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The impacts of the water intake operation on the hydraulic transients, sediment resuspension and water quality of the largest multi-use reservoir in Latin America

Os impactos da operação da tomada d'água nos transientes hidráulicos, na ressuspensão de sedimentos e na qualidade da água do maior reservatório de uso múltiplo da América Latina

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ABSTRACT

This study investigates numerically the effects of the water intake operation of Castanhão reservoir, Ceará, Brazil. First, transient hydraulic modelling was carried out using ALLIEVI. The results indicated that, even for the fastest closing conditions of the water intake valve, the impact of hydraulic transients was negligible. Next, computational fluid dynamics (CFD) simulations were performed using FLUENT to investigate the induced flow patterns approaching the water intake. With the turbulence values obtained, an empirical model as a function of the turbulent kinetic energy was applied to assess the thresholds for sediment resuspension. The results showed that the converging flow towards the water intake generated enough turbulence at the bottom of the reservoir to resuspend the sediment. However, the longitudinal extent of resuspension was limited to the areas relatively close to the intake. Finally, CFD simulations were carried out under well-mixed and thermally/chemically stratified conditions and for different withdrawal rates. For low rates, most of the flow was withdrawn from the upper water layers. Contrastingly, for high flow rates, a significant flow was also withdrawn from the lower water layers. As a result, the values of water quality parameters at the outlet increased up to about 30% for stratified water conditions.

Keywords: Water intake operation; Hydraulic transients; Sediment resuspension; Water quality; Tropical semiarid regions; Large reservoirs.

RESUMO

Esse estudo investiga numericamente os efeitos da operação da tomada d'água do reservatório Castanhão, Ceará, Brasil. Primeiramente, foi realizada a modelagem hidráulica transiente utilizando o ALLIEVI. Os resultados indicaram que, mesmo para as condições de fechamento mais rápido da válvula da tomada d'água, o impacto dos transientes hidráulicos foi desprezível. Em seguida, foram realizadas simulações de dinâmica de fluidos computacional (CFD) utilizando o FLUENT para investigar os padrões de fluxo induzidos próximos à captação de água. Com os valores de turbulência obtidos, um modelo empírico em função da energia cinética turbulenta foi aplicado para avaliar os limiares para ressuspensão de sedimentos. Os resultados mostraram que o fluxo convergente em direção à tomada d'água gerou turbulência suficiente no fundo do reservatório para ressuspender o sedimento. Entretanto, a extensão longitudinal da ressuspensão foi limitada às áreas relativamente próximas à tomada d'água. Finalmente, simulações de CFD foram realizadas sob condições bem misturadas e estratificadas termicamente/quimicamente, considerando diferentes vazões de retirada. Para baixas vazões, a maior parte do fluxo foi retirada das camadas de água superiores. Por outro lado, para altas vazões, um fluxo significativo também foi retirado das camadas de água inferiores. Como resultado desses diferentes padrões de escoamentos induzidos, os valores dos parâmetros de qualidade da água na saída aumentaram até cerca de 30% para condições de água estratificada.

Palavras-chave: Operação da tomada d'água; Transientes hidráulicos; Ressuspensão de sedimentos; Qualidade da água; Regiões tropicais semiáridas; Grandes reservatórios.



INTRODUCTION

Water intake operations can significantly impact water quantity and quality in reservoirs. The abrupt opening or closing of control valves installed at the water intake pipelines can cause hydraulic transients that negatively affect the hydraulic structures and the upstream lake/downstream river by promoting significant changes in the pressure and flow regimes (Chaudhry, 2014; Ding et al., 2019). Moreover, sediment resuspension induced by the different flow patterns approaching the water intakes and changes in water level, mixing conditions and withdrawal rates are also processes that can significantly impact water quality in the upstream lake/downstream river (Politano et al., 2019; Duka et al., 2021; Sirunda et al., 2021; Carvalho et al., 2022).

The Brazilian Northeast is one of the most populous semiarid regions of the globe, where thousands of reservoirs have been built to minimize the impacts of droughts and water scarcity (Rabelo et al., 2021). This study presents a case study of the Castanhão reservoir, located in the above-mentioned region, which is considered the largest multi-use reservoir in Latin America, excluding the hydropower dams (Raulino et al., 2021). Differently from most reservoirs located in other climatic regions, Castanhão reservoir has been subject to extreme operational conditions spanning from droughts to floods, resulting in reservoir volumes ranging from 2 to 100% of the total storage capacity. Due to

significant external and internal loads to Castanhão reservoir, including the contributions from diffuse and point-sources from soil, agriculture, sewer, livestock, fish-farming, and bed sediments, the water quality of this reservoir has faced a progressive degradation from oligotrophic to hypereutrophic since its construction in 2003, resulting in several economic and environmental issues such as extremely high water treatment costs and massive fish kills (Wiegand et al., 2021; Rocha et al., 2024).

