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Modeling the impacts of climate extremes and multiple water uses to support water management in the Icó-Mandantes Bay, Northeast Brazil

Short title: **Modeling the impacts of climate and multiple water uses in a Brazilian bay**

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ABSTRACT

The hydropower production, water supply and aquaculture services of the Itaparica Reservoir are of immense importance for the Brazilian Northeast. Uncontrolled water resources consumption (e.g. irrigation, water supply), climate and land use change effects deteriorated the water quantity and quality in the reservoir, leading to socio-economic and environmental problems. In this work, a depth-averaged shallow water model was set up for the Icó-Mandantes Bay, one major branch of the reservoir, using the open TELEMAC-MASCARET system. The aim was to assess the impacts of the newly built water diversion channel, as well as the effects of a flood and tracer transport from an intermittent tributary, both located in the bay. An alternative approach to estimate the water retention times was additionally implemented. The simulations showed that though the diversion channel did not significantly influence the hydrodynamics of the bay, it is necessary to continuously monitor water quality parameters in the withdrawal, especially during rainy periods after droughts, because of the nutrient inputs from the tributary and the overflows of the nearby drainage systems. Management measures adapting to the continuously changing natural conditions and anthropogenic impacts are thus indispensable and the model presented can be a valuable supporting tool for this purpose.

Keywords: Itaparica Reservoir, multiple uses of water, semi-arid, TELEMAC-2D, water diversion project, water residence time

INTRODUCTION

The current drought in Northeast Brazil is considered the harshest in recent decades, if not of the last 100 years, devastating agricultural, livestock, and industrial producers (Gutiérrez *et al.* 2014). The consequent water scarcity, mostly attributed to climate change (Marengo & Bernasconi 2015), the illegalities in water withdrawals (Hirata & Conicelli 2012) and the water quality issues (Tundisi & Matsumura-Tundisi 2003; Gunkel & Sobral 2013) generate concern among Brazilian government, water managers and academic institutions, which endeavor to understand the extent of such impacts (Marengo *et al.* 2016). Nowadays, due to the pressure of water resources allocation to multiple uses, population growth, and economic factors, water resources managers face a number of challenges to overcome (Tundisi & Matsumura-Tundisi 2003). Such natural phenomena as droughts or floods can aggravate existing problems, affecting irrigation and agriculture as well as key water uses including hydropower and industry, and thus, the welfare of the residents (Marengo *et al.* 2016). To cope with such complex tasks there is a strong need for effective, sustainable water management strategies, supported by strong policies, and stakeholder and water users' dialogues, as well as modeling support for scenarios and possible strategies evaluation.

The INNOVATE project, a joint trans-disciplinary research project in collaboration between German and Brazilian institutions, emerged in this context, with the aim to find solutions and strategies to enhance a more sustainable watershed management for the São Francisco River Basin (Siegmund-Schultze 2017a). The project is embracing different disciplines, objectives and scales, e.g. catchment scale hydrological (SWIM) and water quality (MONERIS) modeling (Siegmund-Schultze 2017b). This work is part of the project and provides the hydrodynamic modeling at the reservoir scale. During the INNOVATE Status Conference and the so-called Environmental Days workshops in October 2014 in Recife and Petrolândia (Brazil), the existing challenges in the Itaparica Reservoir were discussed and specific requests were raised by water authorities and local stakeholders, which we intend to address in this paper.

The focus of this work is the Icó-Mandantes Bay, part of the meandered Itaparica Reservoir, in the Sub-Middle São Francisco River, Northeast Brazil (Fig. 1). Similarly to other big reservoirs in Brazil (Tundisi & Matsumura-Tundisi 2003), the main use of the Itaparica Reservoir is water storage for hydropower production (HPP). Nowadays, the reservoir also serves to develop large areas of irrigation agriculture, abstraction of drinking water, fishery, aquaculture and recreation activities. Over the past 20 years, the demand for energy has increased. The adopted practices for fertilization and the release of sewage from urban areas, combined with climate change, lead to significant environmental impacts, as well as increasing pressure on the aquatic systems and sedimentation in the inflow area, water losses and a trophic upsurge with severe eutrophication related processes, concerning in particular Icó-Mandantes Bay (Gunkel & Sobral 2013; Arruda 2015).

In previous studies in the region, Cirilo (1991) analyzed the formation process of surface runoff for the entire São Francisco Basin, with the purpose to identify the potential inundation areas in case of floods during and after dam construction. Another group of Brazilian scientists has been working for several years on remote sensing techniques (e.g. Landsat-TM) in the Itaparica Reservoir, with the aim to improve water management, in particular analyzing chlorophyll a dynamics, to assess potential eutrophication processes (e.g. Lopes *et al.* 2015). Nevertheless, very limited studies can be found in this region, especially concerning CFD (computational fluid dynamics) applications at the reservoir scale.

This article presents the application of a depth-averaged modeling tool for hydrodynamic and transport processes in the Icó-Mandantes Bay, developed using the modeling system TELEMAC-2D (Hervouet 2007), in order to simulate climate, stakeholders- and project issue-oriented scenarios. This bay is overstressed by various factors and has gained increasing attention in recent years (Matta *et al.* 2016; Selge *et al.* 2016). Withdrawals for human and animal consumption, as well as for irrigation agriculture, are located there. Moreover, the eastern channel of the controversial water diversion project (e.g. De Castro 2011) is withdrawing water directly from Icó-Mandantes, to transfer it to nearby watersheds. This bay is rather isolated from the dynamics of the reservoir main stream, behaving as two separated systems with different flow velocities (1 order of magnitude higher in the main stream, i.e. about 10 cm/s); thus exchange hardly occurs (Matta *et al.* 2014).

