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## Is it really necessary to use complex methods for silting estimation in reservoirs?

*É realmente necessário usar métodos complexos para estimar o assoreamento em reservatórios?*

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### ABSTRACT

The study aimed to evaluate whether primary hydrosedimentometric monitoring data would be sufficient to estimate the total siltation of the Pimental Reservoir (Belo Monte HPP) or whether more complex methods would be required. Three mass balance approaches were applied: the sedimentometric method, the simplified Sediment model, and three-dimensional hydrodynamic and sediment transport modeling (Delft3D). The three-dimensional model was calibrated and the silting was evaluated for a period where observed data was available. Subsequently, a future scenario (2018–2039) was simulated based on extrapolations of existing flood hydrographs and operational data. The results showed similar average siltation rates between the sedimentometric method (1.37 hm<sup>3</sup>/year) and the 3D modeling (1.31–1.48 hm<sup>3</sup>/year), while the Sediment model overestimated siltation rates (2.29 hm<sup>3</sup>/year) because it did not represent the outflow through the diversion channel. When evaluating sedimentation rates over decades, an increase in rates was observed in the second decade for all methods. It was observed that less complex methods can provide representative estimates for siltation management, provided there is adequate monitoring, especially in the diversion channel, and monitoring during flood peaks.

**Keywords:** Reservoir; Three-dimensional modelling; Mass balance; Silting rate.

### RESUMO

O estudo teve como objetivo avaliar se dados primários de monitoramento hidrossedimentométrico seriam suficientes para estimar o assoreamento total do reservatório de Pimental (UHE Belo Monte) ou se seriam necessários métodos mais complexos. Foram aplicadas três abordagens de balanço de massa: método sedimentométrico, modelo simplificado Sediment e modelagem hidrodinâmica e de transporte de sedimentos tridimensional (Delft3D). Foi realizada a calibração do modelo tridimensional e avaliada a sedimentação no período com dados observados. Posteriormente, foi avaliado um cenário futuro (2018–2039) com base em hidrogramas de cheia e dados operativos. Os resultados mostraram taxas médias de assoreamento semelhantes entre o método sedimentométrico (1,37 hm<sup>3</sup>/ano) e a modelagem 3D (1,31–1,48 hm<sup>3</sup>/ano), enquanto o modelo Sediment superestimou (2,29 hm<sup>3</sup>/ano) por não representar a saída pelo canal de derivação. Avaliando as taxas de sedimentação por décadas, observou-se aumento nas taxas na segunda década simulada em todos os métodos. Observou-se que métodos menos complexos podem fornecer estimativas representativas para a gestão do assoreamento, desde que haja monitoramento adequado, especialmente no canal de derivação, e monitoramento em picos de cheia.

**Palavras-chave:** Reservatório; Modelagem tridimensional; Balanço de massa; Taxa de assoreamento.

## INTRODUCTION

Damming a river to create a reservoir reduces water velocities, and reducing sediment transport capacity, which favors sediment deposition and, therefore, reservoir silting. This, in turn, is a natural process that, over time, can reduce water storage capacity (Hilgert et al., 2024) and affect its intended uses (Endalew & Mulu, 2022). Therefore, understanding and estimating siltation are essential for water resources management. In the electricity sector, silting can directly impact water availability for hydropower electricity generation, reducing production and system reliability. Thus, studies on sedimentation rates and silted quantities are essential for system planning and operation.

In previous studies reservoir siltation has been carried out using different approaches, either through traditional bathymetry monitoring and comparison with previous measurements (Khasanov, 2025; Hilgert et al., 2024; Endalew & Mulu, 2022), sediment balances (Lemma et al., 2024; Jansson & Erlingsson, 2000), remote sensing (Yao et al., 2023; Lopes & Araújo, 2019; Collischonn & Clarke, 2016), numerical modeling or simplified models (Rabelo et al., 2025; Reisenbüchler et al., 2020; Costa et al., 2018) or a combination of these methods (Luz et al., 2025a).

Regarding bathymetric surveys, which represents the direct method of measuring siltation, Collischonn & Clarke (2016) argue that the cost of the survey depends on the location and access, reservoir volume, and level at the time of measurement. Furthermore, when comparing bathymetries, there are always doubts about the consistency of the older data, given the technologies previously adopted (Collischonn & Clarke, 2016).

In general, to calculate the estimated siltation, measurements are necessary. Brazil's river monitoring network evolved during the 20th century, primarily focused on the implementation of stations specifically designed to support studies on hydraulic developments for hydropower generation (Agência Nacional de Águas e Saneamento Básico, 2009). However, considering 2021 data from the National Water and Sanitation Agency (ANA) of the 2,024 active river measuring stations in Brazil, only 463 of them (22.9%) monitor suspended sediments (solid discharge) (Agência Nacional de Águas e Saneamento Básico, 2021). This relationship points to a historical weakness in solid discharge monitoring in Brazil, which limits, for example, analyses of siltation in hydroelectric plant reservoirs. Despite this gap in sedimentological monitoring (which, when present, is generally conducted on a quarterly basis), this data gap is even greater, when we evaluate historical data from topobathymetric surveys of reservoirs.

Based on the ANA data collection (Agência Nacional de Águas e Saneamento Básico, 2019), considering 132 hydroelectric projects that had their Depth-Area-Volume (DAV) curves updated in accordance with ANA/ANEEL Joint Resolution No. 03/2010 (Brasil, 2010) (Table SP 1, presented in the supplementary material), approximately half of the projects began operating before the 1990s (Table SP 2). Furthermore, 47% of the projects had their topobathymetric surveys updated at least 30 years ago (Table SP 3), of which two were updated only after 90 years of operation.

Furthermore, bathymetric surveys are expensive and generally have low temporal and spatial resolution and uncertainty relative to older surveys. Therefore, studies evaluate alternatives to siltation estimates using other methods (Luz et al., 2025a; Luz et al.,

2025b; Rabelo et al., 2025; Lemma et al., 2024; Yao et al., 2023; Jansson & Erlingsson, 2000; Reisenbüchler et al., 2020; Lopes & Araújo, 2019; Costa et al., 2018; Collischonn & Clarke, 2016).

In the specific context of the Belo Monte HPP, hydrosedimentological data monitoring at reservoir in and outflows is carried out monthly, i.e., with better temporal resolution than that typically used in Brazilian reservoirs (quarterly). However, one of the reservoir outlets is not monitored yet. For this reservoir, two DAV curves are available: one from the Consolidated Basic Project (PBC) (Intertechne, 2011), based on few bathymetric sections and therefore having uncertainties in the survey, and another updated in 2018, with higher spatial resolution. Luz et al. (2025a) assessed siltation by directly comparing these datasets and concluded to not recommend their use until a new survey with better resolution is conducted.

Considering this gap of topobathymetric data and measurements in the hydroelectric power plants (HPP), the aim of this paper was to verify if primary data from hydrosedimentometric monitoring is sufficient for a representative total siltation estimate in Pimental reservoir, or if it is necessary to use more complex methods for that. This evaluation was performed by using hydrosedimentometric data from monitoring stations to calculate mass balance (directly and with simplified models) and comparing these with results from a 3D hydrodynamic and sediment transport modeling. This study also aimed to make this comparison for the medium-term silting period. For this purpose, future discharge series were generated based on the operational discharge and flood studies for Belo Monte HPP.

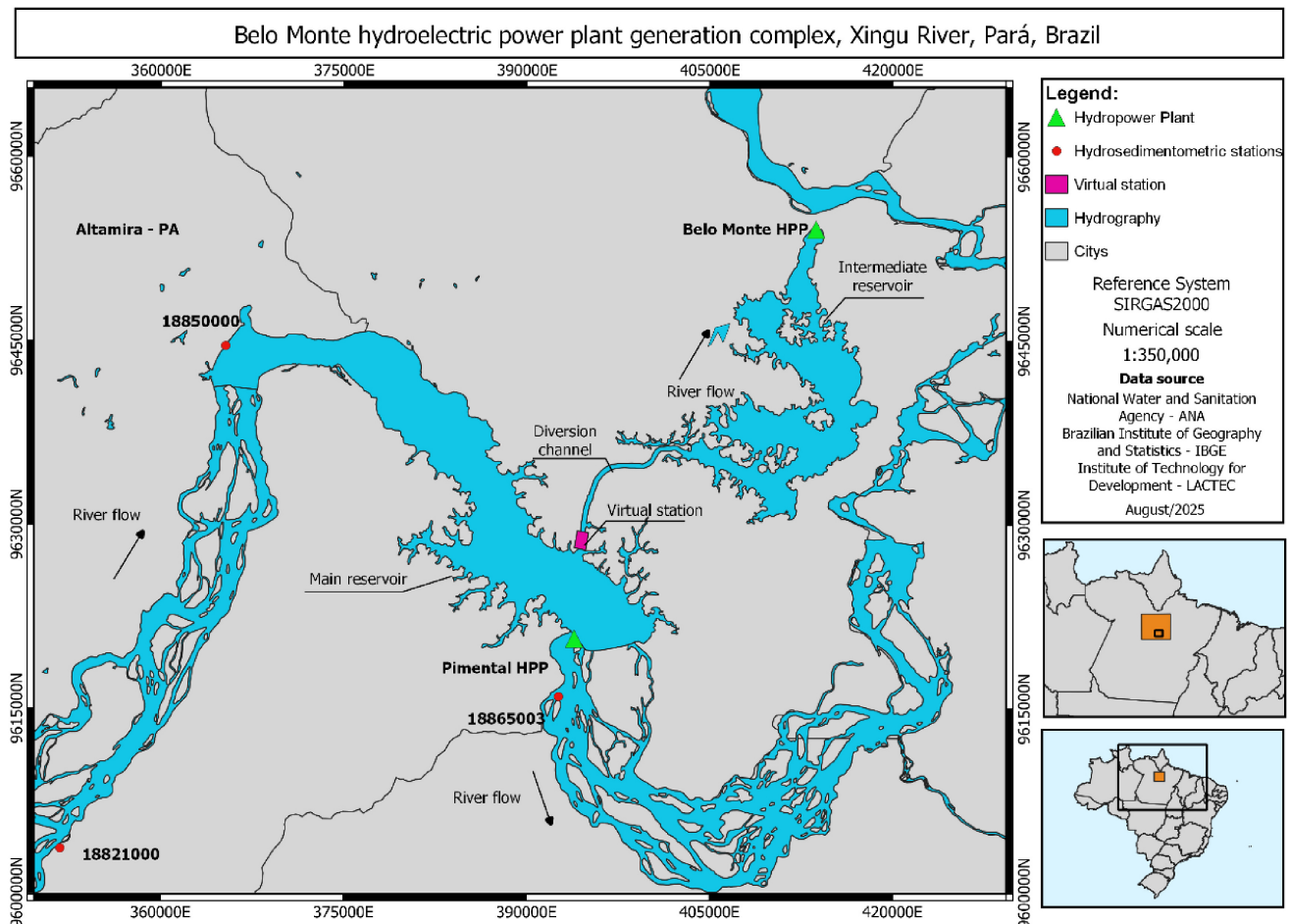
## MATERIALS AND METHODS

### Study area and data

The study area is the Pimental HPP reservoir, which is the main reservoir of the Belo Monte HPP complex. The HPP complex is located on the Xingu River, in the Volta Grande do Xingu region, in southwestern state Pará, Brazil.

The Complex is formed by Belo Monte HPP (11,000 MW) and Pimental HPP (233 MW), with two reservoirs – the intermediate reservoir (119 km<sup>2</sup>) and the main reservoir (359 km<sup>2</sup>), respectively. The main reservoir is the focus of this work, as it is shown in Figure 1. Both reservoirs are connected by a diversion channel (20 km). The operation of this HPP Complex started in January 2016 (Norte Energia, 2024).

Data considered in this paper was provided by Norte Energia SA and consisted of a hydrosedimentometric database, with data of water level elevation, discharge, rating curve, cross-sectional profiles, concentration of suspended sediment, among others, for stations located in the interest region. For this paper and analysis, datasets of the station 18821000 (UHE Belo Monte Montante), located upstream of the complex and station 18865003 (UHE Belo Monte Mangueiras), located downstream of the Pimental HPP were used. It is worth noting that the frequency of monitoring of suspended solids concentration on a monthly scale is higher than that commonly monitored in Brazil. The location of these stations is shown in Figure 1. The sedimentometric data was estimated using the solid discharge curves established for the stations 18821000, 18865003 and for the virtual station named diversion channel, as in Table 1.



**Figure 1.** Location of the study area with the main fluviometric monitoring stations used in the study (upstream: 18821000 (UHE Belo Monte Montante) and downstream Pimental HPP: 18865003 (UHE Belo Monte Mangueiras).

**Table 1.** Sediment rating curve coefficients equation for stations 18821000, 18865003, and diversion channel. The equation is  $Q_{ST} = a Q_{Liq}^b$ , in which  $Q_{ST}$  = Total solid discharge (t/d);  $Q_{Liq}$  = Liquid discharge ( $m^3/s$ ); a and b = coefficients of the equation.

| Station           | Coefficient a | Coefficient b | Source             |
|-------------------|---------------|---------------|--------------------|
| 18821000          | 0.180946      | 1.2535        | Luz et al. (2025a) |
| 18865003          | 0.019441      | 1.4997        | Luz et al. (2025a) |
| Diversion channel | 0.654900      | 1.0738        | Luz et al. (2025b) |

Source: Luz et al. (2025a, 2025b).

The measured operation data was used to represent the outlet flows (flow through turbines, spillway and diversion channel) and the water level measurements defining the boundary condition of the spilled flows from Pimental.

In addition, bathymetric data and depth-area-volume (DAV) curves were also provided by Norte Energia, which survey was performed after the start of operation (2018) (Ruraltech, 2019). Bathymetric measures were performed each 300 m of the reservoir and were used to define the initial bathymetry for the modeling.

### Future scenario analysis (2018 to 2039)

To evaluate the medium-term sediment estimate (15 years), it was necessary to estimate future inflows and outflows into the reservoir.

This was done based on flood studies provided by Norte Energia and using the observed flows from stations 18821000 and 18865003 (period from January 1, 2016, to May 9, 2024) to define a future hydrograph (May 10, 2024, to September 30, 2039). The hydrograph shape was obtained by averaging the annual hydrographs observed at the site. First, the hydrographs were normalized by the peak value, and then the average of the normalized hydrographs was obtained. Finally, the average hydrograph was multiplied by the desired peak value (corresponding RT).

The composition of this hydrograph was given by 3CMA, RT5, 3CMA, RT10, 4CMA, RT5, and 2CMA, where CMA is the hydrograph of an average flood, RT5 is the flood hydrograph with a 5-year return period (RT), and RT10 is a flood hydrograph with a 10-year return period (Intertechne, 2020a).