The present study aims to investigate the effects of the operation of the water intake of Castanhão reservoir on the hydraulic transients, sediment resuspension, and water quality, by using numerical simulations and primary/secondary data. To the authors knowledge, this is the first numerical study that combines the above-mentioned aspects of the flow in a large reservoir located in a tropical semiarid region, subject to extreme operational conditions.

METHODOLOGY

Study area

The Castanhão reservoir is located in the state of Ceará, in the Brazilian semiarid region, as shown schematically in Figure 1. The location of the dam (water intake), fish-cages and water quality

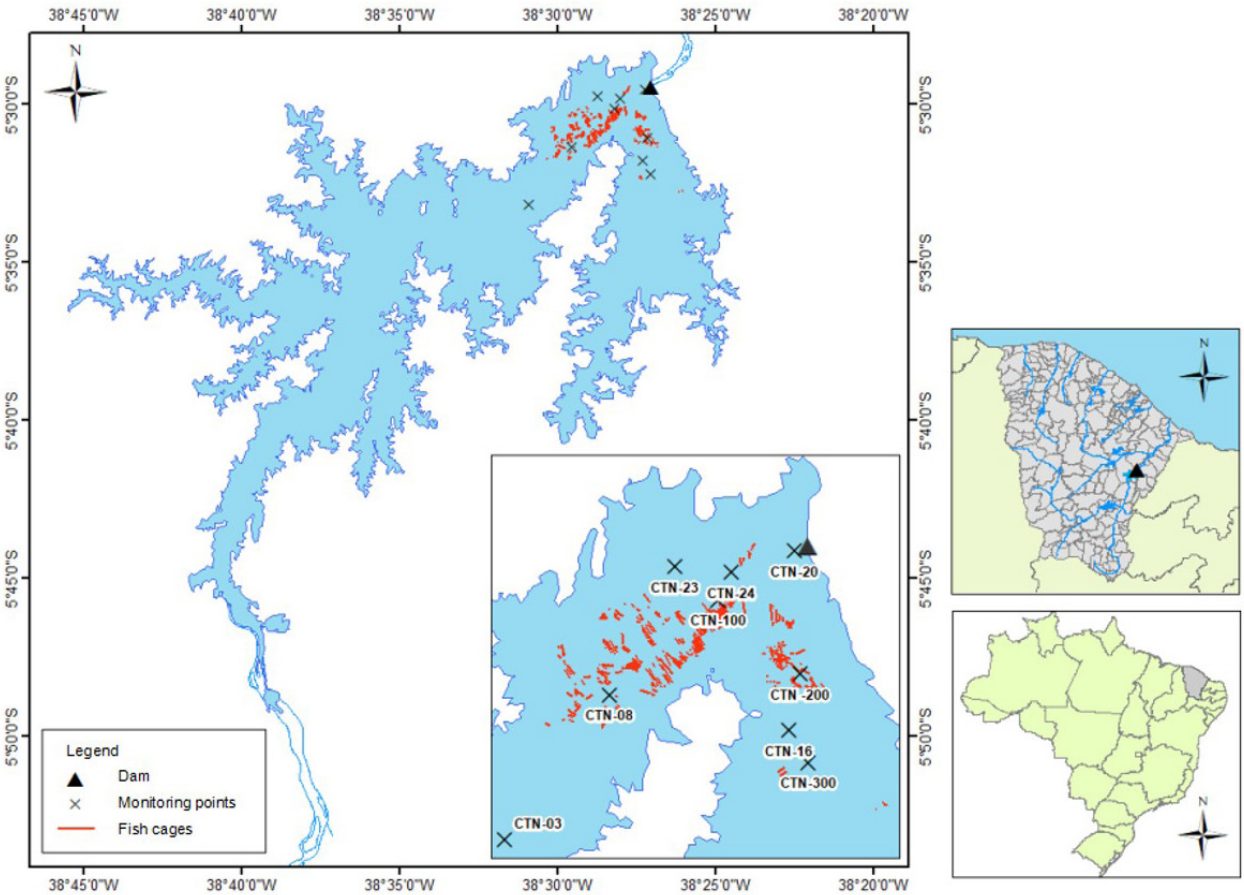


Figure 1. Castanhão reservoir in the state of Ceará, Brazilian semiarid region. The location of the dam (water intake), fish-cages and water quality monitoring points from the Water Resources Management Company (COGERH) is also shown.

monitoring points from the Water Resources Management Company (COGERH) are also depicted in Figure 1. Although this reservoir has a maximum depth of 60 m and a storage capacity of 6,700 hm³, reservoir volumes of up to about 2% of its storage capacity have been observed at the end of prolonged drought events (Figure 2), which has also impacted water quality. Figure 3 illustrates the changes in the thermal/chemical stratification patterns between the wet and dry periods in the Castanhão reservoir.