In this work, we investigated the effects of the eastern channel of the water diversion project and a flood from the intermittent tributary Riacho dos Mandantes, combined with tracer transport, on the bay's water dynamics. Since the reservoir is characterized by high water level fluctuations up to a maximum 5 m per year due to HPP (Keitel *et al.* 2015) the simulations have been run with alternating low and high water level conditions. Moreover, in order to quantify the mechanisms and timescales of exchange between the Icó-Mandantes Bay and the reservoir main stream, we applied an alternative method, imposing an initial uniform distribution of a mass-conservative passive tracer, tracking its evolution in time and, thus, estimating water residence times.

The aim of this research is to provide a first modeling set-up for the region, capable of simulating hydrodynamic and transport processes at the local scale, in order to respond to the above-mentioned urgent challenges in the Itaparica Reservoir. The methodology presented integrates the large-scale modeling studies (Koch *et al.* 2018) and the São Francisco River Basin Management Plan 2016-2025 (Nemus 2017) in order to provide state-of-the art support for water management in the region.

THE STUDY SITE

The São Francisco River with its length of 2,914 km is the longest river that runs entirely in Brazilian territory. The Icó-Mandantes Bay is located in the Itaparica Reservoir, in the Sub-Middle São Francisco River Basin. The reservoir is characterized by a total capacity of 10,781 hm^3 and an active capacity of 3,549 hm^3, with an installed power of 1,480 MW. Its flow is regulated by the upstream reservoir Sobradinho and has a mean discharge of 2,060 m^3/s and a mean water elevation of 302.8 m above sea level (a.s.l.) (Hydroelectric Company of the São Francisco River [CHESF] 2016), fluctuating seasonally up to 5 m between 299 and 304 m a.s.l. every six months. The average and the maximum water depths of the reservoir are respectively 13 and 42 m. The Icó-Mandantes Bay is oriented northeast of the reservoir main stream, located between the municipalities of Petrolândia and Floresta, with a surface area of about 25.1 km^2 and a volume of about 0.18 km^3. The length of the bay is 13.7 km, with a shoreline length of 42.4 km, a mean depth of 6.8 m and a maximum depth of 22 m. The climate conditions are semi-arid: the average annual temperature is 26 °C and the rainy season extends from January to April with an average annual precipitation of 475 mm. The Icó-Mandantes Bay covers approximately 3% of the annual mean surface area of the reservoir.

Figure 1 provides information on the multi-functionality of the bay. As depicted, there are four pumps (named EB-n), irrigating large agricultural areas: Block-3 and Block-4, of respectively 149.81 and 79.99 km^2, and supplying water for human and animal consumption. The total withdrawal reaches about 1.3 m^3/s (Arruda 2015). Further, there are the intermittent tributary Riacho dos Mandantes (mean flow rate of 1.18 m^3/s) and the eastern channel of the water diversion project. In the outer bay, there is a net-cage aquaculture system and another water intake for irrigation agriculture and human consumption (EB-01). In Fig. 1, one can also observe the consequences of the recent drought: EB-04 and EB-05 used to be wet (Google Earth 2012), but currently they are dry, with a minimum distance from water of about 1.7 km (Google Earth 2016); nevertheless, there are channel constructions for water supply of the pumps.

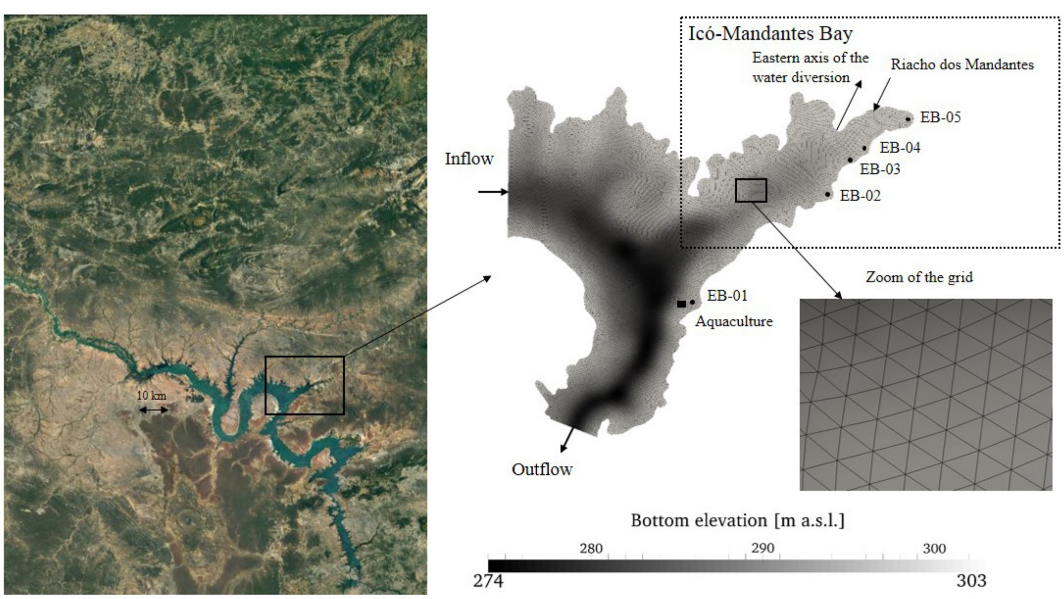

Fig. 1 Study area and computational domain: Itaparica Reservoir (*left*); unstructured triangular high-resolution grid for high water level scenarios (*right*), where the multiple uses and a zoom of the mesh are shown. Figure elaborated by the authors after Arruda 2015, Matta *et al.* 2016 and Google Earth 2016 (left satellite image).