This arrangement was made because the period of interest was 15 years and, therefore, should include a hydrograph equivalent to a 10-year RT, at least two hydrographs equivalent to a 5-year RT, and for the remaining years, the average hydrograph was used.

It should be noted that changes in land use and occupation, the effects of climate change or other factors that may alter the distribution of flows and the contribution of sediment in the basin may be considered; however, this was not the focus of this article, thus not included.

To define future operational flows, a polynomial trend-fit analysis was performed between station 18821000 and the corresponding structure (turbines, spillway, and diversion channel) for the observed data period. Subsequently, the future hydrograph was used to estimate future operational flows. It should be noted that for the spillway, the relationship used was based on the dam water level.

### Sedimentometric method (mass balance)

Considering the flood study carried out for the Pimental HPP reservoir (Intertechne, 2012, 2020a), the occurrence of flow records and suspended solids concentration monitoring were evaluated and classified according to the flow magnitude. This was done to demonstrate the distribution of the available data for the application of this method.

Together with the discharge data (11/06/2018 to 09/05/2024) and the future data obtained from 10/05/2024 to 30/09/2039 in *Future scenario analysis (2018 to 2039)*, historical series of solid discharge were estimated using the solid discharge curves established for the stations 18821000, 18865003 and for the virtual station named diversion channel, according to Luz et al. (2025a, 2025b) to close the mass balance, using the Colby Method (Colby, 1957).

It should be noted that changes in land use and occupation, climate change or other factors that may alter the solid discharge curve of the stations may be considered, however, this was not the focus of this article, thus not included.

For each station, the solid discharge values were evaluated in total terms per year and accumulated daily values. Thus, the deposited mass was determined through cumulative analysis using a mass balance approach, in which it was calculated by input (18821000) minus output (station 18865003 plus diversion channel station). Finally, the deposited volume was determined through the soil's apparent specific mass.

### Simplified model Sediment

The Sediment model is a computational tool developed to estimate reservoir silting over time using simplified empirical methods (Braga, 2005). Based on the methodology of Borland & Miller (1958), it calculates the annual volume of deposited sediment and updates reservoir area-volume curves accordingly. The model incorporates key sedimentation processes, such as the apparent specific weight of deposited materials (Lara & Pemberton, 1963), sediment retention efficiency (Brune, 1953; Churchill, 1948), and sediment grain size distribution. It is used

for long-term sedimentation analysis due to its practical input requirements and ease of implementation (Luz et al., 2025a).

Using the discharge data from station 18821000 available since 2011, together with the data estimated in *Future scenario analysis (2018 to 2039)*, the average liquid discharge ( $7610 \text{ m}^3/\text{s}$ ), the solid discharge series – using the same solid discharge curves (Luz et al., 2025a) – and the annual average solid discharge were calculated ( $5,433,125 \text{ t/year}$ ). These data are input to the model, as are grain size composition (24% clay, 32% silt, 44% sand), and a 2% annual increase in sediment load. Considering the initial volume as null, the reservoir water volume at the maximum normal water level ( $2022 \text{ hm}^3$  at the 97.0 m elevation) and the average Brune curve, simulations using Sediment covered the period from 2018 to 2039, resulting in silting volumes for each year.

### Hydrodynamic and sediment transport model description

Hydrodynamic modeling aims to better understand water dynamics (time series of levels and velocities and profiles and maps of level and velocity fields) and the representation of sediment transport (time series of concentrations and maps of concentration, erosion and sedimentation) and which in turn will provide indications of the silting process of the Pimental reservoir, an integral part of the Belo Monte HPP.

To achieve the objectives, the provided data were preliminarily analyzed, and it was observed that the simulation must be capable of representing hydrodynamic processes in a river regime and with three-dimensional resolution. For this purpose, the Delft3D model was chosen due to its large number of integrated applications (hydrodynamics and sediment transport), and being an open-source model. The Delft3D package was developed by Deltares in the Netherlands and consists of several modules, each with a different simulation focus. In this article, the hydrodynamics module (FLOW) was used.

The hydrodynamic module (Deltares, 2025) solves the transient shallow water equations, that are, a system formed by the mass balance and momentum equations for free surface flows. It assumes a hydrostatic pressure distribution, which disregards accelerations in the vertical direction. The other assumptions adopted in the mathematical formulation of the model are: the continuum hypothesis; incompressible flow; and the Boussinesq hypothesis, which consists of considering the flow acceleration to be less than that of gravity and, therefore, density variations are only important when they affect gravitational terms and not inertial terms.

Turbulence is solved through Reynolds decomposition and has four closure models for the vertical profiles: constant coefficient, algebraic method,  $\kappa$ -L model and  $\kappa$ - $\epsilon$  model (Deltares, 2025). This work used the  $\kappa$ - $\epsilon$  model because it is a more accurate model than the others. In the horizontal, constant eddy diffusivity values are used, as grid sizes are usually not capable to resolve small-scale turbulent structures. The value used here was  $1 \text{ m}^2/\text{s}$ .

For sediment transport and morphological change calculations, the model calculates the concentration of suspended sediments and bed transport, as well as exchange processes at the water-bed interface (erosion and sedimentation) that result in accumulation or reduction of material at the bed. The model allows for the simulation of different sediment fractions, which can be cohesive and non-cohesive.



The numerical model includes hydrodynamic changes due to bottom morphological changes and vice versa during the hydrodynamic calculation in a fully coupled manner (Deltares, 2025). For more information, see Deltares (2025).

#### Definition, calibration and validation of the hydrodynamic model

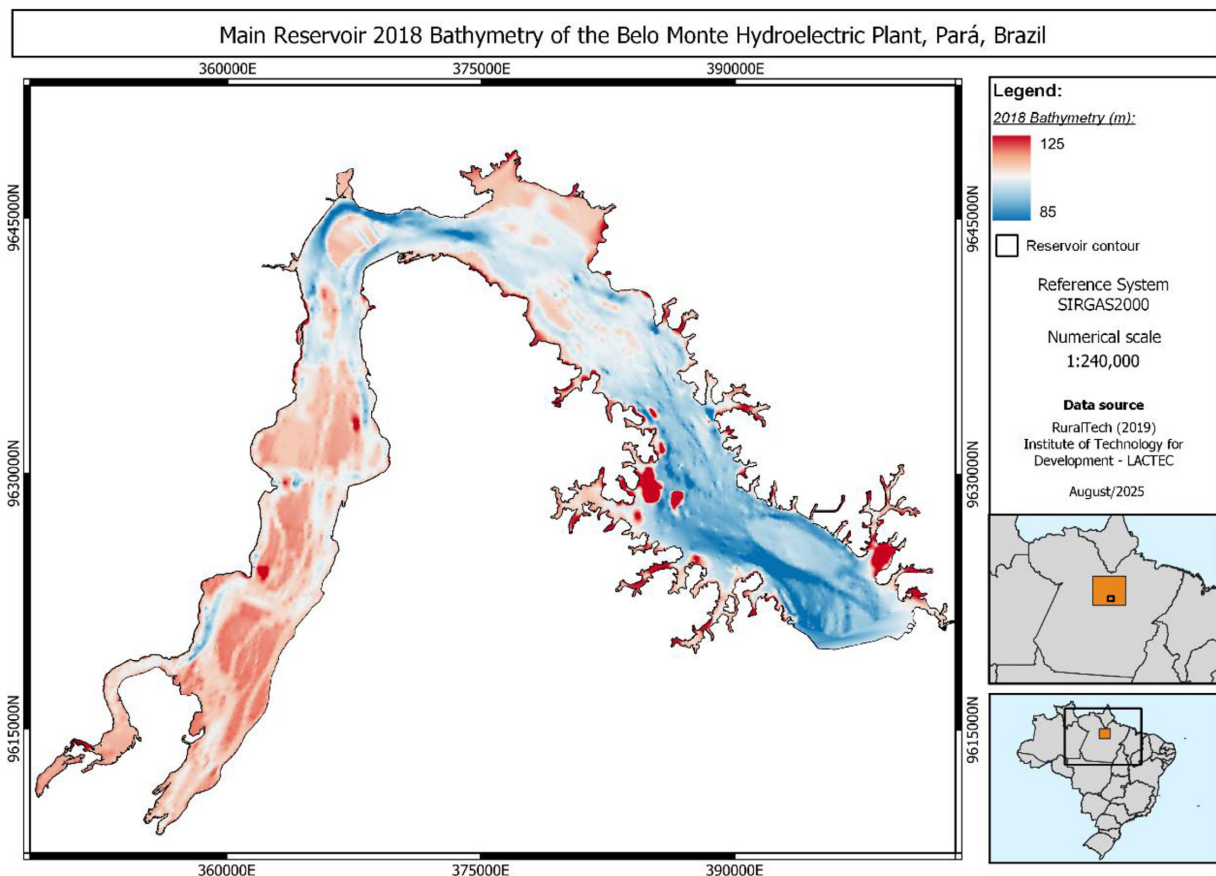
The modeling was performed by defining a three-dimensional grid based on the bathymetry for the Pimental reservoir, which used the reservoir contour and bathymetric data from 2018, provided by Norte Energia. To define the bathymetry of the numerical model, data from single-beam bathymetry carried out by Ruraltech (2019) in the Pimental reservoir were used. Figure 2 presents the original data (single-beam bathymetry) used to obtain the physical closed boundary condition (bathymetry) of the model.

The open boundary conditions used were the discharge time series from station 18821000 (upstream), the discharge transferred to

the Belo Monte HPP (diversion channel), and the water level at the dam for the spillway (downstream). The turbined flow (powerhouse) was considered as a forcing factor in the model, since the turbine process occurs below the water surface and must be represented as such in the hydrodynamic model. Therefore, the turbine flow was included in the reservoir bottom layer as a discharge with negative values.

The modeling time step was defined, as well as the physical parameters of the model (Table 2). In the calibration process, the Manning coefficient was adjusted and a spatial distribution has been defined for it over the hydrodynamic grid (showed in the results section).

Reports from previous studies using 1D and 2D steady-state models (in which measurements were also available) were used to compare the results for long-term average flow rates and with a 5-year TR (Intertechne, 2020a, 2020b). This was done considering that in the Pimental HPP backwater studies, field measurements were also taken and used to calibrate the HEC-RAS and RiverFlow2D models, thus ensuring that both simulations can be used to calibrate other models.



**Figure 2.** Bathymetry of 2018 measured every 300 m (Source: Ruraltech, 2019).

**Table 2.** Physical parameters of the three-dimensional hydrodynamic model

| Parameter                          | Value                            | Unit              |
|------------------------------------|----------------------------------|-------------------|
| Gravity acceleration               | 9.81                             | m/s <sup>2</sup>  |
| Specific mass of water             | 1000                             | kg/m <sup>3</sup> |
| Horizontal eddy viscosity          | 1                                | m <sup>2</sup> /s |
| Vertical background eddy viscosity | 3D Turbulence Model - k- Epsilon | -                 |
| Time step                          | 30                               | s                 |

For calibration, the water levels at the Altamira Trapiche fluviometric station (18850000) (Figure 1) were used through the rating curve (with reservoir) obtained from Intertechne (2020b). A visual comparison of the velocity and water level maps was also carried out for the flows of 8,045 m<sup>3</sup>/s and 26,224 m<sup>3</sup>/s, respectively.

After verifying the quality of the model (calibration), simulations were carried out for the period between 06/11/2018 and 05/09/2024. The data used for this period were the discharge data from the upstream station (18821000) which was used as the open boundary condition, as well as the discharge data on spilled and transferred flows (boundary conditions), turbine flows (discharge in the model) and reservoir level according to the history of this period (Figure 3).

For this period, the verification of the hydrodynamic model was carried out based on the results of the Nash-Sutcliffe coefficient (NSE), which was evaluated in terms of simulated outlet flows and operational data from HPP Pimental.

### Sediment transport model

Sediment transport modeling used as initial bathymetry the one from the 2018 survey, along with the flow and water level data described in the previous section. The simulated period was between June 11, 2018, and May 9, 2024.

The solid flow rates used were the same as those obtained for stations 18821000 and 18865003 in *Sedimentometric method (mass balance)*. The model considered the non-cohesive and cohesive fractions, which represent 60% and 40% of the total solid discharge, respectively (Intertechne, 2011). A  $D_{50}$  diameter of 480  $\mu$ m was adopted in the simulation for non-cohesive sediment, in agreement with granulometry information provided by Norte Energia. The initial sediment thickness in the reservoir for the cohesive and non-cohesive fractions was set to 0 m, and the initial concentrations in the reservoir was set to 7.63 mg/L for the cohesive fraction and 11.45 mg/L for the non-cohesive fraction, distributed uniformly over the entire reservoir. It should be noted that there are no measurements available in the

reservoir for suspended and bottom sediment concentrations or transport measurements.

To verify the quality of the modeling, the results from the suspended sediment concentration at the location of the diversion channel were compared with estimated values from literature (Luz et al., 2025b), which were obtained through satellite image analysis, given that there are no available measurements of sediment concentration in the reservoir. The period used in this step coincides with June 11, 2018, and May 9, 2024.

To estimate the silted volume, two methods of calculating the mass balance were used, based on the results obtained by the Delft3d model. The first was by exporting the accumulated volumes calculated by the hydrodynamic model at the locations of the open boundary conditions by total cumulative transport (in this article, referred to as method 1). The second was by estimating the loads at the inlet and outlet (method 2) from the concentrations and flow rates (i.e., Load = QC, where Q is the flow rate in m<sup>3</sup>/s and C is the concentration in mg/L).