The water flow rate at the outlet also varies significantly (4–42 m³/s), depending on the rainfall and stored volume conditions. The water is withdrawn from the reservoir through a circular steel pipeline of 3.7 m diameter and 260 m long, located at about 16 m from the bottom of the reservoir. Figure 4 shows the water intake tower, and a sketch of the control volume used in the numerical simulations of the flow approaching and inside the water intake pipeline. The tower has two parallel conduits with a single inlet, both at the same level. However, since the beginning of operation, only one gallery has been used.

Numerical simulations and analyses

As detailed as following, numerical simulations and analyses of secondary data provided by COGERH were performed to investigate the effects of the operation of the water intake of Castanhão reservoir on the hydraulic transients, sediment resuspension, and water quality.

Modeling hydraulic transients

The transient hydraulic modeling was carried out using the software ALLIEVI, which is based on the method of characteristics (Universitat Politècnica de València, 2010). Boundary conditions were defined by the water level upstream the control volume (see Figure 4) and a relationship between the percentage of valve opening and flow rate downstream the water intake pipeline provided by COGERH. Thus, the impact of hydraulic transients on pressure

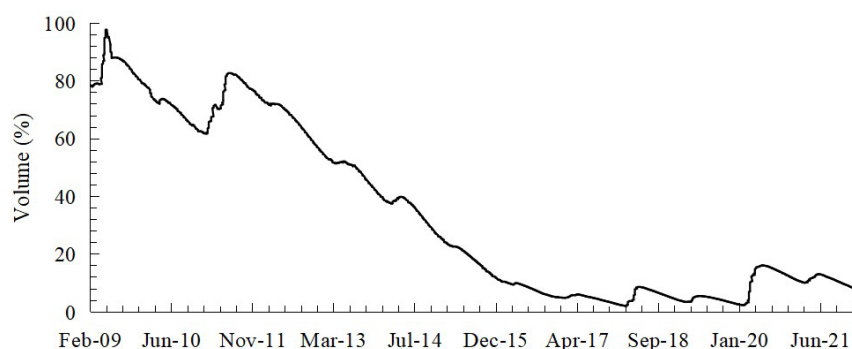


Figure 2. Variation of the volume of Castanhão reservoir throughout the years.

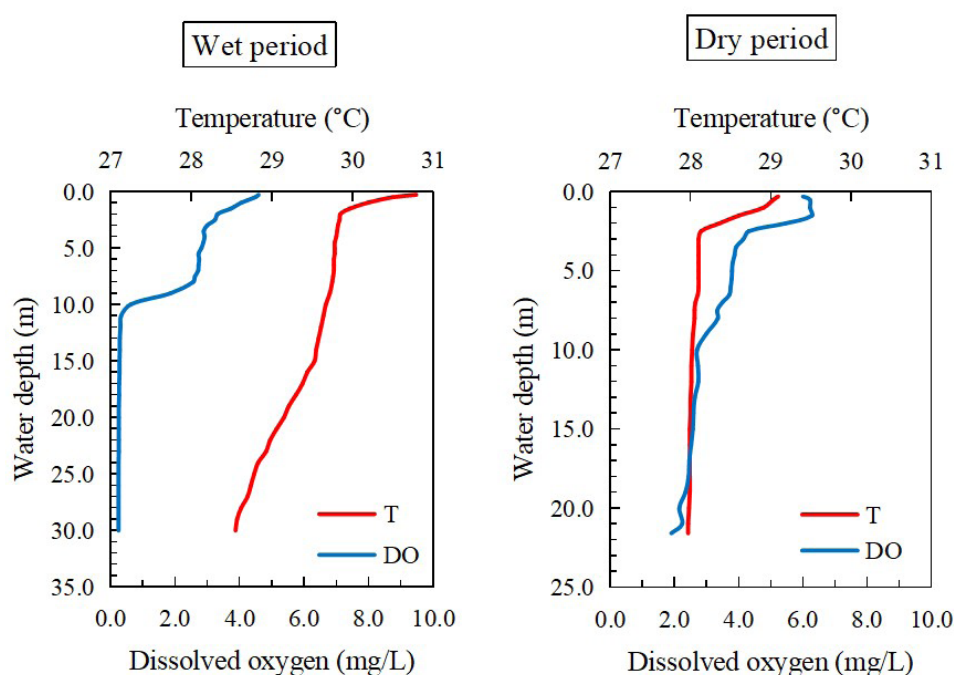


Figure 3. Typical changes in the thermal/chemical stratification patterns between the wet and dry periods in the Castanhão reservoir.

and flow rate regimes at the water intake pipeline was evaluated by testing different water levels and closing conditions of the water intake valve (from $t = 1$ to 60 min).