The water diversion project of the São Francisco River (i.e. in Portuguese “Projeto de integração do rio São Francisco com bacias hidrográficas do nordeste setentrional”) is the largest water infrastructure project in the country, and it has raised strong political and social debates between governmental bodies and local stakeholders. The project aims to ensure the water supply (human and animal consumption) of 12 million people in 390 municipalities through two axes (East 220 km and North 402 km) in the states of Pernambuco, Ceará, Rio Grande do Norte and Paraiba, in particular to the big cities of the region, i.e. Fortaleza, Juazeiro do Norte, Crato, Mossoró, Campina Grande, and Caruaru, partly to mitigate the effects of frequent droughts in those regions. The project belongs to the Federal Government, under the responsibility of the Ministry of National Integration and its costs are currently estimated at R$ 8.2 10^9. For this study, we considered only the eastern channel of the project, as it diverts water directly from the Icó-Mandantes Bay, supplying it to the dry regions of Pernambuco and Paraíba. The planned operational flow for the eastern channel is 10 m^3/s, which can be increased up to 28 m^3/s maximum flow, exclusively when precise restrains concerning the volume of the upstream Sobradinho Reservoir are satisfied (National Water Agency [ANA] 2005). However, the management strategy of the two axes is still under discussion. The Brazilian Ministry of National Integration reported that while negatively affecting the biotic environment, the water diversion project is expected to stimulate the local economy and increase water supply for the semi-arid regions, which is of great importance for the development of the country (de Castro 2011; Melo *et al.* 2012; Ministry of National Integration 2016).

Riacho dos Mandantes is a small stream in a critical location: next to the water diversion channel, the intakes used for the irrigated lands and the drainage system for irrigation agriculture. The tributary itself is dry most of the year, but reaches significant discharges during rainy periods (i.e. up to 100 m^3/s). During rare but intense rain events, large amounts of nutrients are likely to enter water bodies by erosion, wash-out, leaching and run-off (e.g. from tributaries and drainage systems). In the case of bays with low exchange rates such as Icó-Mandantes, which are most vulnerable to eutrophication processes, such effects must be considered and effectively managed, to prevent water quality deterioration and associated health risks for drinking and irrigation water.

MATERIAL AND METHODS

The modeling system

The modeling system was already presented in Matta *et al.* (2016); therefore, we report hereafter only the most important related information. The hydrodynamic software applied to the Icó-Mandantes Bay is TELEMAC-2D, a module of the open TELEMAC-MASCARET system, a powerful integrated modeling tool for free-surface flows, that solves the two-dimensional (2D) shallow water and transport equations with complex algorithms based on the finite element method, computing the water depth, the two velocity components and the concentration at each point of the mesh and at each time step (Hervouet 2007). Since TELEMAC itself is not supplied by any graphical interface, the results were analyzed with ParaView, an open-source multi-platform data analysis and visualization application (Ayachit 2015).

The 2D depth averaged shallow water and transport equations are reported in Equations (1) – (3), where (1) is the continuity equation, and (2) and (3) are the momentum equations in x- and y-directions, respectively:

$$\frac{\partial h}{\partial t}+\frac{\partial uh}{\partial x}+\frac{\partial vh}{\partial y}=r \qquad (1)$$

$$\frac{\partial uh}{\partial t}+\frac{\partial u^2h}{\partial x}+\frac{\partial uvh}{\partial y}-\frac{\partial}{\partial x}\left(\nu_t\frac{\partial u}{\partial x}\,h\right)-\frac{\partial}{\partial y}\left(\nu_t\frac{\partial u}{\partial y}\,h\right)=h\,\left(\frac{f_x}{\rho}-g\frac{\partial(h+z_b)}{\partial x}\right) \qquad (2)$$

$$\frac{\partial vh}{\partial t}+\frac{\partial uvh}{\partial x}+\frac{\partial v^2h}{\partial y}-\frac{\partial}{\partial x}\left(\nu_t\frac{\partial v}{\partial x}\,h\right)-\frac{\partial}{\partial y}\left(\nu_t\frac{\partial v}{\partial y}\,h\right)=h\,\left(\frac{f_y}{\rho}-g\frac{\partial(h+z_b)}{\partial y}\right) \qquad (3)$$

where u and v are the x- and y-component of the velocity vector, respectively, ν_t is the turbulent viscosity, f_x and f_y are the shear stresses (bottom and surface) in x- and y- directions, respectively, h is the water depth, g is the gravity acceleration, ρ is the fluid density, z_B is the bottom elevation and r is the source or sink term (e.g. evaporation or rainfall).

The depth-averaged transport equation is shown in Equation (4):

$$\frac{\partial c}{\partial t} + u\frac{\partial c}{\partial x} + v\frac{\partial c}{\partial y} - \frac{\partial}{\partial x}\left(\nu_{t,t}\frac{\partial c}{\partial x}\right) - \frac{\partial}{\partial y}\left(\nu_{t,t}\frac{\partial c}{\partial y}\right) = r \tag{4}$$

where c is the concentration and $\nu_{t,t}$ is the turbulent diffusivity.