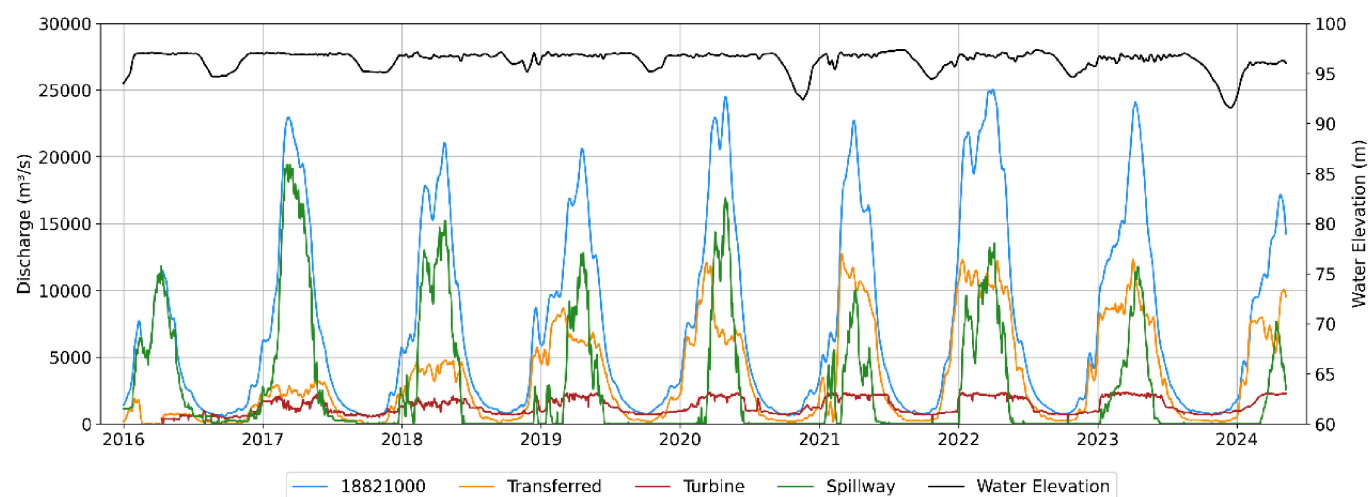
For the powerhouse, however, the load was calculated and subsequently converted to volume (using the default value of the model for the reference density of 1600 kg/m<sup>3</sup>), given that this output was considered a discharge and therefore did not allow the definition of a cross-section for controlling the total cumulative transport.

After calibration and verification, a simulation was performed considering the future period 06/11/2018 to 09/30/2039.

## RESULTS AND DISCUSSION

### Future scenario analysis (2018 to 2039)

The hydrograph composition was 3CMA, RT5, 3CMA, RT10, 4CMA, RT5, 2CMA in which CMA is the hydrograph of an average flood, RT5 is the flood hydrograph with a return time (RT) of 5 years and RT10 a flood hydrograph with a return time of 10 years, whose flood studies are available in Intertechne (2020a).



**Figure 3.** Flow rates at station 18821000, operating flows at Belo Monte HPP (transferred, turbined and spilled) and level up to 2025.

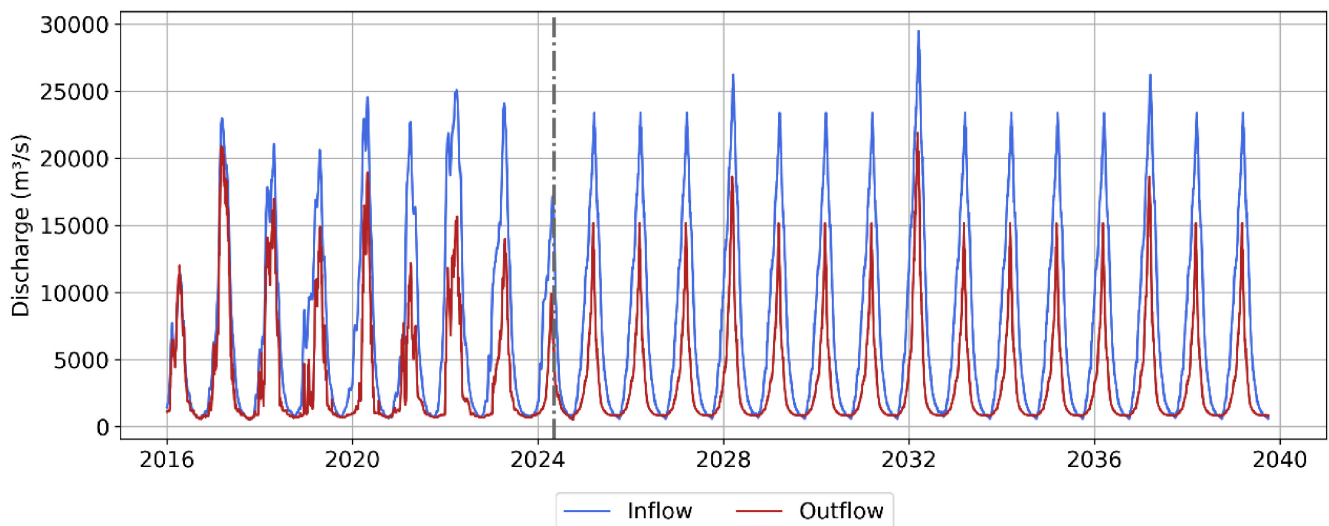
From the composition of the hydrograph for the future period (May 10, 2024, to September 30, 2039), the reservoir inflow and outflow rates were obtained by the polynomial trend-fit analysis, as shown in Figure 4. It can be seen that the future flows present less noise compared to the observed data, which was expected, since they were obtained from average hydrographs.

Camargo (2019) also generated future flow series for the Xingu River in the Belo Monte HPP region for the period 2020-2050, however using precipitation projections from five CMIP5 climate models (RCP8.5 scenario). This study assessed the potential impacts on power generation from the Belo Monte HPP. Saboia et al. (2025) used climate change projections based on CMIP6, from which flows were obtained for all basins of the National Interconnected System (SIN). However, it should be noted that assessing climate change in siltation is not the objective of this article.

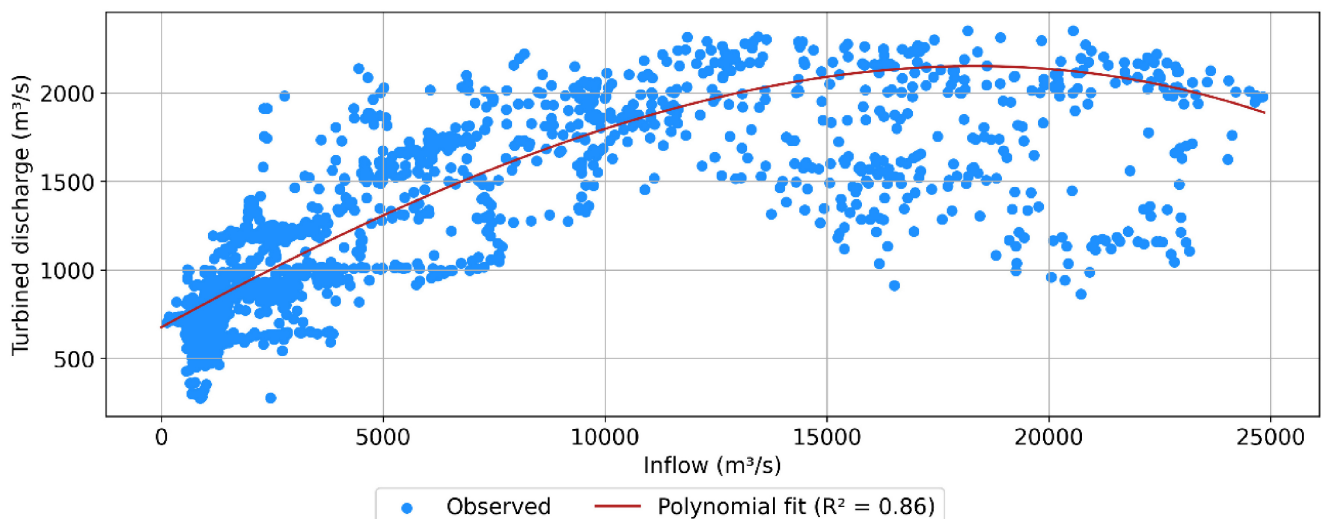
The future series of turbine flow at HPP Pimental and flow transferred to HPP Belo Monte, and the dam level data (spillway) were obtained from the future hydrograph and the polynomial trend adjustment analysis as illustrated in Figure 5, Figure 6 and Figure 7, respectively.

For the turbine flow (Figure 5 and Equation 1), the trend curve was used up to the maximum turbine swallowing and kept constant at  $2,152 \text{ m}^3/\text{s}$ . The quality of the fit was defined using the  $R^2$ , which was 0.86. For the flow transferred through the diversion channel (Figure 6 and Equation 2), the trend curve was used up to its maximum value ( $9,150 \text{ m}^3/\text{s}$ ) and kept constant for values above that. For the dam level (Figure 7 and Equation 3), the trend curve was used up to its maximum value ( $96.94 \text{ m}$ ) and kept constant for values above that.

It is important to highlight that energy generation at Belo Monte HPP increased gradually starting in 2016, with the activation of several generating units at different times.

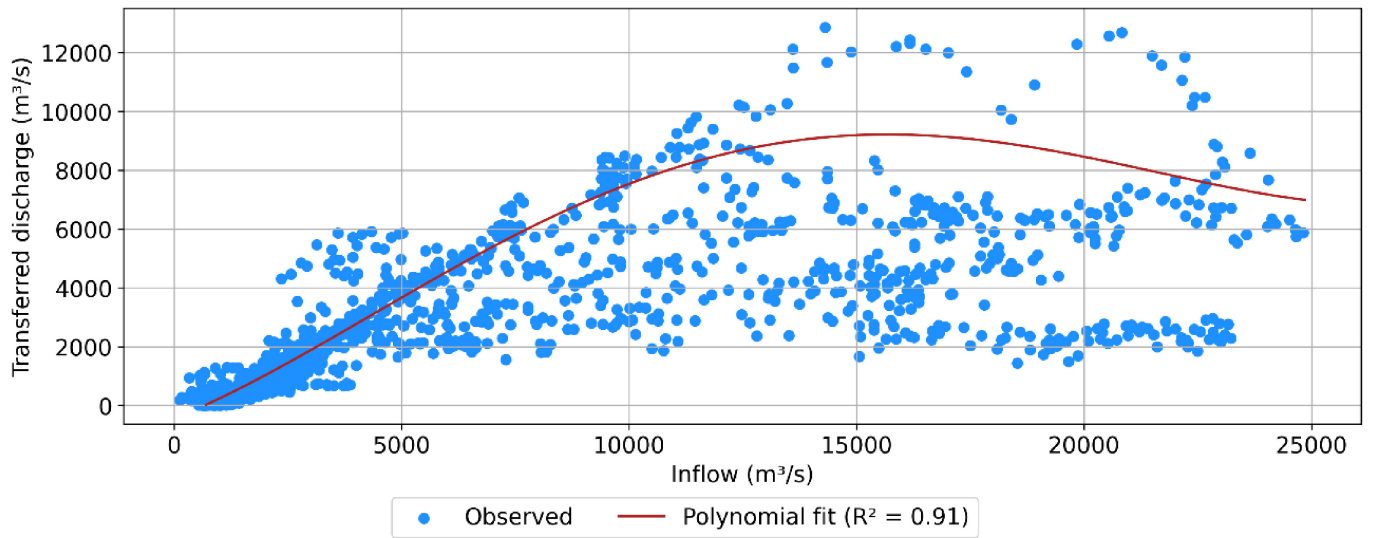


**Figure 4.** Flow series from the medium-term scenario simulation for the Pimental Reservoir. The gray vertical line indicates the division between observed and future data.

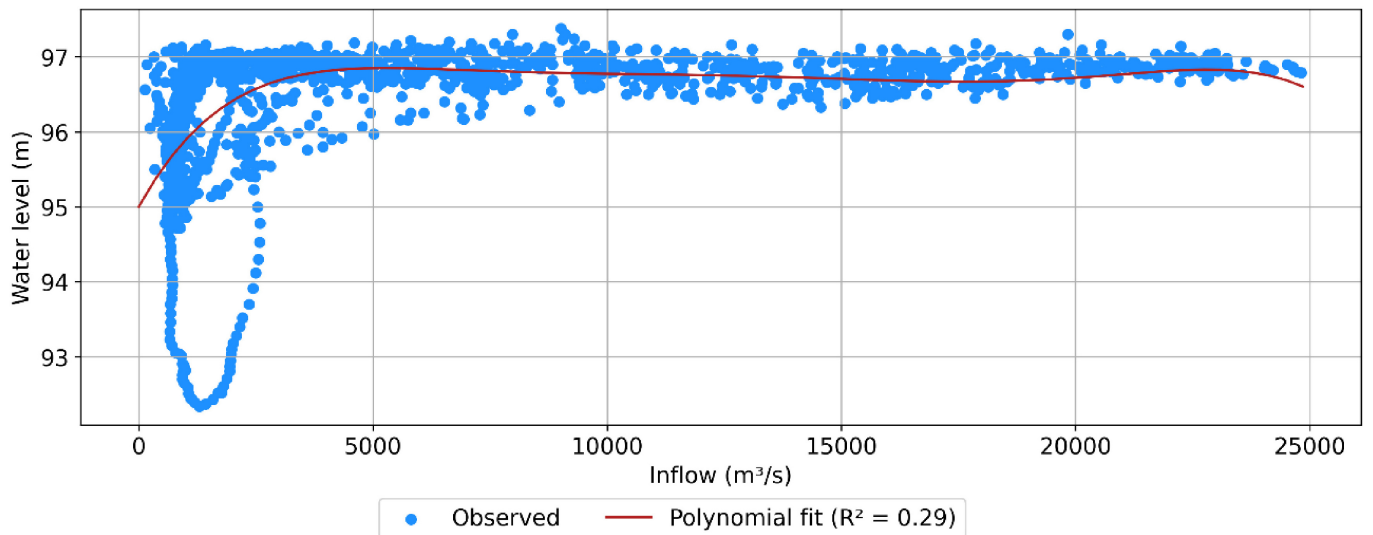


**Figure 5.** Relationship between turbine flow and inflow to the Pimental reservoir.





**Figure 6.** Relationship between flow diverted by the canal and flow inflow to the Pimental reservoir.



**Figure 7.** Relationship between reservoir water level and inflow to the Pimental reservoir.

Therefore, its full operating capacity took several years to be reached. Thus, when adjusting the transferred flow rate to the inflow rate to the reservoir, for example, for higher inflow rates, there is a greater dispersion of transferred flows. Therefore, priority was given to adjusting the flow rate considering higher transferred flows for higher inflow rates.

$$-7.1510^{-11}x^3 - 1.7710^{-6}x^2 + 1.3710^{-1}x + 676 \quad (1)$$

$$1.2010^{-13}x^4 - 6.2310^{-9}x^3 + 6.7610^{-5}x^2 + 6.2510^{-1}x - 445 \quad (2)$$

$$7.610^{-25}x^6 + 6.110^{-20}x^5 - 1.910^{-15}x^4 + 3.110^{-11}x^3 - 2.610^{-7}x^2 + 1.110^{-3}x + 9.5 \quad (3)$$

### Sedimentometric method (mass balance)

Based on flood studies (Intertechne, 2020a), flow records and suspended sediment concentration measurements from station 18821000 were quantified. It was observed that even in 13 years of data, there are no records of flows equivalent to or greater than events with a RT greater than 10 years. Regarding suspended sediment concentration measurements, there were even fewer measurements, which occurred only once and in an event with a RT equivalent to 5 years (Table 3 and Figure SP 1), that is, only one measurement was performed in the interval between the CMA flow and the RT5 flow. This suggests a limitation of suspended sediment monitoring data during flood peaks, that is, at times when sediment transport is greatest, which can produce underestimated results on the solid discharge. Even so, its use is not discouraged, and its application was carried out.