Modeling flow patterns and impacts on sediment resuspension

Computational fluid dynamics (CFD) simulations were performed using the software ANSYS FLUENT (version 2020 R2), which is based on the finite volume method, in order to investigate the induced flow patterns approaching the water intake. The control volume adopted in the simulations is detailed in Figure 5. Note that the tests were carried out for a water depth of $H = 40$ m. The turbulence models $k-\varepsilon$ and $k-\omega$ were used in the external and internal regions of the boundary layer, respectively. Different element sizes were tested and a mesh with 349.617 elements of 0.1 m was considered sufficient for the purpose of the present

study. Note that the inflation function of the software was applied to refine the mesh near the bottom of the reservoir (Figure 6).

With the turbulence values obtained from the CFD simulations, an empirical model as a function of the turbulent kinetic energy was applied to assess the thresholds for sediment resuspension (Belinsky et al., 2005):

$$\theta = \frac{k}{g \cdot R \cdot D} ; \theta_c = 0.135 Re_p^{-0.261} \quad (1)$$

where θ is a dimensionless parameter, θ_c is the limit of θ for sediment resuspension, k is the turbulent kinetic energy given by $k = 0.5(u'^2 + v'^2 + w'^2)$, g is the gravitational constant, R and D are respectively the specific gravity and particle diameter (obtained from field surveys and laboratory analysis), and Re_p is the particle Reynolds number.

Critical value (θ_c) is used to determine the conditions under which bed sediment particles are stable, but at the limit of resuspension. Thus, points located above the critical line are in motion, while points located below the critical line are at rest.

For the particle diameter D , samples collected from the reservoir bed were considered, from which the grain size distribution was determined. At the point closest to the water intake inlet, the average particle diameter obtained was $D = 0.012$ mm, and this value was considered in the analyses.

Modeling flow patterns and impacts on water quality dynamics

CFD simulations were also carried out under well-mixed and stratified conditions of the water column and for different flow rates at the outlet to determine the percentages of the induced flow field at each vertical layer that reaches the water intake. This analysis was important to assess the effect of the water intake operation on the quality of the water withdrawn in the dry and wet periods. The data provided by COGERH included the water quality parameters dissolved oxygen (DO), total nitrogen (TN),



Figure 4. Water intake tower of Castanhão reservoir. A sketch of the control volume used in the numerical simulations of the flow approaching and inside the water intake pipeline is also indicated.

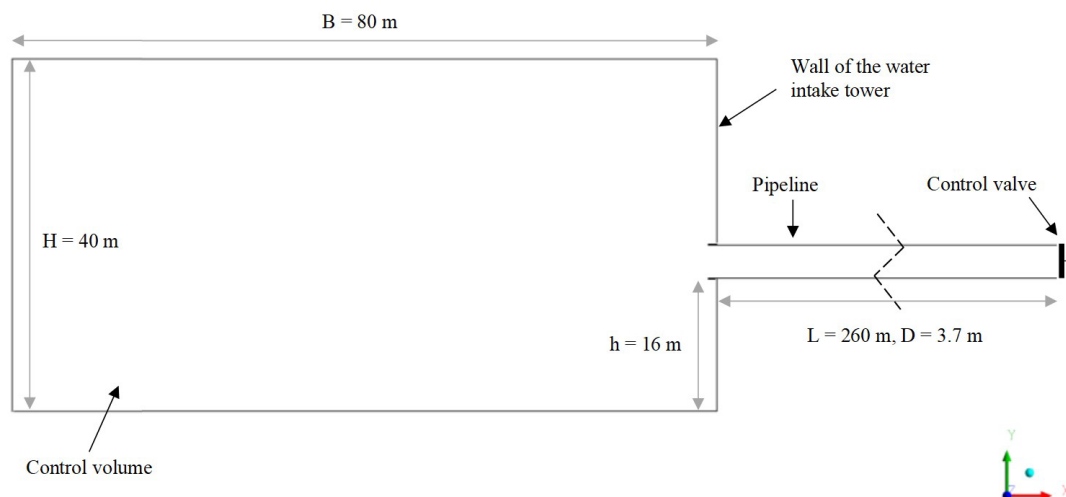


Figure 5. Sketch of the vertical section employed for CFD simulations using the $k-\varepsilon$ and $k-\omega$ models.