The constant viscosity model was adopted for turbulence, where the turbulent viscosity ν_t and the turbulent diffusivity were both set equal to 10^{-4} m^2/s (in agreement with Hervouet 2007; Jourieh 2015). The bottom and the surface friction, presented on the right-hand side of Equations (2) and (3), were respectively determined by the empirical laws of Strickler (Hervouet 2007) and Flather (1976). The first depends in particular on the flow field and on a roughness coefficient [$m^{0.33}$ s^{-1}], chosen equal to 30, according to model calibration of this reach carried out by Cirilo (1991). The latter is a function of the wind speed measured at 10 m above ground and a dimensionless wind coefficient, variable with wind magnitude and direction (Hervouet 2007). In Matta *et al.* (2014), a statistical analysis of meteorological data of a 12 years' time span was conducted, obtaining a mean wind velocity and direction of respectively 5.5 m/s and 140° (southeast wind). The above-mentioned values of bottom roughness, wind intensity and direction, have been set for each of the scenarios presented in this work as constant forcing conditions.

The computational domain chosen to conduct simulations in the bay has an area of around 100 km^2: it covers the Icó-Mandantes Bay itself and it includes a part of the reservoir main stream, in order to assess water exchange, enabling inflow and outflow for the bay (Fig. 1). For the open boundaries we set Neumann and Dirichlet boundary conditions, respectively, imposing velocities and water levels at the inflow and the outflow. The conditions are explained in detail for each scenario in the correspondent paragraph.

The bathymetry of the model was set up using measured data mapping, conducted by echo sounder profiling during different water quality field campaigns, performed by project partners between 2012 and 2014. These data were imported and elaborated in Janet (Smile Consult GmbH), a powerful and efficient pre-processor tool for mesh generation. Different high-resolution unstructured grids with triangular elements were created in order to consider different scenarios: one is for low water level cases and another one is for mean and high water level cases, with a maximum bottom elevation of 299.5 m a.s.l. and 302.8 m a.s.l., respectively, and around 20,000 triangular cells, characterized by an averaged cell length of 150 m (Matta *et al.* 2016). The mesh used for wet scenarios is shown in Fig. 1 (*right*).

Hydrological data

Daily values provided by the Hydroelectric Company of the São Francisco River (CHESF 2016) were used as reference database for the principal inflow and outflow boundaries, where the water elevation is the mean at the so-called Luiz Gonzaga dam (forming Itaparica) and the discharge is controlled by the dam and by the upstream Sobradinho Reservoir. Consequently to the prolonged drought affecting the region, in recent years, CHESF was forced to gradually reduce the mean operating discharge of 2,060 m^3/s down to values much lower than the planned minimum of 1,300 m^3/s. In order to reflect the extremes emerging by climate change, we chose low and high operating conditions in the reservoir to simulate some of our scenarios. The values at the boundaries for the low (LWL) and high water level (HWL) cases were set in agreement with project partners and stakeholders as standard LWL and HWL conditions, in agreement with CHESF.

The WATCH Era-40 data (Weedon *et al.* 2011) were used for the simulations of the eco-hydrological model SWIM (Krysanova *et al.* 2015; Koch *et al.* 2018), in order to obtain runoff values [Q, m^3/s] for the intermittent tributary Riacho dos Mandantes. SWIM results for Riacho dos Mandantes were computed on a daily basis and for a period of 30 years (1981-2010). Its daily flow rates were statistically analyzed and a discharge with a return period of 10 years (HQ_{10}) was determined using the Pearson Type III distribution. We obtained a value equal to 40.2 m^3/s, which was chosen as the peak of the simulated event, set 3 days long. This is an extreme event for the small tributary; thus, we will refer to it as a *flood*.

Data regarding the expected withdrawal from the eastern channel of the water diversion project were available from the Brazilian Water Agency ANA 411/05 (ANA 2005): 10 m^3/s for normal operation and 28 m^3/s as a maximum intake.

Simulation scenarios, initial and boundary conditions

The scenarios developed in this work reflect specific project partners (e.g. water quality group) and stakeholders (e.g. AGB Peixe Vivo, Belo Horizonte, Brazil) enquiries:

i. LWL and HWL: reference cases under steady state low and high water level- and flow-operating conditions, respectively;
ii. Q_OC and Q_MC: respectively operative and maximum withdrawal from the eastern channel of the water diversion project with the reservoir under steady state LWL-operating conditions;
iii. F_LWL and F_HWL: flood event from the intermittent tributary, with the reservoir respectively under steady state LWL- and HWL-operating conditions;
iv. RT_LWL, RT_HWL and RT_VWL: water residence times-simulations with the reservoir respectively under steady state LWL- and HWL-operating conditions, as well as time-variable water level (VWL).

A zero initial velocity and zero tracer concentration were the initial conditions for each scenario. Initial water elevation was set equal to the prescribed elevation at the outflow boundary, varying depending on the case and described in detail hereafter.

Boundary conditions after Neumann and Dirichlet at the inflow and outflow of the domain (Fig. 1) were given for the reference cases (i.) respectively imposing a constant water elevation and a constant discharge of 300 m a.s.l. and 800 m^3/s for LWL, and 304 m a.s.l. and 8,000 m^3/s for HWL. Reference cases were run until steady state conditions were achieved (i.e. few days).