Using the liquid discharge obtained in *Future scenario analysis (2018 to 2039)* and the solid discharge curve (Table 1), the solid discharge series of each station was calculated and daily accumulated. The reservoir sedimentation estimates were calculated by the difference in accumulated mass between the output (stations 18865003 plus diversion channel station) and the input (station 18821000), as in Table 4.

The results obtained indicated a sedimentation of 29 hm<sup>3</sup> throughout the entire evaluated period, which is equivalent to a sedimentation rate of 1.37 hm<sup>3</sup>/year. This value corroborates the results obtained by Luz et al. (2025a) since the solid discharge curve equation used is coincident between both studies.

Sediment balance has been used in other studies for different purposes. Lemma et al. (2024), for example, used

mass balance to assess the sediment retention efficiency of reservoirs. The authors considered the impact of reservoirs currently under construction and operation (scenario 1) and also included those in the planning phase (scenario 2). This study observed that, in scenario 1, sediment retention by dams led to a 15% reduction in the annual sediment load reaching Lake Tana (Ethiopia). In scenario 2, the sediment load reduction reached 52%, demonstrating the sediment retention efficiency of reservoirs (Lemma et al., 2024).

In Cachí reservoir (Costa Rica), the sediment balance was used to evaluate the efficiency of the flushing process (Jansson & Erlingsson, 2000). According to the sediment input, approximately 80% was retained in the reservoir between two flushing events (one year). After the process, approximately 71.4% of the input was released from the reservoir.

**Table 3.** Net flow records and suspended sediment concentration measurements from station 18821000 by flow interval.

| Return times     | Flow rate (m <sup>3</sup> /s) <sup>1</sup> | Flow records | Sediment measurement |
|------------------|--------------------------------------------|--------------|----------------------|
| MMA <sup>2</sup> | Until 999                                  | 492          | 17                   |
| MLT <sup>3</sup> | 8,045                                      | 2,639        | 71                   |
| CMA <sup>4</sup> | 23,368                                     | 1,755        | 41                   |
| RT 5             | 26,224                                     | 34           | 1                    |
| RT 10            | 29,472                                     | 11           | 0                    |
| RT 25            | 33,766                                     | 0            | 0                    |
| RT 50            | 37,014                                     | 0            | 0                    |
| RT 100           | 40,262                                     | 0            | 0                    |
| RT 1000          | 51,052                                     | 0            | 0                    |
| TR 10000         | 61,842                                     | 0            | 0                    |

**Note:** 1 – Intertechne (2020a); 2 – average of annual minimums; 3 – historical average; 4 – average of maximum annual flows.

**Table 4.** Estimated volume of accumulated sediment from 2018 to 2039 at Pimental HPP.

| Date       | Accumulated solid discharge (10 <sup>6</sup> t/d) |                              |                | Accumulated volume in the year (hm <sup>3</sup> ) |
|------------|---------------------------------------------------|------------------------------|----------------|---------------------------------------------------|
|            | Input<br>18821000                                 | Output<br>18865003 + Channel | Input - Output |                                                   |
| 12/31/2018 | 0.76                                              | 0.51                         | 0.24           | 0.20                                              |
| 12/31/2019 | 5.60                                              | 4.14                         | 1.46           | 1.20                                              |
| 12/31/2020 | 11.28                                             | 8.57                         | 2.72           | 2.23                                              |
| 12/31/2021 | 16.45                                             | 12.09                        | 4.36           | 3.59                                              |
| 12/31/2022 | 23.83                                             | 17.41                        | 6.42           | 5.28                                              |
| 12/31/2023 | 29.43                                             | 21.33                        | 8.09           | 6.66                                              |
| 12/31/2024 | 33.23                                             | 23.95                        | 9.28           | 7.64                                              |
| 12/31/2025 | 38.69                                             | 27.63                        | 11.06          | 9.10                                              |
| 12/31/2026 | 44.14                                             | 31.30                        | 12.84          | 10.56                                             |
| 12/31/2027 | 49.68                                             | 35.04                        | 14.63          | 12.04                                             |
| 12/31/2028 | 55.91                                             | 39.56                        | 16.36          | 13.45                                             |
| 12/31/2029 | 61.37                                             | 43.23                        | 18.13          | 14.92                                             |
| 12/31/2030 | 66.82                                             | 46.91                        | 19.91          | 16.38                                             |
| 12/31/2031 | 72.46                                             | 50.73                        | 21.73          | 17.88                                             |
| 12/31/2032 | 79.59                                             | 56.26                        | 23.32          | 19.19                                             |
| 12/31/2033 | 85.04                                             | 59.94                        | 25.10          | 20.65                                             |
| 12/31/2034 | 90.50                                             | 63.62                        | 26.87          | 22.11                                             |
| 12/31/2035 | 95.95                                             | 67.30                        | 28.65          | 23.57                                             |
| 12/31/2036 | 101.51                                            | 71.06                        | 30.46          | 25.05                                             |
| 12/31/2037 | 107.72                                            | 75.55                        | 32.17          | 26.46                                             |
| 12/31/2038 | 113.18                                            | 79.23                        | 33.95          | 27.92                                             |
| 09/30/2039 | 118.04                                            | 82.49                        | 35.55          | 29.25                                             |

## Simplified model Sediment

The simulation of the Sediment model yielded, for each year, the corresponding values of deposited solid volume, effluent solid volume, retention efficiency, specific weight, and influent and effluent solid discharges (Table 5). The total silted volume was estimated until 2039 to 50.3 hm<sup>3</sup>, which corresponds to a silting rate of 2.52 hm<sup>3</sup>/year.

The retention efficiency decreases from 41.7 to 41.2%, corroborated by the values obtained for effluent solid discharge increases. The apparent specific weight of the soil obtained was 1,216 kg/m<sup>3</sup>, which was close to that achieved by Luz et al. (2025a) also with Lara & Pemberton (1963) method. This value is lower than the reference value adopted in the 3D modelling. Since there are no measurements of specific weight in situ, these values were considered in their respective simplified model and 3D modeling applications.

Another study also used the Sediment model to estimate siltation in the Pimental HPP reservoir (Intertechne, 2011), in which, up to the 22nd year of simulation, 39 hm<sup>3</sup> were obtained, a result 21% lower than that obtained in the present study. This difference may be linked to the fact that the average annual inflow data for liquid and solid discharge to the reservoir used were respectively higher and lower than those used in the present study.

## Hydrodynamic and sediment transport modeling

Definition, calibration and validation of the hydrodynamic model

The model was initially defined using the computational grid (Figure 8a), a three-dimensional sigma grid with five equally distributed

depth layers, with cells measuring between 136 m and 650 m in horizontal resolution. Figure 8b shows the bathymetry interpolated over the model grid. Figure 8c shows a longitudinal section of the computational grid and its vertical distribution. With the used 30s time step, the Courant criterion (Courant<10) (Deltares, 2025) was met.

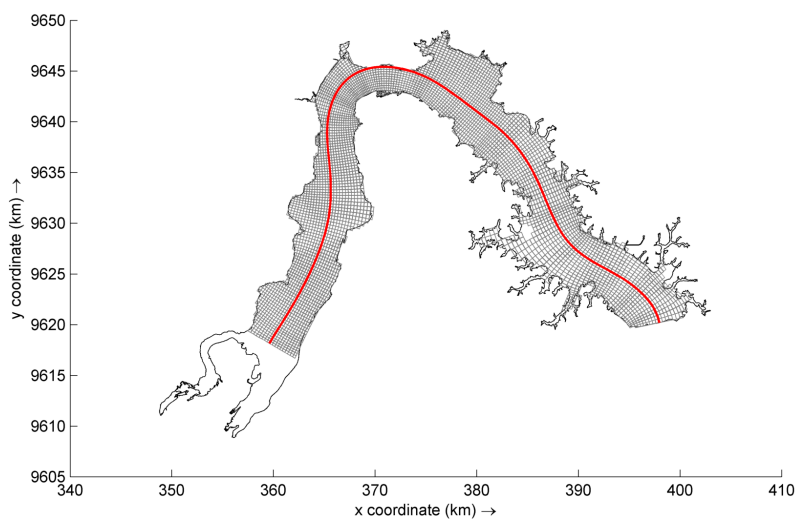
During calibration, the final Manning coefficient obtained varied spatially over the modeling domain, as shown in Figure 9, with values ranging from 0.01 to 0.04. The representation of the boundary conditions is shown in Figure 10, considering the inlet and outlets (spillway and diversion channel). The powerhouse, represented in the model as a negative discharge, is also shown in this figure.

To evaluate the quality and accuracy of the hydrodynamic model in the calibration process, comparisons were made with previous studies with results from 1D and 2D models applied for steady flow studies and calibrated to measured data.

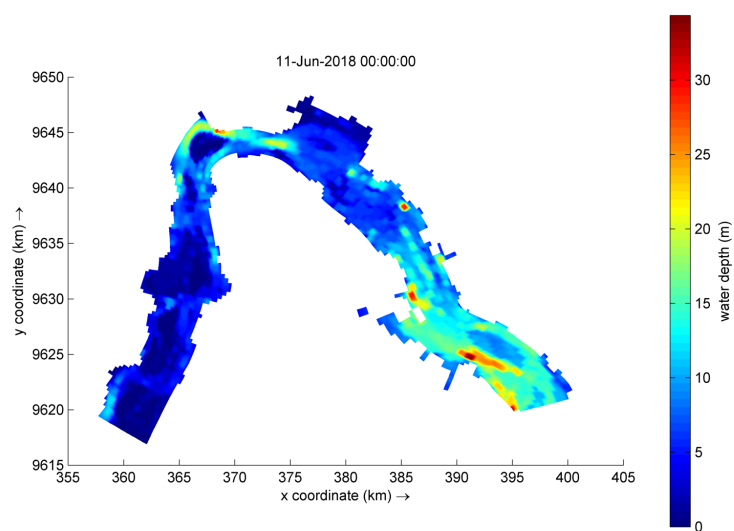
From the results obtained with the calibrated HEC-RAS 1D model (Intertechne, 2020a) for flows of 26,224 m<sup>3</sup>/s (flow in the diversion channel of 9,000 m<sup>3</sup>/s), corresponding to a 5-year return period (RT5), and 8,046 m<sup>3</sup>/s (flow in the diversion channel of 6,210 m<sup>3</sup>/s), corresponding to the long-term average flow a comparison was performed. The comparison for both flows is presented in Figure 11. Upstream of the urban area of Altamira (more than 40,000 m in the graph), the difference between the models is due to the fact that the previous study carried out in a 1D model and the modeling performed in the project is 3D, which is considered more suitable for the region that has many islands and a main flow not being parallel to the reservoir banks. In general, there is good agreement between the models, with Nash-Sutcliffe coefficient (NSE) resulting in 0.82 and 0.99, for long term averaged and RT5 discharges, respectively.

**Table 5.** Sediment model simulation results from 2018 to 2039 at Pimental HPP.

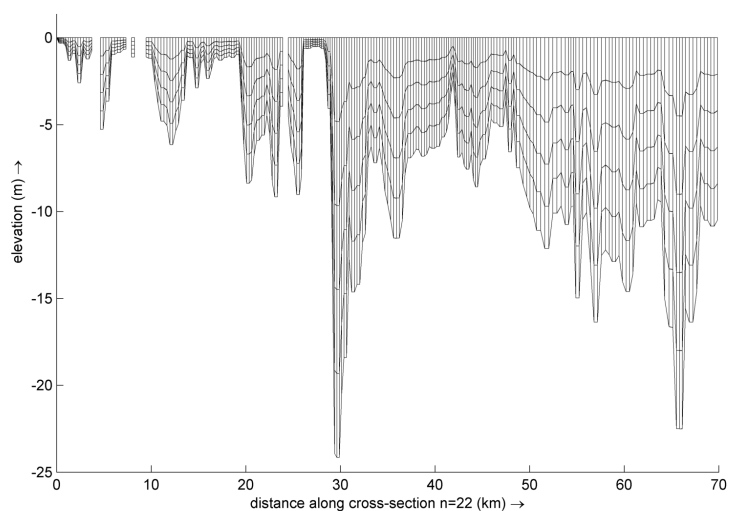
| Year | Solid volume deposited (hm <sup>3</sup> ) | Effluent solid volume (hm <sup>3</sup> ) | Retention Efficiency (%) | Apparent range (kg/m <sup>3</sup> ) | Solid Q Influent (t/year) x 10 <sup>3</sup> | Q solid Effluent (t/year) x 10 <sup>3</sup> | Deposited solid volume/Total reservoir volume |
|------|-------------------------------------------|------------------------------------------|--------------------------|-------------------------------------|---------------------------------------------|---------------------------------------------|-----------------------------------------------|
| 2018 | 2.03                                      | 5.65                                     | 41.76                    | 1142                                | 5542                                        | 3228                                        | 0.001                                         |
| 2019 | 4.02                                      | 8.44                                     | 41.73                    | 1164                                | 5653                                        | 3294                                        | 0.002                                         |
| 2020 | 6.02                                      | 11.25                                    | 41.71                    | 1177                                | 5766                                        | 3361                                        | 0.003                                         |
| 2021 | 8.03                                      | 14.11                                    | 41.69                    | 1186                                | 5881                                        | 3429                                        | 0.004                                         |
| 2022 | 10.08                                     | 17.01                                    | 41.66                    | 1194                                | 5999                                        | 3499                                        | 0.005                                         |
| 2023 | 12.14                                     | 19.96                                    | 41.64                    | 1200                                | 6119                                        | 3571                                        | 0.006                                         |
| 2024 | 14.24                                     | 22.95                                    | 41.62                    | 1206                                | 6241                                        | 3644                                        | 0.007                                         |
| 2025 | 16.38                                     | 25.99                                    | 41.59                    | 1210                                | 6366                                        | 3718                                        | 0.008                                         |
| 2026 | 18.54                                     | 29.09                                    | 41.57                    | 1215                                | 6493                                        | 3794                                        | 0.009                                         |
| 2027 | 20.74                                     | 32.24                                    | 41.54                    | 1218                                | 6623                                        | 3872                                        | 0.010                                         |
| 2028 | 22.98                                     | 35.45                                    | 41.52                    | 1222                                | 6755                                        | 3951                                        | 0.011                                         |
| 2029 | 25.25                                     | 38.71                                    | 41.49                    | 1225                                | 6891                                        | 4032                                        | 0.012                                         |
| 2030 | 27.57                                     | 42.04                                    | 41.47                    | 1228                                | 7028                                        | 4114                                        | 0.014                                         |
| 2031 | 29.92                                     | 45.43                                    | 41.44                    | 1231                                | 7169                                        | 4198                                        | 0.015                                         |
| 2032 | 32.32                                     | 48.88                                    | 41.41                    | 1233                                | 7312                                        | 4284                                        | 0.016                                         |
| 2033 | 34.75                                     | 52.39                                    | 41.38                    | 1236                                | 7459                                        | 4372                                        | 0.017                                         |
| 2034 | 37.23                                     | 55.98                                    | 41.35                    | 1238                                | 7608                                        | 4462                                        | 0.018                                         |
| 2035 | 39.75                                     | 59.63                                    | 41.32                    | 1240                                | 7760                                        | 4553                                        | 0.020                                         |
| 2036 | 42.32                                     | 63.35                                    | 41.30                    | 1242                                | 7915                                        | 4647                                        | 0.021                                         |
| 2037 | 44.93                                     | 67.14                                    | 41.26                    | 1244                                | 8073                                        | 4742                                        | 0.022                                         |
| 2038 | 47.60                                     | 71.00                                    | 41.23                    | 1246                                | 8235                                        | 4839                                        | 0.024                                         |
| 2039 | 50.30                                     | 74.95                                    | 41.20                    | 1247                                | 8400                                        | 4939                                        | 0.025                                         |



a)