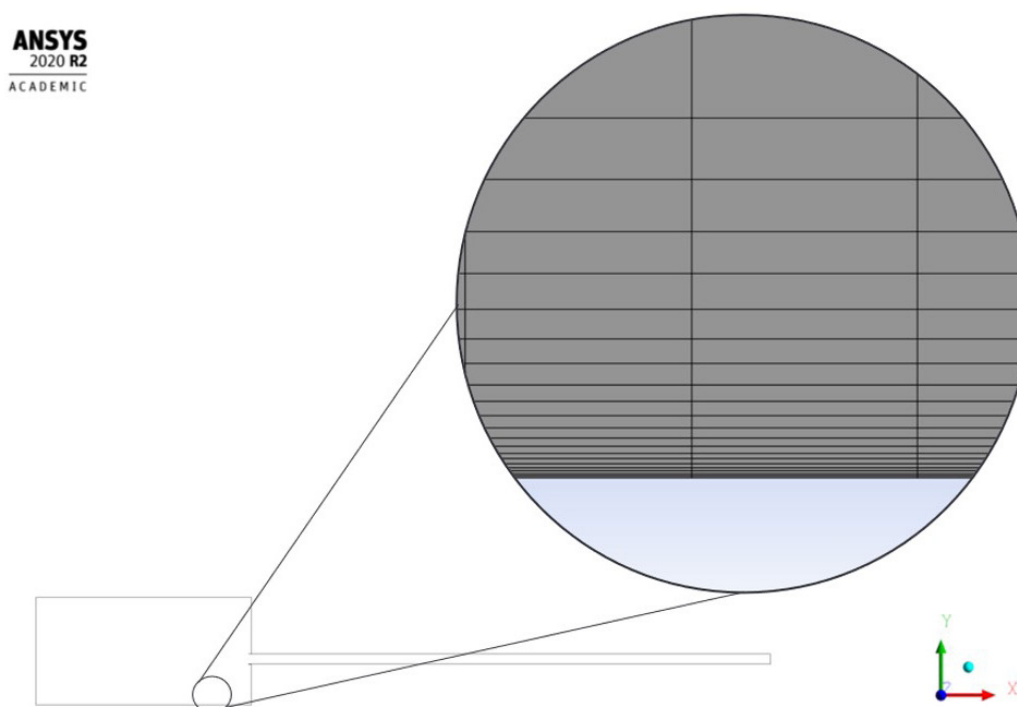


Figure 6. Mesh refinement for improvement of CFD simulations near the bottom of the reservoir.

and total phosphorus (TP), as well as the physical parameter temperature (T), all measured using a multi-parametric probe (YSI, 6600 V2). These data were analyzed according to American Public Health Association (2017).

RESULTS AND DISCUSSION

Hydraulic transients

The results of the simulations with ALLIEVI indicated that, even for the fastest closing conditions of the water intake valve ($t = 1.0$ min), the impact of hydraulic transients was small. While piezometric head fluctuated up to about 10% as compared to those of the permanent flow case (Figure 7), the maximum return flow was up to about 1.0 L/s (Figure 8). This suggests that hydraulic transients have a negligible influence on the hydraulic structures and on the upstream activities in the lake, such as fish-farming, which are located at least 2 km from the water intake (see Figure 1). This is supported by previous studies, in which hydraulic transients only become relevant for lower values of t (see Chaudhry, 2014; Ding et al., 2019).

Sediment resuspension

Figure 9 shows CFD simulations of velocity fields for different opening conditions of the water intake valve (100%, 75%, 50% and 25%), while Figure 10 shows high turbulent kinetic energy values at the bottom, indicating the potential for sediment resuspension at this area.

