observe, that the variation has been of about 3992 m³ and corresponds to an error of 0.044%, resulting in a total of 8.94 Hm³ for the elevation of 493.00 m.a.s.l. Finally, based on the obtained data, the prismatic method has been selected in order to generate the next Level-Area-Volume curve (figure 9). With all the obtained information, it has been possible to construct the 3D sediment output and transport evaluation model in which the result of the washing operation of the reservoir vessel of Manduracu hydroelectric plant is shown (figure 10). Figure 10 is the model built on the basis of the bathymetry so this is a graphic representation of what occurs in reality.
6. Conclusions

The high-tech equipment used in the bathymetry and topography for the sedimentation study for the reservoir Manduriacu project, allowed to obtain a high degree of accuracy of the sediment volumes between the washings of the reservoir, yielding some 4'899.263 m³, which corresponds to 59.1% of the total for the time lapse of one year.

The encountered sediment volume has been within the established range in the construction of the deflector of the hydroelectric plant’s intake work and is greater that the established values of the studied period of the design period.

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