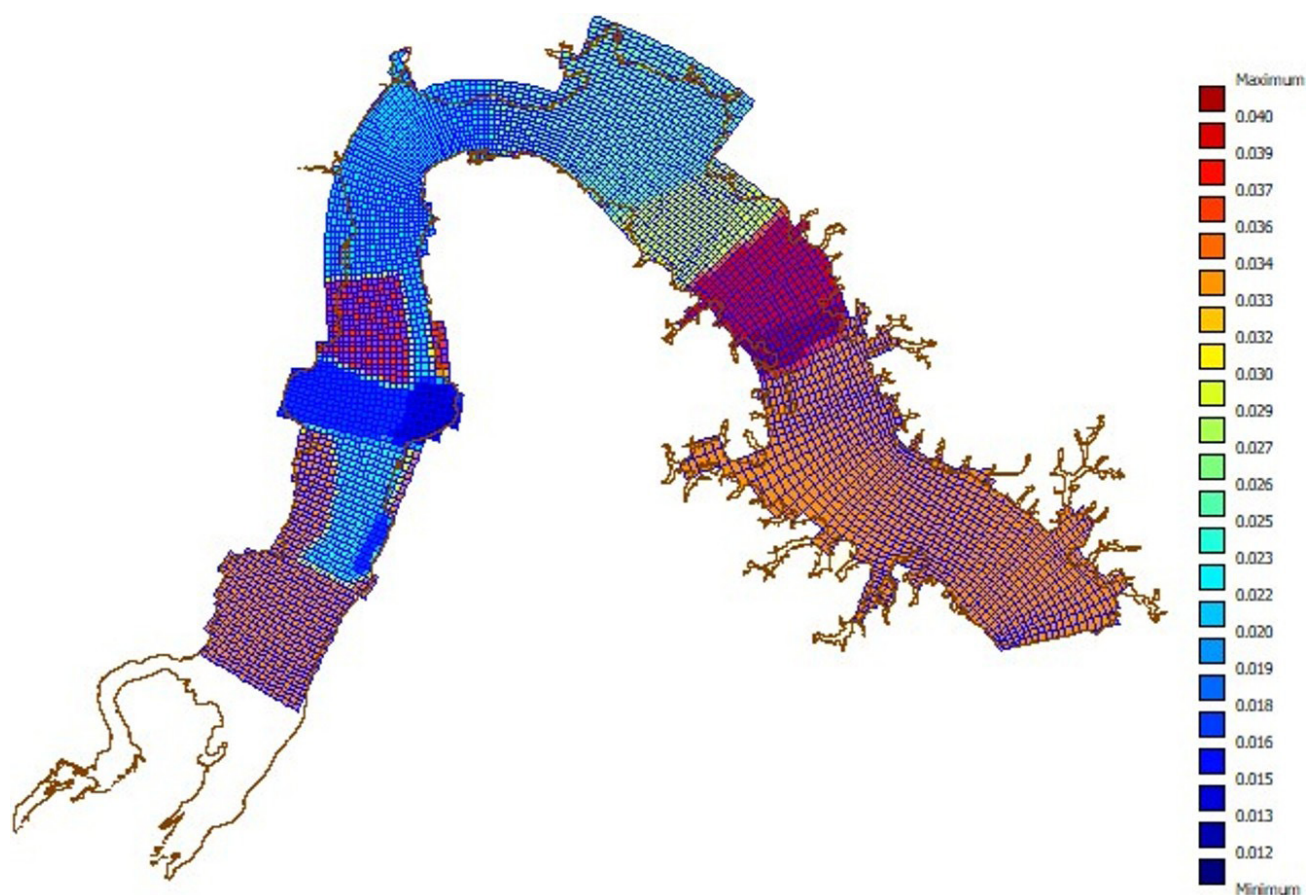
b)



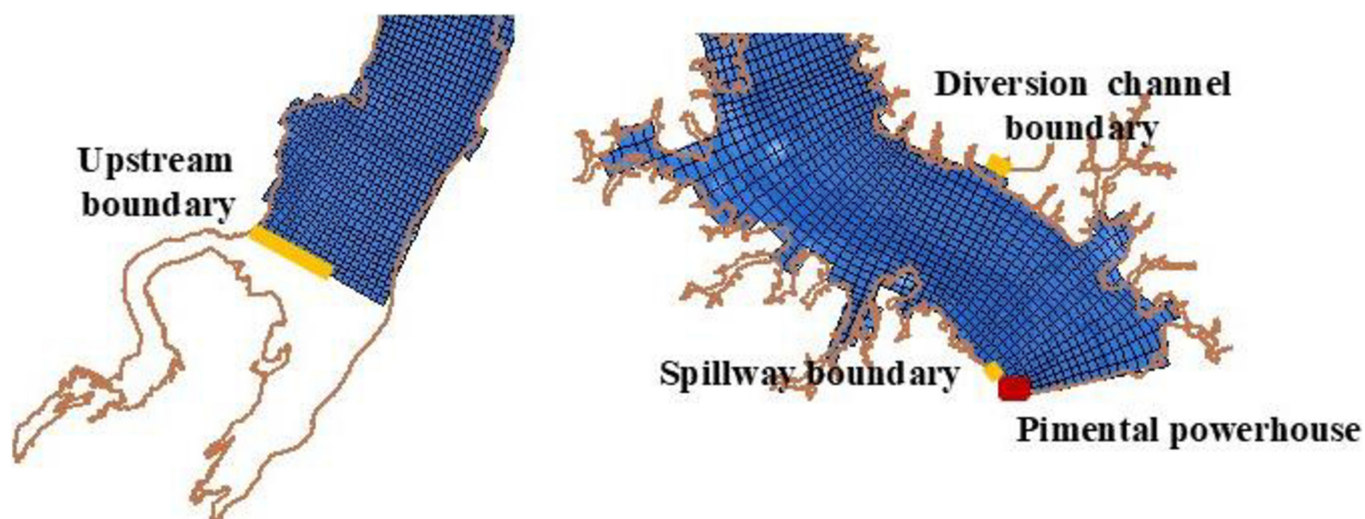
c)

**Figure 8.** (a) Computational mesh – general view; (b) Initial bathymetry provided by topo-bathymetric data – water depth below the water level interpolated for modeling (the water level considered is around 97.50 m); (c) Longitudinal section showing the vertical distribution of the layers in the red section in Figure (8a).





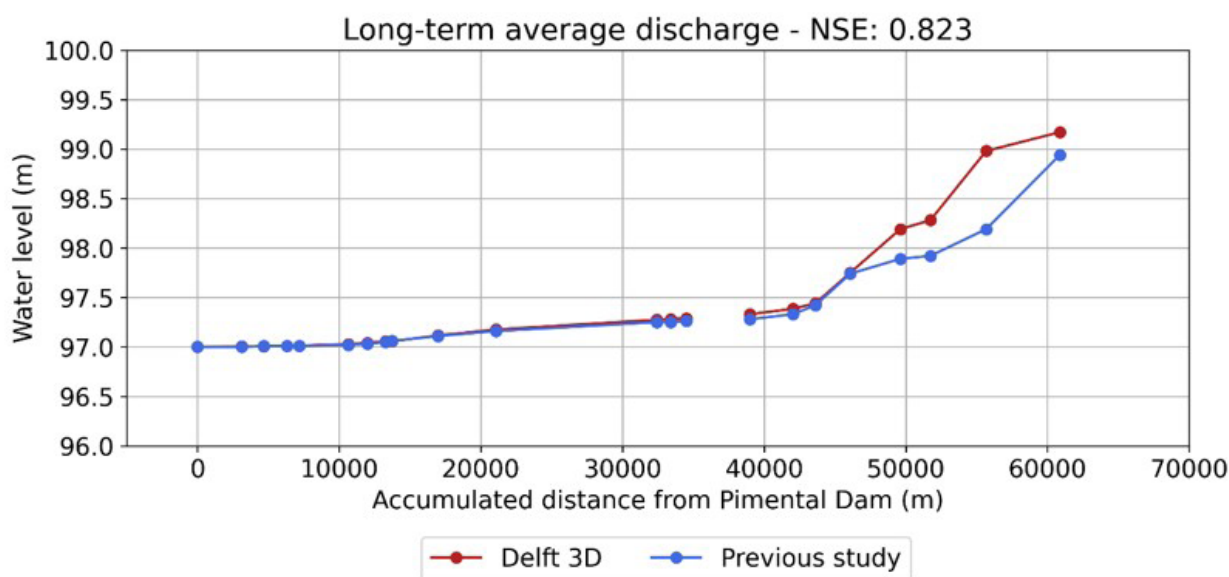
**Figure 9.** Manning coefficient in the Pimental reservoir modeling domain.



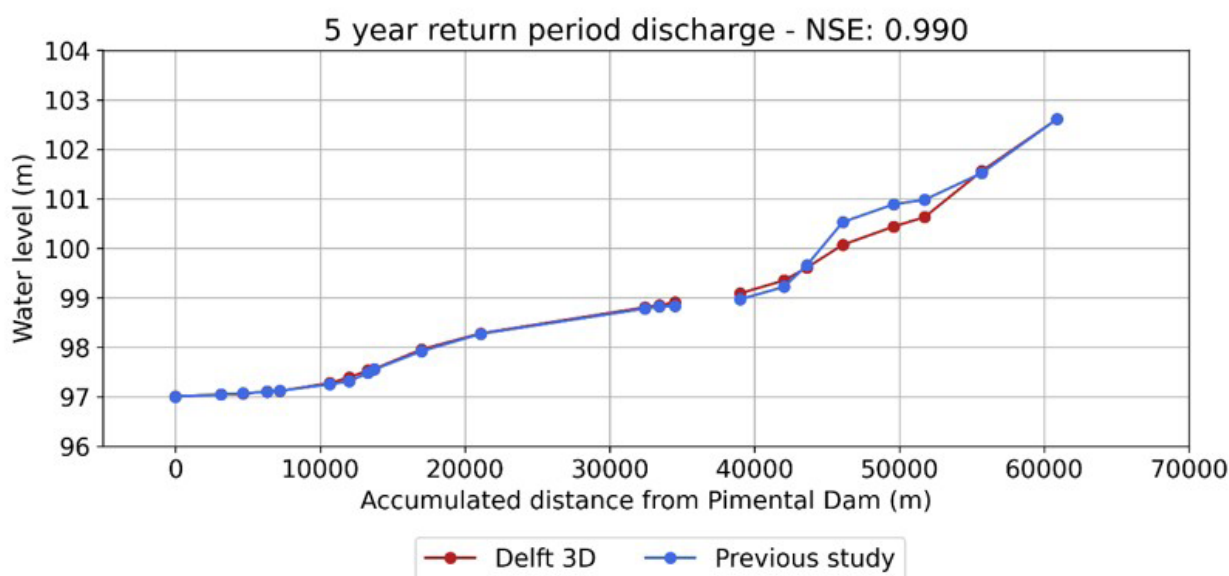
**Figure 10.** Upstream boundary condition (left), downstream boundary condition at the spillway and diversion channel (right) and powerhouse (discharge).

Using the results obtained with the calibrated RiverFlow2D model (Intertechne, 2020b), comparisons were initially made with measured data in Altamira, indicating differences on the order of centimeters between the measurements and the Delft3D model (Table 6). In this case, it was also possible to make comparisons between the flow rates of  $8,045 \text{ m}^3/\text{s}$  and  $26,224 \text{ m}^3/\text{s}$ . The velocity

maps for the respective flow rates are presented in Figure 12 and Figure SP 2 (result of the RiverFlow2D model presented in the supplementary material). The water level maps are presented in Figure 13 and Figure SP 3. In both cases, it was possible to observe that the Delft3D model reproduces orders of magnitude of velocity and water level similar to those obtained by the RiverFlow2D model.