Figure 11 shows the results of the application of Equation 1 to the values of turbulent kinetic energy simulated with CFD for

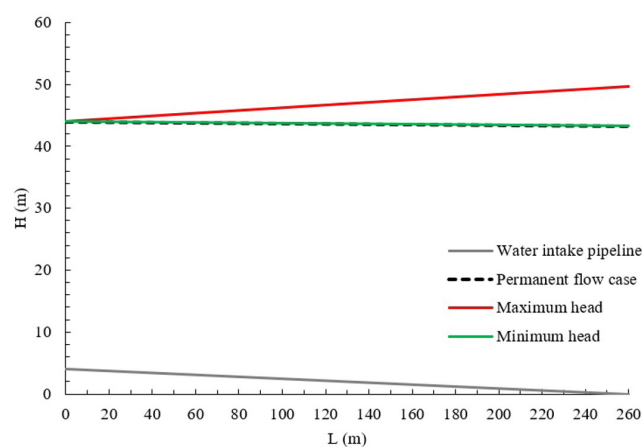


Figure 7. Simulation of piezometric head fluctuation as a result of hydraulic transients for the fastest closing conditions of the water intake valve ($t = 1.0$ min).

the case of 50% opening. It is seen that resuspension is likely to occur between 20 and 80 m from the water intake. Note that this resuspension was greater for higher withdrawal rates. However, even for the case of 100% opening condition, the longitudinal extent of resuspension was limited to the areas relatively close to the water intake (~ 500 m). This result is consistent with that of Politano et al. (2019), in which sediment resuspension is weak close to the water intakes.

It can also be observed in Figure 11 that the point of greatest resuspension induced by the water intake operation occurs approximately at 30 m from the inlet, with $x = 0$ representing the location of the water intake. The simulations indicated that fluid particles move

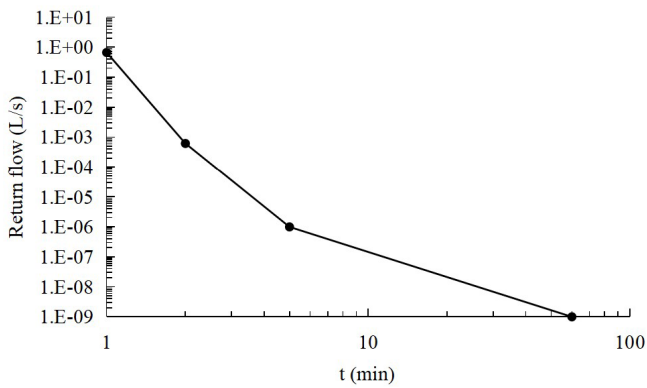


Figure 8. Results of the simulation of return flow due to hydraulic transients for different closing conditions of the water intake valve ($t = 1.0$ to 60 min).

toward the pipe from all directions along converging trajectories. However, due to inertia, the particles cannot abruptly change direction as they approach the pipe. Consequently, they continue moving in curvilinear trajectories, forcing the flow to contract slightly before reaching the inner edge of the pipe's opening (Porto, 2006). Thus, it is understood that the point of greatest resuspension ($x = 30$ m) occurs approximately where this contraction takes place. In this region, in addition to the predominant horizontal components of the flow, the vertical components of velocity and turbulence begin to play a more significant role, induced by the contraction caused by the water intake, and increasing as they approach it. However, near the pipe entrance, these vertical components, although larger, have already moved away from the reservoir bed, causing the resuspension parameters to fall in these areas (a decline observed between $x = 0$ and $x = 30$ m).