Since the severe drought affecting Northeast Brazil from approximately the end of 2012 has increased the concern about the water diversion project, for the scenarios ii. we considered LWL conditions to simulate the impacts of the eastern channel (abbreviated EC_T) on water hydrodynamics (i.e. water depths, velocities and water volumes). In addition to the principal inflow and outflow (Fig. 1), it was necessary to implement a third open boundary in the mesh, in the location of the intake, with a width approximately equal to an averaged element length (approx. 100-150 m). Since TELEMAC needs a minimum of three nodes along an open boundary, the grid was refined in the surroundings of the new boundary with a mean length of about 30 m, obtaining five nodes at EC_T's boundary (Fig. 2, *left*). Here the foreseen withdrawals (negative values) of 10 m^3/s for Q_OC and 28 m^3/s for Q_MC (ANA 2005) were imposed. The duration of the simulations was set to 10 days.

In order to simulate the impacts of a flash flood from the small tributary Riacho dos Mandantes, we followed an analog procedure as for the EC_T, implementing a third open boundary in the meshes used for both scenarios iii. and refining the grid in the near surroundings. The minimal edge length for this case was around 26 m. A typical hydrograph was imposed at the open boundary of the tributary, using the Neumann condition with a discharge variable in time and characterized by a peak of 40.2 m^3/s (HQ_{10}), which was reached 1.5 days after the start of the event, which had a total duration of 3 days. Concerning transport, a mass-conservative passive tracer was set at the same boundary with a concentration of 1 [-], kept constant for the entire duration of the event, in order to reproduce a constant contamination flowing within the flood curve. The results were controlled each 0.5 day before, during and up to one week after the simulated event; afterwards, each month until one year of computation.

Finally, modeling analyses for water residence time estimations were conducted. In general, residence time for a natural straight river flow (one-dimensional approach) can be rather simple, as described by Chapra (1997). In particular, the hydraulic residence time τ [s] is defined as the ratio of the considered volume V [m^3] to the stream outflow rate Q [m^3/s], as reported in Equation (5):

$$\tau = \frac{V}{Q} \quad (5)$$

Using the formula in Equation (5), we obtained a value of about two months for Itaparica Reservoir, considering the mean water level of 302.8 m a.s.l. prescribed at the outflow and the mean dam-controlled discharge of 2,060 m^3/s at the inflow boundary. In more complex cases where bays are present, as in this study area, no constant flow through is ensured and, consequently, Equation (5) is not applicable, since the flow is highly two-dimensional (see Fig. 2, *right*). Several methods can be used, such as Lagrangian Particle Tracking (Banas & Hickey 2005).

In this study, an alternative method was implemented: a mass-conservative passive tracer with concentration equal to 10 [-] was set as initial condition (t = 0) in the whole bay, while zero concentration was set in the rest of the domain. The value of 10 [-] was assigned to each point of the mesh, higher than a specific horizontal coordinate. This limitation (i.e. x-coordinate > 560,157 m = approx. 560 km) was used as well to distinguish the results related solely to the bay. In order to provide an approximated value of residence time for each scenario (iv), the results were divided into different intervals: a code was implemented, starting at t = 0 with c = 10 and counting after each saved time step how many nodes fit to a certain concentration interval including the extremes, i.e. concentration higher than 9, between 8 and 9, between 7 and 8, between 6 and 7, etc. The time at which all points of the bay belong to the latter interval (c < 1), was arbitrarily defined as the approximated water residence time, i.e. when all points of the bay have a concentration lower than 10% of the initial value.

These scenarios were calculated considering steady state conditions in the domain (LWL- and HWL-operating reservoir) and for time-variable conditions (VWL). For VWL, we considered a variable water level (Dirichlet boundary condition at the outflow, variable in time) chosen over the year 2012, in order to observe the influence of variable water levels and discharges on residence time estimations, taking into account the water level fluctuations of the reservoir due to HPP. We used daily water levels (m a.s.l.) at the Luiz Gonzaga dam (CHESF 2016), between 2012 and 2015. We chose the time span between January 17, 2012 and January 16, 2013, characterized by 3 m of yearly water level variation (i.e. 300.8-304.0 m a.s.l.). The discharge was kept constant to the mean 2,060 m^3/s for the entire computation, in order to check only water level impacts on tracer evolution.

Further investigations were conducted assuming constant water elevations of 300 and 304 m a.s.l. combined with a time-variable discharge over the same time span, as well as time-variable discharges together with time-variable water levels. The results obtained are analog to the RT_VWL scenario; therefore, those are not presented in this paper.

RESULTS AND DISCUSSION

Reference cases

LWL and HWL scenarios intend to reproduce the reservoir under dry and wet conditions, respectively. To give an idea about the range of the mean flow velocities in the system, we report the respective values for LWL and HWL: 0.013 and 0.064 m/s considering the entire computational domain, 0.015 and 0.083 m/s in the reservoir main stream only, and 0.001 and 0.007 m/s in the bay. Comparing the values in the bay and in the main stream, we notice that the velocities diverge more than one order of magnitude. The mean water depths [m] differ less than 1 m comparing LWL and HWL, being approx. 11 to 13 m in the main stream and 4 to 5 m in the bay. Looking at the resulting flow field, the bay is much more isolated from the reservoir main stream under wet (HWL) conditions, due to the much higher inflowing discharge (8,000 m^3/s to 800 m^3/s), which tends to separate the systems even more.