(a)



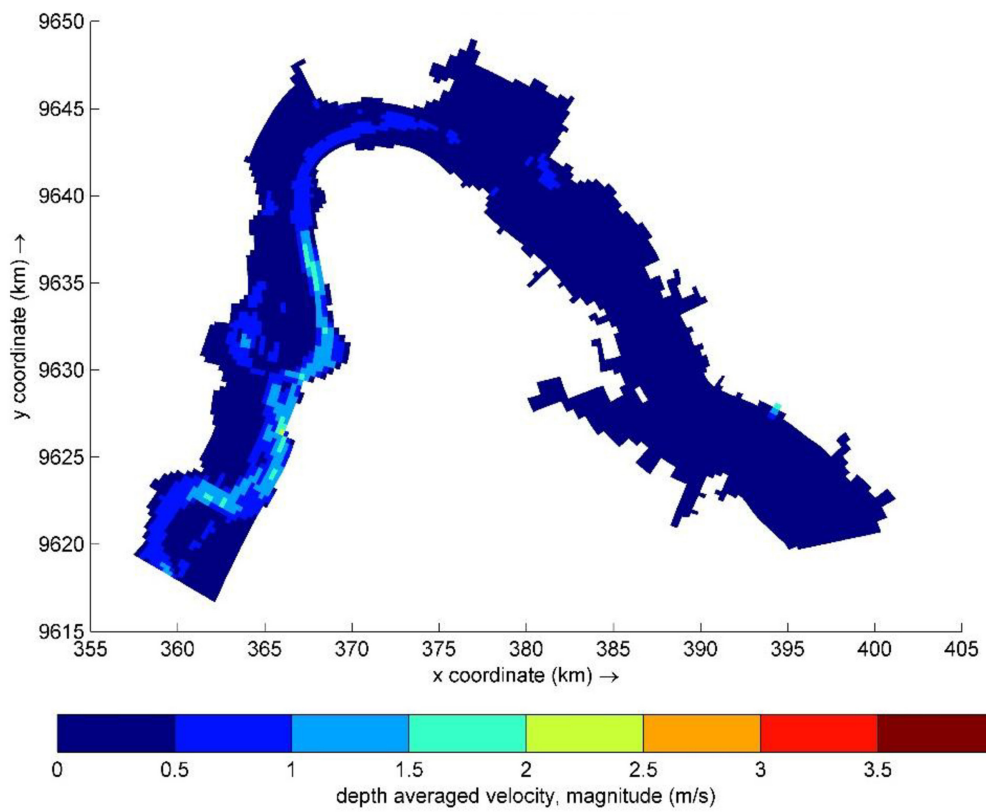
(b)

**Figure 11.** Water level comparison between HEC-RAS 1D and Delft3D model results for (a) MLT (8,046 m<sup>3</sup>/s) and (b) 5-year TR (26,224 m<sup>3</sup>/s) flow. The red line represents the calibrated model.

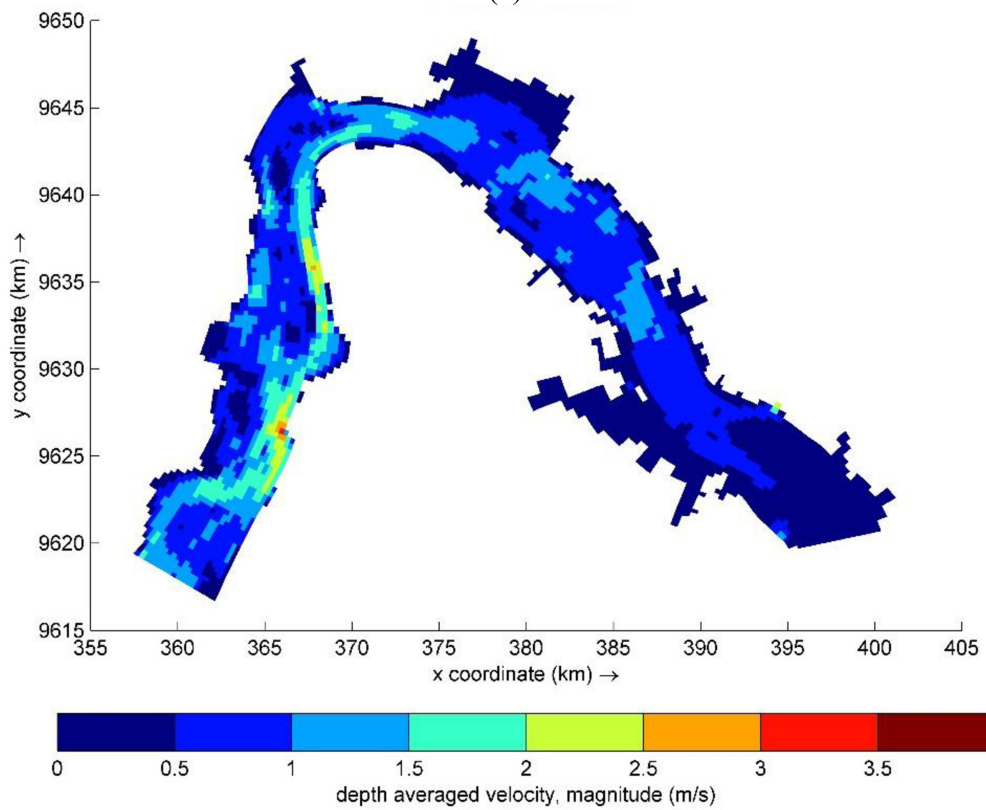
**Table 6.** Comparisons between modeling results (Delft3D) and data measured in Altamira.

| Flow rate Influent (m <sup>3</sup> /s) | Belo Monte flow rate (m <sup>3</sup> /s) | Elevation in Altamira (m) |            |            |
|----------------------------------------|------------------------------------------|---------------------------|------------|------------|
|                                        |                                          | Key curve <sup>1</sup>    | Simulation | Difference |
| 5,000                                  | 3,663                                    | 97.08                     | 97.13      | 0.05       |
| 10,000                                 | 7,521                                    | 97.37                     | 97.47      | 0.10       |
| 15,000                                 | 9,000                                    | 97.84                     | 97.94      | 0.10       |
| 20,000                                 | 9,000                                    | 98.52                     | 98.44      | -0.08      |

Note: 1 – Intertechne data (Intertechne (2020b)).

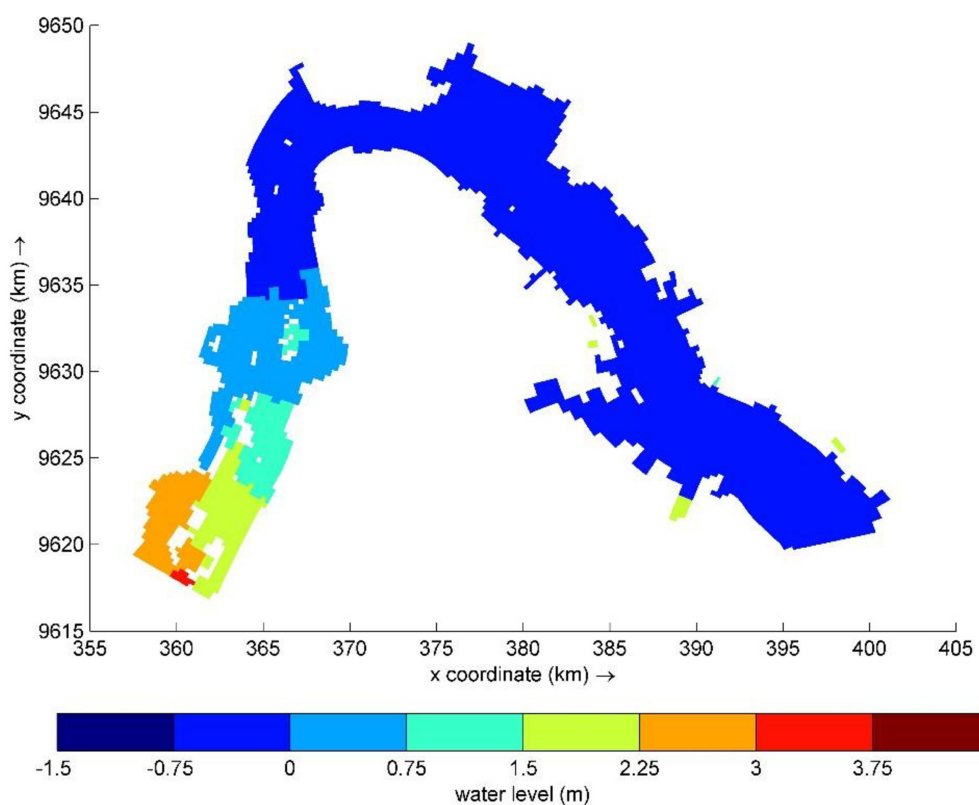


(a)

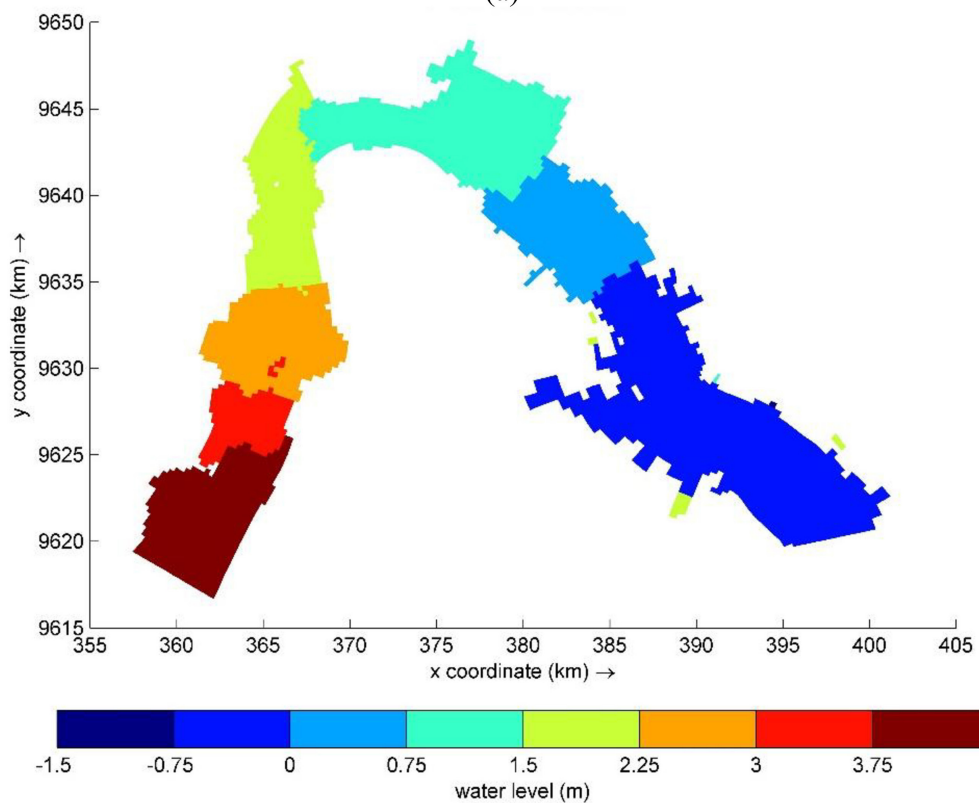


(b)

**Figure 12.** Average vertical velocity results in the Delft3D model. (a) Flow rate of 8,045 m<sup>3</sup>/s (MLT); (b) Flow rate of 26,224 m<sup>3</sup>/s (RT5).



(a)



(b)

**Figure 13.** Water level results in the Delft3D model (in relation to the 97.5 m elevation). (a) Flow rate of 8,045 m<sup>3</sup>/s (MLT); (b) Flow rate of 26,224 m<sup>3</sup>/s (RT5).



During the validation stage, the Delft3d model was simulated for the period from June 11, 2018, to May 9, 2024. The simulation results were compared with observed values to verify the modeling quality, namely: outflow, spillway, powerhouse, and transferred flow rates. Figure 14 shows the comparisons of the simulations with the measured outflow, turbine, overflow, and transferred flow rates, respectively, demonstrating an overlap between the observed and simulated series. Regarding the Nash-Sutcliffe coefficient (NSE), for the four flow rates evaluated, the coefficient ranged from 0.989 to 0.997, which corroborates the good performance of the simulation.

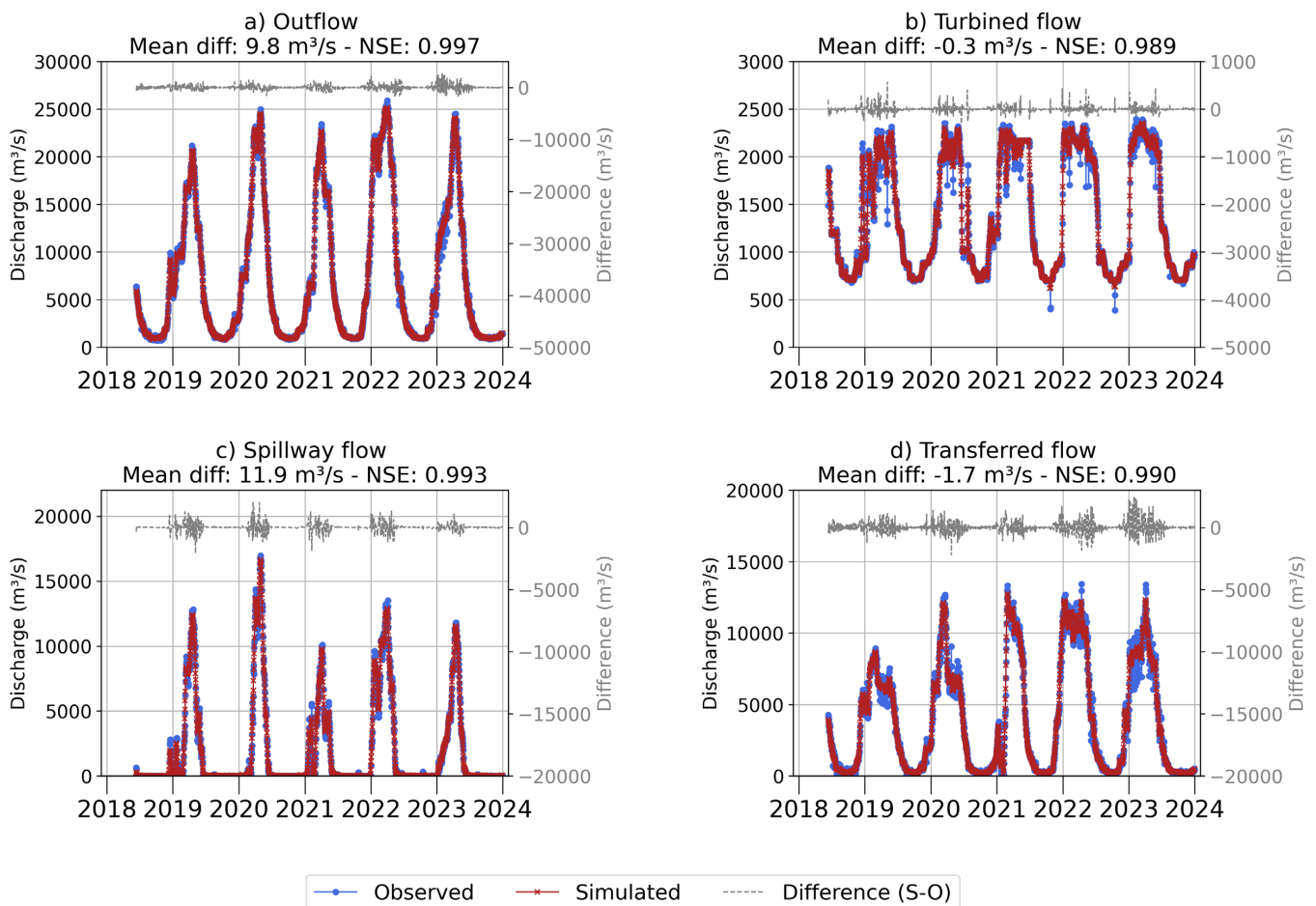
The simulations performed allowed us to observe some characteristics of the reservoir flow. Figure 15a presents the surface velocity magnitude map and velocity vectors at the surface and bottom of the Pimental Reservoir for May 9, 2024. This figure shows the highest velocities in the region from the reservoir inlet (zoomed in on Figure 15b) to the city of Altamira, which decrease after the bend in the Xingu River. In this region, no changes in velocity direction between the surface and the bottom are observed. Figure 15c presents the same results, but focusing on the diversion channel region, where there is a reduction in velocity along the Xingu River, but an increase in velocities within the channel itself.