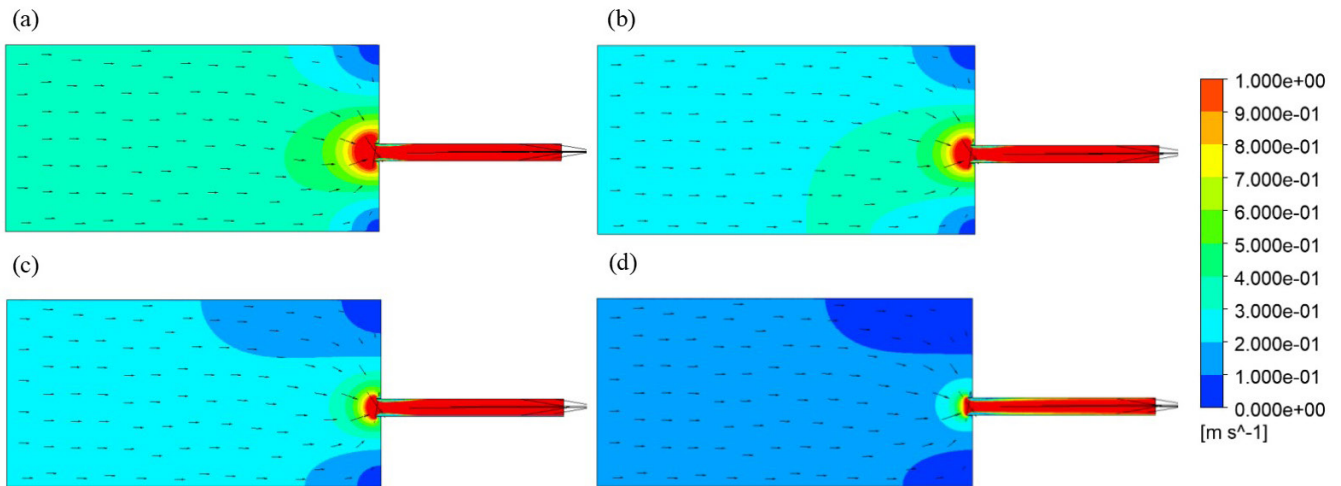


Figure 9. Vertical sections from CFD simulations of velocity fields for different opening conditions of the water intake valve: (a) 100%, (b) 75%, (c) 50%, and (d) 25%.

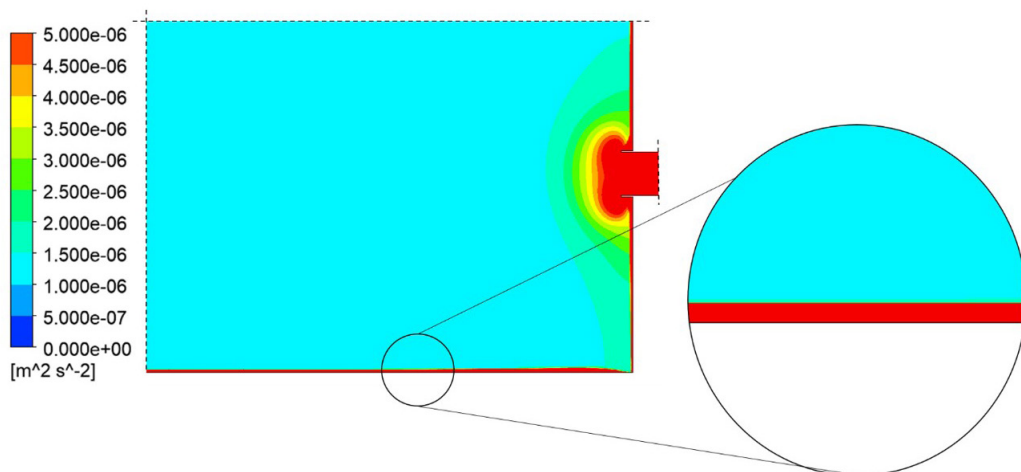


Figure 10. CFD simulations of turbulent kinetic energy field for the case of 50% opening, indicating the potential for sediment resuspension due to the high values at the bottom.

Water quality

The results revealed a relevant impact on water quality, in which different withdrawal conditions induced different upstream flow patterns and different water quality standards at the outlet.

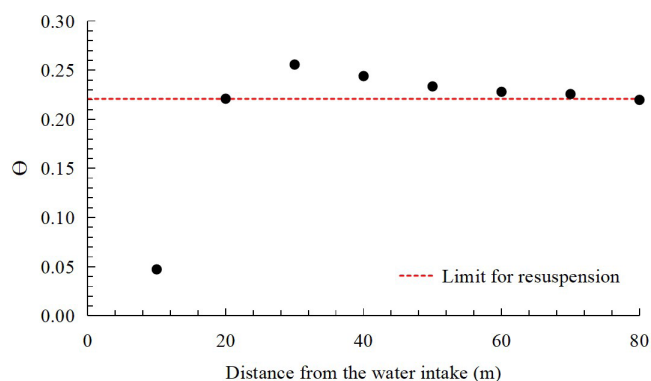


Figure 11. Prediction of sediment resuspension from the application of Equation 1 using the results of CFD simulations for the case of 50% opening (water intake is at $x = 0$ m).

For low water levels and low flow rates at the outlet, which are typical conditions of tropical semiarid reservoirs, most of the flow was withdrawn from the upper water layers (epilimnion). Contrastingly, for high flow rates, a significant flow was also withdrawn from the lower water layers (hypolimnion). These different flow regimes can be observed in Figure 12, where three withdrawal rates ($Q = 42$, 21 and $4 \text{ m}^3/\text{s}$) were tested. On the other hand, Figure 13 shows the impact of these flow patterns on the water quality at the outlet for thermally/chemically stratified conditions, as compared to well-mixed ones. In the wet period, when stratification is relatively strong (see Figure 3), it is clearly seen that TN, DO and TP are, in this order, the most impacted parameters, with differences in concentration of up to 26, 17 and 9%, respectively. In the dry period, when the reservoir is well-mixed (see Figure 3), only DO shows an impact (up to about 8%) as withdrawal decreases. These results suggest that the magnitude of water quality parameters at the outlet tend to increase under stratified water conditions, as compared to well-mixed ones, since more flow is captured from the epilimnion. It is important to observe, however, that during the wet season and for high water levels, much stronger thermal/chemical stratification occurs, resulting in anoxia and higher TN and TP levels in the hypolimnion (see Lima Neto et al., 2022; Carneiro et al., 2023).