Eastern channel of the water diversion project

In this section, the results of Q_OC and Q_MC are presented, considering the effects of the EC_T on the hydrodynamics of the bay in 2D (i.e. changes in velocities, water depths and water volumes). Figure 2 (*right*) shows the flow field for LWL under steady state conditions, completely reached after around 5 days. The flow velocities obtained in the entire computational domain for the scenarios Q_OC and Q_MC are both 0.015 m/s, while they are respectively 0.007 and 0.010 m/s in the bay area. The averaged velocities of the entire domain increase with deltas lower than 10%, while more relevant changes up to 60-70% were observed in the bay, stimulated by the intake. Nevertheless, velocities remained low (order of cm/s).

The results were further analyzed in four points, Their values were extracted at the end of the simulation, under steady state conditions: one in the reservoir main stream and three inside the bay (Fig. 2 *left*). Table 1 shows the impacts of the EC_T on the flow field inside the bay: the higher the discharge withdrawn, the higher the increase of the velocities inside the bay. The influence of the EC_T is also dependent on the distance of the analyzed point from the intake: the lower the impact, the longer the distance (the effect decreases from point 8747 to point 8327). The point 4296 in the reservoir main stream was not influenced by the withdrawal.

While a significant increase of velocities in the near field of the withdrawal was observed, water depths and water volume were not affected by the channel withdrawal. The values of water depth reached in the selected points 1915, 8077, 8327 and 4296 are 2.7, 7.8, 9.3 and 23.0 m, respectively, and did not change during the computation. Mass conservation was always ensured and the water volume showed negligible changes for both scenarios (lower than 0.1‰). Hence, even the maximum amount of 28 m^3/s withdrawn by the eastern channel appears not to be extremely significant compared to the mean continuous discharge flowing at the inflow boundary of 800 m^3/s.

Table 1 Flow velocities in the selected points in the bay (1915, 8077, 8327) and in the mainstream (4296), for scenarios LWL, Q_OC and Q_MC, which respectively indicate the cases considering the operative and the maximum withdrawal from the eastern channel of the water diversion project, with the reservoir under steady state LWL-operating conditions as reference.

	Velocity [m/s]			Increase of velocities [%]		
Points ID	LWL	Q_OC	Q_MC	Δ (Q_OC/LWL)	Δ (Q_MC/LWL)	Δ (Q_MC/Q_OC)
8747	0.005	0.015	0.035	206	638	141
1915	0.007	0.008	0.012	23	83	39
8077	0.011	0.012	0.012	16	15	-1
8327	0.006	0.007	0.008	14	34	18
4296	0.033	0.033	0.033	0	0	0

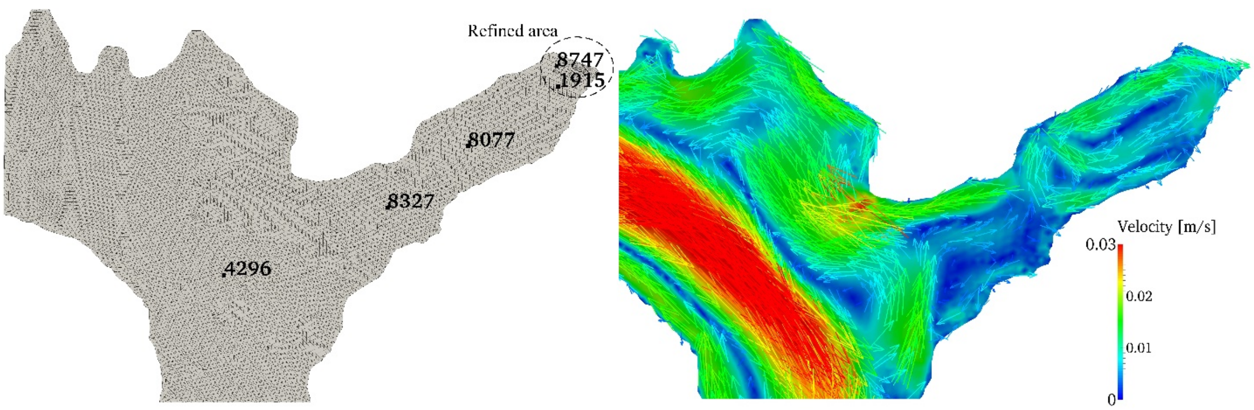

Fig. 2 Detail of the LWL model used for Q_OC and Q_MC scenarios, where (*left*) the selected points (in the main stream: 4296; in the bay: 1915, 8077, 8327), the refinement near the channel open boundary of the triangular unstructured grid and (*right*) the flow field for LWL under steady state conditions are shown.

The results reported here were analyzed exclusively with regard to hydrodynamics and relative changes due to the eastern axis in action, showing small effects, except for the near field of the withdrawal. Regarding another issue – water quality, Rossiter *et al.* (2015) conducted a study on heavy metals levels about 30 km downstream of Itaparica, in the Sertão Alagoano Channel (Apolônio Sales Reservoir). Such water quality assessments at the intake of the water diversion channel or inside it are still missing. Gunkel *et al.* (2018) reported high peaks. e.g. of Chlorophyll a up to 70 µg/L in the inner Icó-Mandantes Bay, especially during rainy periods. Studying water quality will be a necessity for the system. Additionally, regular monitoring of water quality is vital, due to the low water depths, the high evaporation rates and the low velocities inside Icó-Mandantes Bay, which do not facilitate exchange nor recirculation with the reservoir main stream.