Figure 16 shows the velocities in a longitudinal section of the reservoir for the date of 09/05/2024. From the figure, velocities greater than 1 m/s were observed in the upstream region, while approaching the dam there is a reduction in velocities.

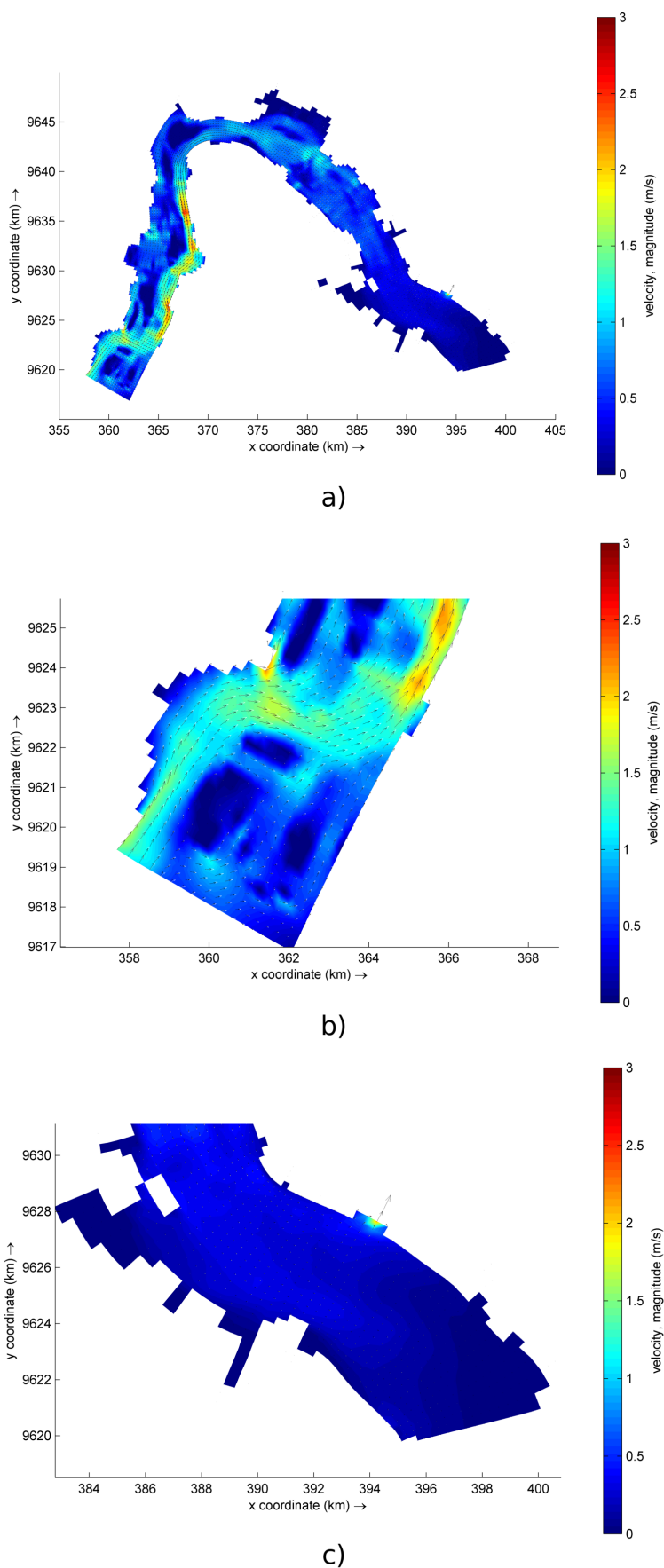
Figure 17 shows the velocities in three cross-sections: upstream, near Altamira, and the section contemplating the diversion channel, respectively, for the date of May 9, 2024. The upstream section (Figure 17a) presented velocities of up to 1.5 m/s in the river channel. In the Altamira section (Figure 17b), there is a reduction in velocities, as well as in the diversion channel section (Figure 17c), with the exception of the channel entrance, which presented velocities of up to 3 m/s.

### Sediment transport model

To verify the quality of the modeling results, comparisons were made between the simulated and estimated suspended sediment concentrations in the literature (Luz et al., 2025b) as shown in Figure 18. In this figure, it can be seen that there are no satellite images available during the flood period, but there are data on the rise and fall of the hydrograph, which were reproduced by the numerical model, with concentrations between 6 and 12 mg/L.



**Figure 14.** Comparison between the flow rate (a) effluent; (b) turbine; (c) spilled and (d) transferred measured and simulated by the Delft3D model.



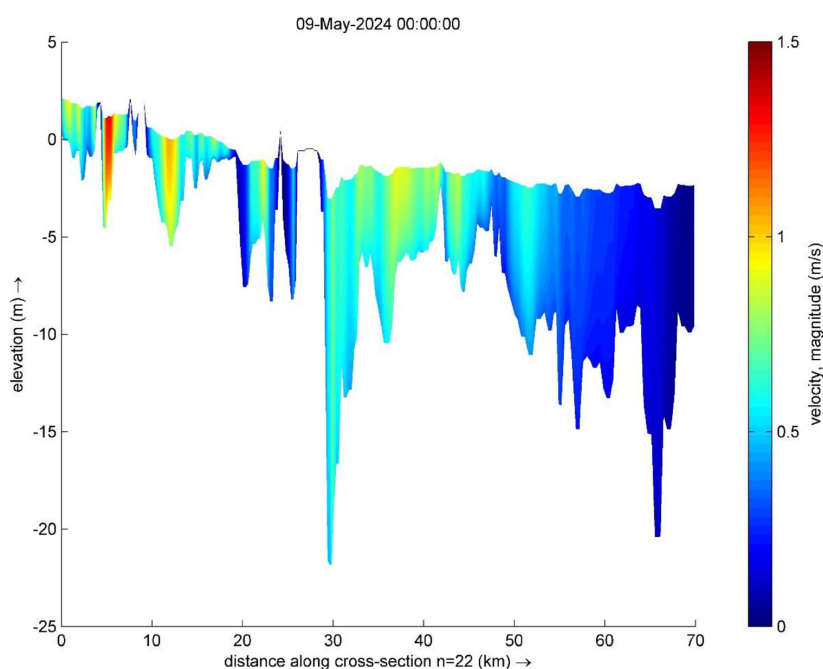
**Figure 15.** Map of average velocity magnitude and velocity vectors: white vector: surface velocity; black vector: bottom velocity for the date of 09/05/2024. (a) Entire simulated domain; (b) Focus on the reservoir inlet; (c) Focus on the diversion channel region.

To estimate the silted volume through modeling, the results of the total cumulative transport were exported for the model's boundary conditions, which are represented in Figure SP 4. The largest sediment accumulations occur due to the flood periods.

Table 7 presents the sediment volume results from the mass balance for methods 1 and 2. For method 1, a siltation of  $7.17 \text{ hm}^3$  was estimated by the mass balance in the period 2018 to 2024, which corresponds to a sedimentation rate of  $1.21 \text{ hm}^3/\text{year}$ . For the volume estimated using method 2, a total volume of

$7.95 \text{ hm}^3$  was obtained, which corresponds to a siltation rate of  $1.34 \text{ hm}^3/\text{year}$ .

The results of the three-dimensional model in relation to sedimentation rates were compared with other methods, namely: comparison of two CAV curves, sedimentometric methods (with and without remote sensing) and comparison of cross sections (Luz et al., 2025a). In the aforementioned study, sedimentation was observed in the reservoir, which was also reproduced by hydrodynamic modeling according to the sedimentation rates of methods B, C and D present in Table 8.



**Figure 16.** Longitudinal section (shown in Figure 8) with the average velocity magnitude of the Pimental reservoir for the date of 09/05/2024. Zero on the x-axis corresponds to the reservoir inlet.

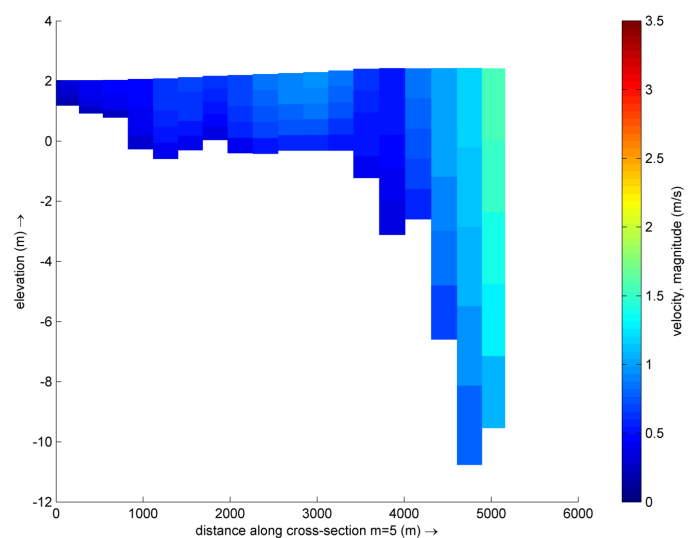
**Table 7.** Sediment mass balance results by method 1 and method 2 from modeling results for the period 2018 to 2024.

| Mass balance                                     | Method 1                        | Method 2                            |
|--------------------------------------------------|---------------------------------|-------------------------------------|
| Upstream                                         | $15.30 \text{ hm}^3$            | $3.17 \cdot 10^{10} \text{ kg/day}$ |
| Diversion channel                                | $3.87 \text{ hm}^3$             | $1.01 \cdot 10^{10} \text{ kg/day}$ |
| Spillway                                         | $1.96 \text{ hm}^3$             | $5.28 \cdot 10^9 \text{ kg/day}$    |
| Powerhouse                                       | $2.27 \text{ hm}^3$             | $3.63 \cdot 10^9 \text{ kg/day}$    |
| Mass balance <sup>1</sup>                        | $7.17 \text{ hm}^3$             | $1.27 \cdot 10^9 \text{ kg/day}$    |
| Total volume (2018-2024)                         | $7.17 \text{ hm}^3$             | $7.93 \text{ hm}^3$                 |
| Sedimentation rate ( $\text{hm}^3/\text{year}$ ) | $1.21 \text{ hm}^3/\text{year}$ | $1.34 \text{ hm}^3/\text{year}$     |

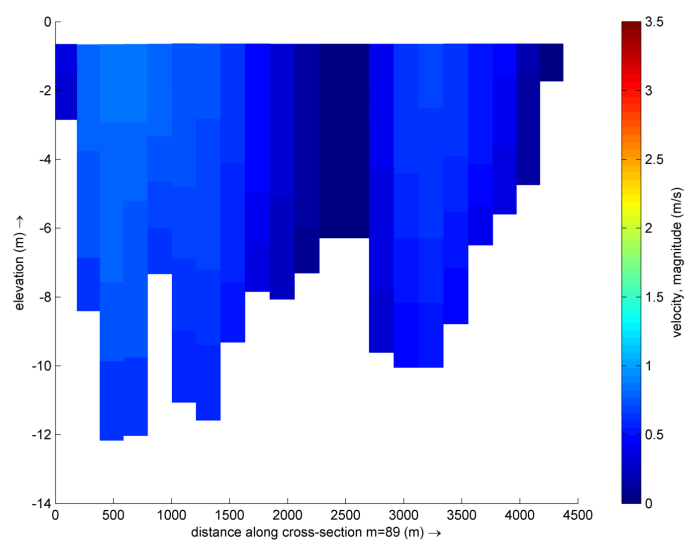
**Note:** 1: Balance = Input – Output = Upstream – (Diversion channel + Spillway + Powerhouse).

**Table 8.** Sedimentation rate calculated with the hydrodynamic and sediment transport model and calculated by Luz et al. (2025a).

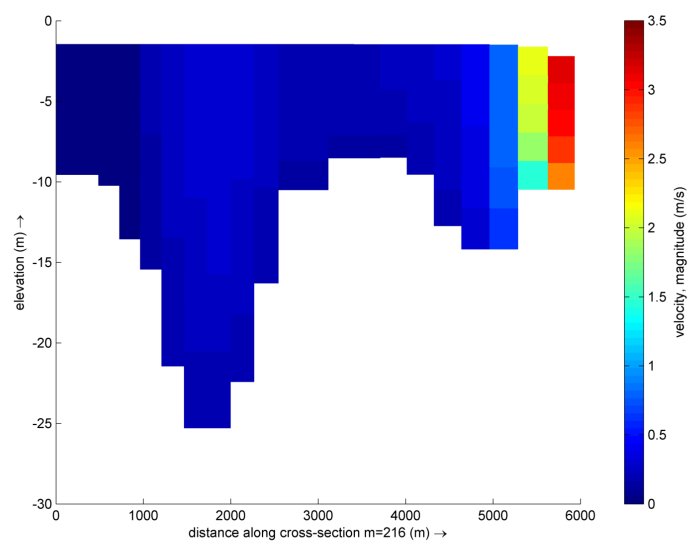
| Method | Method                            | Sedimentation rate ( $\text{hm}^3/\text{year}$ ) | Source             |
|--------|-----------------------------------|--------------------------------------------------|--------------------|
| -      | Modelling Mass balance (method 1) | 1.21                                             | This paper         |
| -      | Modelling Mass balance (method 2) | 1.34                                             |                    |
| A      | DAV                               | 83.24                                            | Luz et al. (2025a) |
| B      | Sedimentometric                   | 1.00                                             |                    |
| C      | Sedimentométrico + SR             | 0.45                                             |                    |
| D      | Sediment / Dposit                 | 2.12                                             |                    |
| E      | Cross Sections                    | 16.43                                            |                    |



a)



b)



c)

**Figure 17.** Velocity magnitude in the cross sections of the Pimental reservoir for the date of 09/05/2024. (a) Upstream section; (b) Altamira section; (c) Diversion channel.