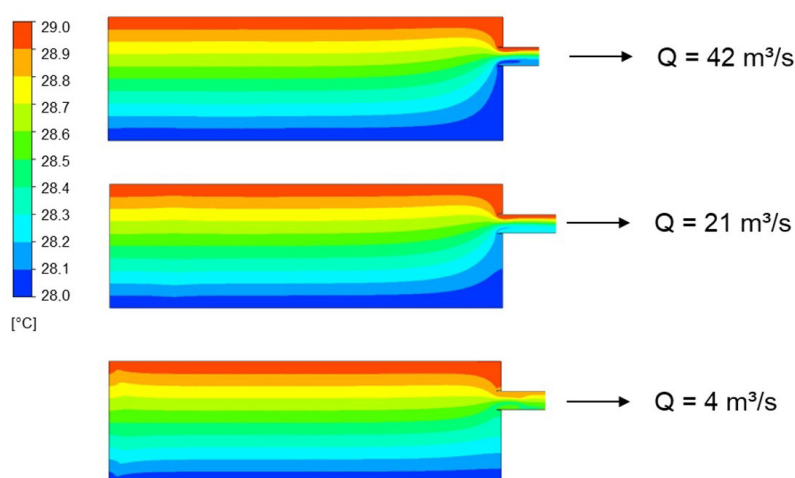


Figure 12. Vertical sections from CFD simulations of the thermal regimes and flow patterns induced by different withdrawal rates.

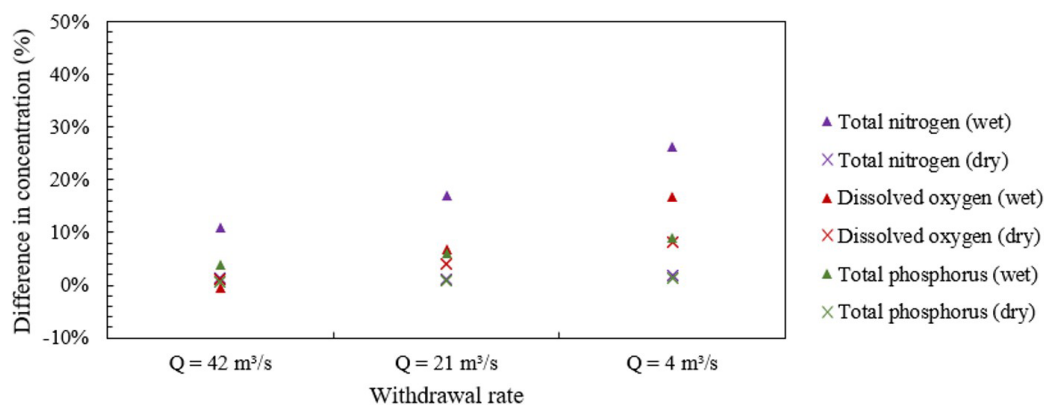


Figure 13. Difference in concentration at the outlet considering the simulated flow patterns for stratified and well-mixed conditions and for the wet and dry periods, as a function of withdrawal rates.

CONCLUSIONS

This paper investigated numerically the effects of the water intake operation of a large tropical semiarid reservoir in Brazil. The results revealed that while hydraulic transients and sediment resuspension were not significantly affected by the water intake operation, water quality at the outlet was strongly impacted by the withdrawal rates and mixing conditions of the water column.

The results obtained from the sediment resuspension analysis indicated that the flow induced by the water intake operation generates sufficient turbulence at the reservoir bed to resuspend the sediment. However, this effect ceases at approximately 500 meters from the intake, with its influence limited to the areas close to the water intake structure.

On the other hand, as a result of the different simulated flow patterns, the magnitude of water quality parameters at the outlet increased up to about 30% for low withdrawal rates and for stratified water conditions, as compared to well-mixed ones.

These results are important not only to advance in the knowledge of the flow patterns induced by water intakes in large reservoirs and under extreme operational conditions, but also to potentially improve water resources management, especially in drylands.

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Authors contributions

Luísa Ciriaco Silva de Oliveira: Data curation, methodology, formal analysis, investigation, writing – original draft.

Iran Eduardo Lima Neto: Conceptualization, funding acquisition, methodology, project administration, supervision, writing – review and editing.

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