Intermittent tributary Riacho dos Mandantes: impacts of a flood and tracer transport

Analyzing the results in different observation points, the flow velocities in the reservoir main stream were not influenced by the flood event, except for a slight increase of 0.001 to 0.002 m/s near the outflow boundary, not relevant compared to the mean velocities registered in the same location in the reference cases (i.e. 0.033 and 0.241 m/s, respectively for LWL and HWL). On the other hand, inside the bay the effects of the flood were large and were analyzed in two specific points: 8077 and 8327, same as shown in Fig. 2 (*left*). In those locations, velocities decreased in both scenarios, because the water flowing from the small tributary enters a distinct current along the northern shore and changes the circulation patterns in the inner bay, slowing them down. The highest impact was at 8077, which is nearer to the tributary boundary, for the F_LWL case (i.e. Δ = 0.006 m/s compared to a velocity of 0.009 m/s for LWL, while Δ = 0.003 m/s compared to a velocity of 0.012 m/s for HWL). Approximately three to four days after the end of the event, the velocities inside the bay reached the steady state conditions again (Fig. 3, *left*). Such results can be expected concerning hydrodynamics, since the imposed discharges of 800 or 8,000 m^3/s at the main inflow boundary are predominant in the flow field, compared to a secondary inflow of maximum 40.2 m^3/s. Nevertheless, it confirms the isolated condition of the bay from the main river.

Regarding tracer transport, higher values of concentration were reached for F_LWL, but on the other hand, the tracer was retained longer for F_HWL. Analyzing the results in the selected points of Fig. 2 (*left*), the maximum concentrations of 38.2% and 0.38% were reached four and six days after the end of the flood event in the center of the bay (point 8077) respectively for F_LWL and F_HWL (Fig. 3, *right*). The spreading process was much faster under drought conditions; in fact, the concentrations at 8077 were almost a third of the peak value already one week after the event, while in F_HWL the tracer concentrations reached after one month merely 2.8% and 0.33% at the observation points 8077 and 8327, respectively. In this case, the tracer moved much slower, because of the larger water volume to be mobilized and because of the dominant inflow of 8,000 m^3/s, clearly separated by the bay. Tracer values started to be lower than 0.1% four months after the flood for F_LWL, while after six months for F_HWL.

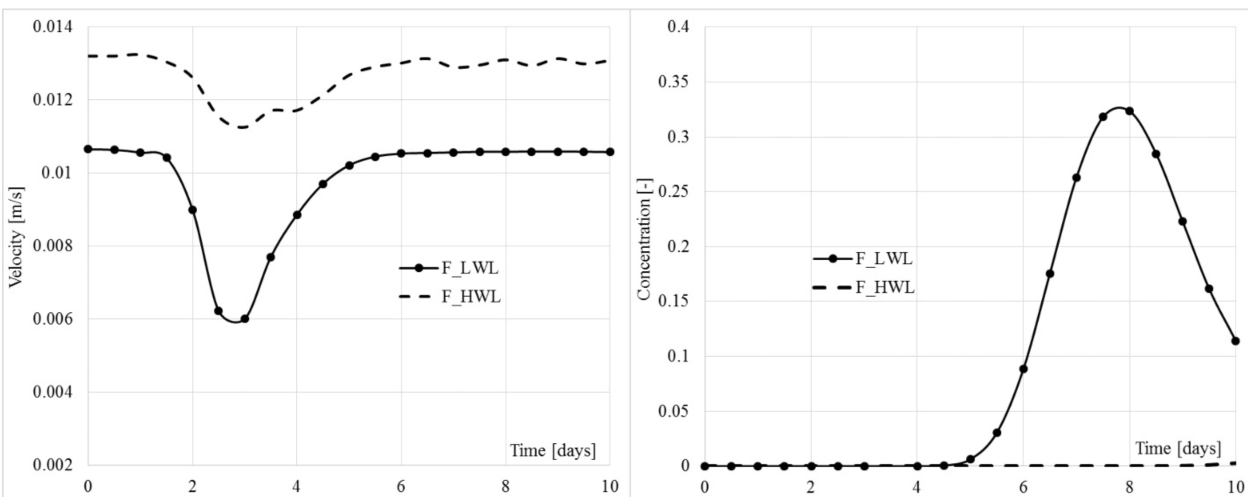

Fig. 3 Flow velocity vs. time (*left*) and tracer concentration vs. time (*right*) registered in the center of the bay (point ID 8077) during the flood event for F_LWL and F_HWL scenarios. The flood event takes place between day 1 and day 4.

In the context of climate change, water multi-functionality and conservation of environmental resources, the outcomes of the F_LWL and F_HWL scenarios intend to enhance a more sustainable watershed management in the Icó-Mandantes Bay, and thus in the reservoir. Considering the findings in relation to the locations of the existent intakes for irrigation agriculture and water supply, we can affirm that small effects were observed regarding hydrodynamics, except for the local impacts (near the tributary/intake boundary). On the other hand, the changes were more relevant regarding transport. Concentrations reached high values (80-100% of the initial) for both wet and dry scenarios (F_HWL, F_LWL) in the northern tip of the bay in the short term (up to one week after the flood), where the eastern channel and the pumps EB-04 and EB-05 are located. There, the values remained higher than 10% for F_HWL until one month of computation, while for F_LWL the concentrations had already decreased by 90% a few days after the extreme event, reaching concentrations of approx. 1 to 2%. Near the intakes EB-02 and EB-03, maximum values of around 2% are reached after one month for F_HWL, while for F_LWL these values are around 5%. Near EB-01, we obtained values lower than 0.5% for both scenarios and for the whole computation time.