Costa et al. (2018) developed a one-dimensional sediment transport model in the Taiaçupeba Reservoir Basin (SP), using HEC-RAS software, to estimate the sediment load being delivered to the reservoir. The authors highlighted that sediment monitoring was carried out during periods of drought, which restricted the range of sampled flows. Thus, the model reproduced a total modeled load of 0.4 hm<sup>3</sup>, while the observed load was 5 hm<sup>3</sup>. Costa et al. (2018) also discussed the need for sampling based on hydrological events to represent different flow conditions and validate discharge curves, similar to that discussed in this study, given the small number of sediment collections at peak flows.

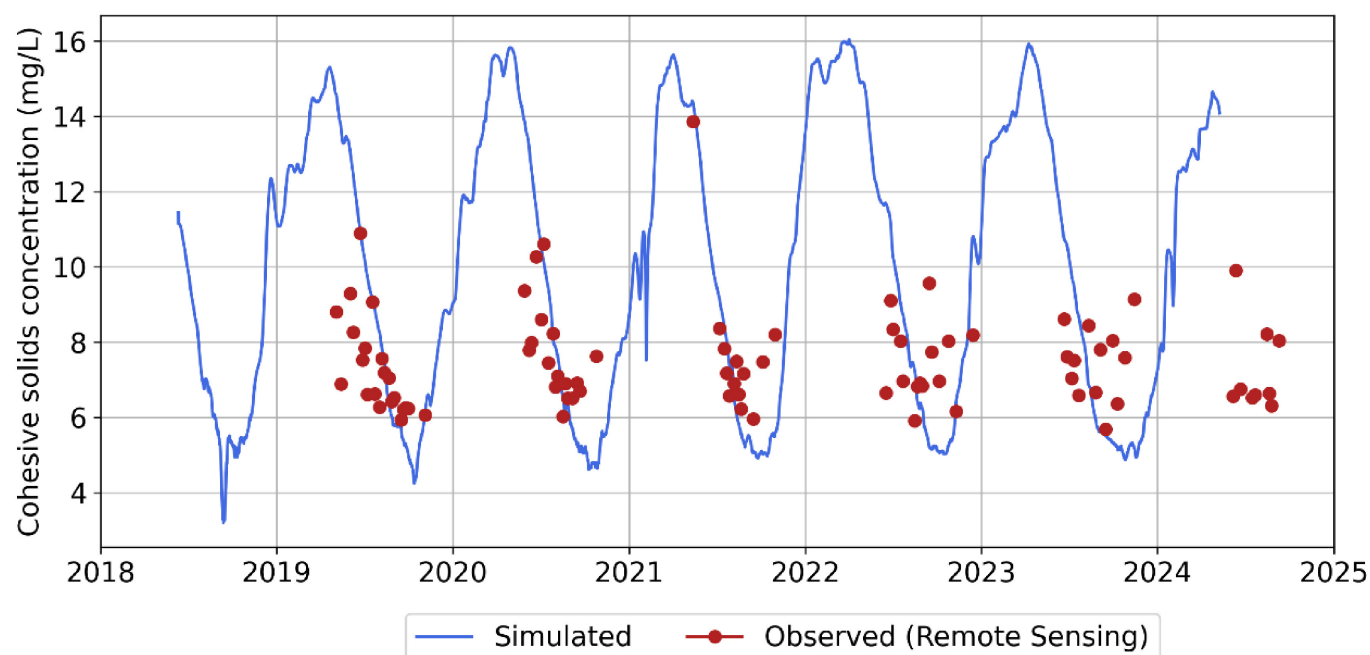
Lopes & Araújo (2019) proposed a simplified approach to assess reservoir siltation in Brazil's semiarid regions, using remote sensing and reduced field bathymetry, which was compared with the traditional bathymetric survey method. Overall, the simplified approach resulted in twice the siltation estimated with the traditional survey. According to the aforementioned article, these results were sufficient to assess the potential impacts on water availability over time. Similarly, this paper aimed to evaluate a simplified alternative for estimating sedimentation that can also be applied more frequently than traditional field measurements and even more complex models.

After simulating the periods with observed data (June 11, 2018, to May 9, 2024), a simulation was performed considering the future period (June 11, 2018, to September 30, 2039). Table 9 presents the results of methods 1 (Figure SP 5) and 2. For method 1, the silted volume was estimated at 27.88 hm<sup>3</sup>, which corresponds to a sedimentation rate of 1.31 hm<sup>3</sup>/year. For method 2, the total silted volume was estimated at 31.47 hm<sup>3</sup>, which corresponds to a siltation rate of 1.48 hm<sup>3</sup>/year.

Reisenbüchler et al. (2020) evaluated the sediment management strategy using 2D numerical modeling using the TELEMAC model for different reservoir discharge and operating conditions (with and without flushing operations), demonstrating that modeling is an important tool for managing water resources and sediments in reservoirs. In this study, a scenario without the influence of climate change or changes in land use and occupation was considered, therefore, a conservative scenario.

### Comparison of sedimentation methods until 2039

The sedimented volume in the Pimental reservoir estimated by the different methods is presented in Table 10 and indicates



**Figure 18.** Comparison between simulated and satellite imagery cohesive sediment concentration for the diversion channel.

**Table 9.** Sediment mass balance results by method 1 and method 2 from modeling results for the period 2018 to 2039.

| Mass balance                               | Method 1                   | Method 2                      |
|--------------------------------------------|----------------------------|-------------------------------|
| Upstream                                   | 57.60 hm <sup>3</sup>      | 11.78 10 <sup>10</sup> kg/day |
| Diversion channel                          | 1.48 hm <sup>3</sup>       | 3.57 10 <sup>10</sup> kg/day  |
| Spillway                                   | 7.00 hm <sup>3</sup>       | 1.89 10 <sup>10</sup> kg/day  |
| Powerhouse                                 | 8.00 hm <sup>3</sup>       | 1.28 10 <sup>10</sup> kg/day  |
| Mass balance <sup>1</sup>                  | 2.79 hm <sup>3</sup>       | 5.04 10 <sup>10</sup> kg/day  |
| Total volume (2018-2039)                   | 27.88 hm <sup>3</sup>      | 31.47 hm <sup>3</sup>         |
| Sedimentation rate (hm <sup>3</sup> /year) | 1.31 hm <sup>3</sup> /year | 1.48 hm <sup>3</sup> /year    |

Note: <sup>1</sup>: Balance = Input – Output = Upstream – (Diversion channel + Spillway + Powerhouse).

reservoir sedimentation. Therefore, it can be observed that the values between the methods are similar, with the exception of the Sediment method, which overestimated sedimentation due to its limitation of not representing the outflow of the diversion channel, as shown in *Simplified model Sediment*.

Luz et al. (2025a) also highlighted as a limitation of the Sedimentometric method the absence of a monitoring station with measurements of suspended solids concentrations in the diversion channel. However, the use of remote sensing to overcome this limitation by Luz et al. (2025b) was satisfactory when compared with the cohesive solids concentration values calculated by the Delft3d modelling (Figure 18).

Sediment method's results, however, presented higher values than the other methods. This was due the limitation in representing outflows as the reservoir's only outlet. However, the Pimental HPP's arrangement presents a different configuration due to the presence of the diversion channel. When evaluating the proportion between the inflow to the reservoir and the flow that is transferred to the Belo Monte HPP, which is on average 50%, if this proportion were also reflected in the transport of sediment through the diversion channel, the total siltation would be around 25 hm<sup>3</sup> (with a rate of 1.15 hm<sup>3</sup>/year).

Between the evaluated methods, hydrodynamic and sediment transport modeling considers physical processes most comprehensively and provides the best representation. However, this benefit is often associated with increased processing, a larger amount of input data, and, like all modeling, the need for calibration and validation steps. All of these issues ultimately require more time to obtain results and greater user expertise.

Despite this, estimating the siltation of the Pimental HPP reservoir using hydrodynamic and sediment transport modeling resulted in similar sedimentation volumes and rates to other methods. Therefore, employing less robust methods would allow for expanded access to estimating and monitoring siltation in reservoirs, in addition to benefiting water resources management.

Other studies have also evaluated reservoir sedimentation rates. Rabelo et al. (2025) evaluated sedimentation rates using hydrosedimentological modeling in eight reservoirs in the Brazilian semiarid region and found rates ranging from 0.12% to 8.12% per decade. Endalew & Mulu (2022) estimated sedimentation in the Shumburit

reservoir in Ethiopia during its operational period (2016–2021) using more traditional methods for assessing sedimentation: topographic survey (pre-damming) and bathymetric survey. A 7.52% reduction in reservoir storage capacity was observed in six years. Hilgert et al. (2024) evaluated different methods for detecting and quantifying sedimentation in reservoirs. In the Passaúna reservoir (PR), for example, a free-fall penetrometer was used, which, after processing, showed a volume loss of 4.7% in 30 years. Rodriguez et al. (2023) conducted a literature review on mapping sedimentation rates in lakes and reservoirs. Overall, of the articles that quantified storage loss due to siltation, the average capacity loss was 0.53% per year, ranging from 0.05% to 3.93% per year. Yao et al. (2023) estimated a storage capacity loss of 0.18% per year in eight evaluated reservoirs. Khasanov (2025) evaluated sedimentation in the Akhangaran Reservoir (Uzbekistan), operating since 1972, using a comparison of three surveys (1972, 2002, and 2022). A total storage loss of 14.44% was verified in the period evaluated and 11.52% in useful volume, and this loss affected the volume available for operational use. In the present study, a result between 0.35% and 0.81% was obtained in five years across the evaluated methods.

When it is analyzed the temporal evolution of siltation rates, by dividing the total simulated period between two similar 10-year periods (2018–2028 and 2029–2039) (Table 11), an increase in sedimentation rates was observed in all methods evaluated, varying between 4.7% and 15.7%.

These results can be considered conservative because this study did not consider changes in land use and occupation, the effects of climate change, or other factors that may alter the distribution of flows and sediment inputs to the basin. Other authors have evaluated reservoir siltation projections. Khasanov (2025) evaluated future siltation projections for the Akhangaran Reservoir over a 50-year horizon using a simplified approach. This approach considered a simplified equation relating turbidity and minimum data (design and filling curves), in addition to available historical data to establish sedimentation trends. The projection indicates a 39.45% and 36.45% reduction in total and useful volumes, respectively. By 2062, total siltation of the dead volume is projected. In this study, for 2039, with the simulated scenario, the reduction in total volume would be between 1.38% and 2.49% in the evaluated methods.

**Table 10.** Comparison of the results of the silted volume between the sedimentometric, Sediment and modeling methods (method 1 and 2).

| Method               | Total volume<br>(hm <sup>3</sup> ) | Relation to the total volume <sup>1</sup><br>(%) | Relation to the useful volume <sup>2</sup><br>(%) | Sedimentation rate<br>(hm <sup>3</sup> /year) |
|----------------------|------------------------------------|--------------------------------------------------|---------------------------------------------------|-----------------------------------------------|
| Sedimentometric      | 29.25                              | 1.45                                             | 6.39                                              | 1.37                                          |
| Sediment             | 50.30                              | 2.49                                             | 10.99                                             | 2.29                                          |
| Modelling (Method 1) | 27.88                              | 1.38                                             | 6.09                                              | 1.31                                          |
| Modelling (Method 2) | 31.47                              | 1.56                                             | 7.88                                              | 1.48                                          |

**Note:** 1 – Total reservoir volume (Pimental HPP) according to the 2018 CAV curve (2022.1 hm<sup>3</sup>); 2 – Useful reservoir volume (Pimental HPP) according to the 2018 CAV (Ruraltech, 2019) curve (457.7 hm<sup>3</sup>).

**Table 11.** Comparison between sedimentation rates in 10-year periods between 2018 and 2039.

| Period                       | Sedimentation rate (hm <sup>3</sup> /year) |          |                     |                     |
|------------------------------|--------------------------------------------|----------|---------------------|---------------------|
|                              | Sedimentometric                            | Sediment | Modeling (method 1) | Modeling (method 2) |
| 2018–2028                    | 1.27                                       | 2.30     | 1.21                | 1.40                |
| 2029–2039                    | 1.33                                       | 2.50     | 1.40                | 1.56                |
| Increase between periods (%) | 4.72                                       | 8.70     | 15.70               | 11.43               |

## CONCLUSIONS

This study evaluated three tools for estimating the silted volume in the Pimental HPP reservoir using mass balance: a sedimentometric method, a simplified model, and three-dimensional modeling. Results showed sedimentation and an increase in the sedimentation rate over the two decades evaluated. Despite the advantages and limitations observed between the methods, the results obtained were similar, indicating that less complex methods are sufficient to represent the siltation of the Pimental HPP reservoir. This may contribute to greater control of siltation in reservoirs and more accessible water resources management, since reliable estimates can be obtained using simpler methods that require fewer data, resources, and computational effort.

Anyhow, if the spatial sediment distribution over the reservoir is of interest, only the hydrodynamic modeling methods are providing those results in detail.

Based on the analyses, it was identified that a monitoring station should be installed at the inlet of the diversion channel to measure sediment concentrations. This would provide a more representative mass balance closure, considering the use of remote sensing techniques to overcome this limitation of the present study.

It is also recommended that sedimentometric measurements at existing (and future) stations continue with a monthly monitoring frequency. Furthermore, it is recommended that sediment concentration measurements be taken at flood peaks, and that the solid discharge curve be updated.

## DATA AVAILABILITY STATEMENT

Research data is only available upon request

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## SUPPLEMENTARY MATERIAL

Supplementary material accompanies this paper.

**Table SP 1.** Operation start date and CAV curve update date. Note: 1 – Information not found.

**Table SP 2.** Temporal distribution of the start of operations of hydroelectric projects

**Table SP 3.** Number of CAV curve updates classified every 10 years.

**Figure SP 1.** Temporal arrangement of suspended solids concentration measurements in relation to liquid flow rate

**Figure SP 2.** Velocity (Velocidade in Portuguese) results with the RiverFlow2D model (Intertechne, 2020b). a) Flow rate of 8,045 m<sup>3</sup>/s. b) Flow rate of 26,224 m<sup>3</sup>/s. Source: Intertechne (2020b)

**Figure SP 3.** Water level (Nível de água in Portuguese) results with the RiverFlow2D model (Intertechne, 2020b). a) Flow rate of 8,045 m<sup>3</sup>/s. b) Flow rate of 26,224 m<sup>3</sup>/s. Source: Intertechne (2020b)

**Figure SP 4.** Total cumulative transport for the upstream section of the Pimental reservoir for the period between 06/11/2018 and 05/09/2024. In blue: Upstream; Green: Diversion Channel; Purple: Spillway.

**Figure SP 5.** Total cumulative transport for the upstream section of the Pimental reservoir for the period between 06/11/2018 and 30/09/2039. In blue: Upstream; Green: Diversion Channel; Purple: Spillway.

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