Water residence time estimations in the Icó-Mandantes Bay

Since the exchange processes between the reservoir main stream and the bay are very slow, it was necessary to compute long-term simulations up to 2 years. The purpose was to assess the time range of those exchange processes in the system, as described in the methods: the so-called residence times in this work are the times at which all cells gain a concentration lower than 10% of the initial value (arbitrary concentration limit, which could be set looser or stricter).

Figure 4 (*right*) shows the spreading of the passive tracer inside the bay after six months: the concentration retained in the bay after this period is respectively 40% and 60% for RT_LWL and RT_HWL, compared to the initial value (Fig. 4, *left*). Likewise, RT_VWL results showed that the residence times are very high (> 1 year) and they are overall in accordance with the RT_LWL case (Fig. 5). Thus, the time-variable water level does not relevantly encourage water exchange between the bay and the main stream. Indeed, retention graphs of Fig. 5 show that concentrations lower than 10% are reached at the earliest after one year. After about 1.5 years, the RT_LWL and RT_VWL curves overlap. The estimated residence times were defined equal to 725 days for RT_HWL, and 545 days for RT_LWL and RT_VWL. Looking back at Equation (5), the computed residence times for the bay are substantially longer than the reservoir's (about two months).

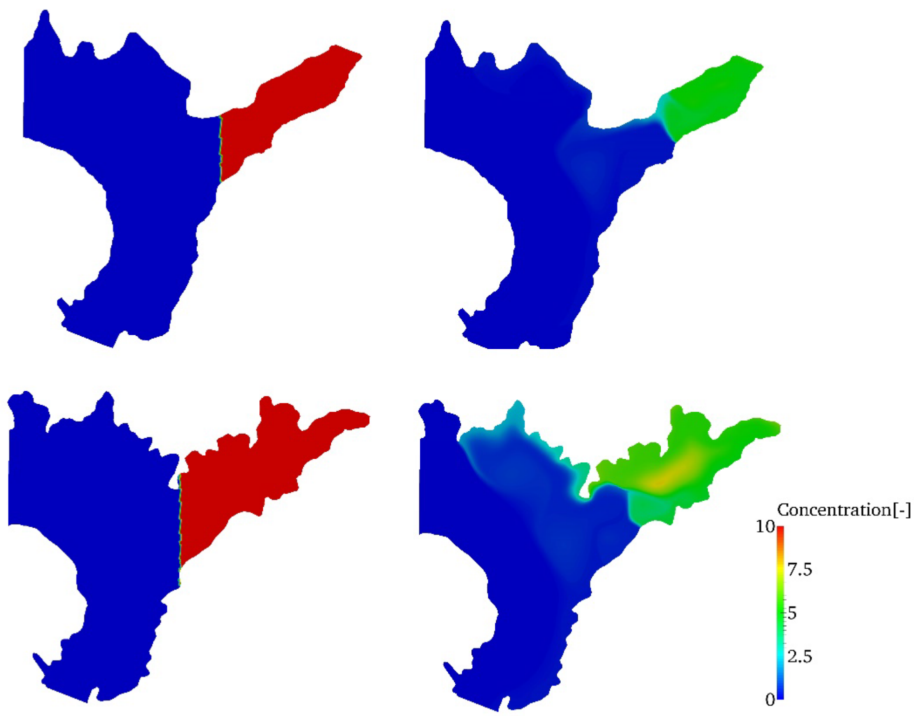

Fig. 4 Spreading of the mass-conservative passive tracer concentration at zero time (*left*) and after 6-months simulation (*right*) for steady state scenarios RT_LWL (*upper*) and RT_ HWL (*bottom*).

Discussion

Comparing RT_LWL and RT_HWL results with the F_LWL and F_HWL scenarios, the tracer spread faster in this latter case, because the flood from the tributary stimulated the hydrodynamics of the bay, usually almost stagnant. Thus, the ideal situation to sustain the bay's water quality would be to have a continuous inflow of water from the northeastern tip, stimulating the exchange between the reservoir main stream and the bay. For example, the water flow withdrawn by the eastern diversion channel could be inverted, in the case of alarming nutrient overloads and a high amount of algae in the shallow stagnant areas of the bay.

The results of this study showed additionally that the water level and discharge variations did not significantly stimulate this exchange; on the contrary, the high water levels and strong discharges (e.g. higher than 3,000 m^3/s) contributed to the isolation of the bay. Furthermore, high water level fluctuations are known to stimulate the development of harmful algae blooms and greenhouse gases emissions (Keitel *et al.* 2015; Gunkel *et al.* 2018). The findings and suggestions proposed should be considered and discussed with the water managers of the Luiz Gonzaga dam (CHESF), to reduce such risks and carry out further studies to properly plan sustainable operation measures.

Finally, in other first exploratory scenarios for the estimation of the bay's residence times, the intake of the water diversion channel was additionally taken into account. The results showed that the residence time of the bay was significantly reduced, up to around 50%, suggesting that the water withdrawal from the Icó-Mandantes Bay might affect the mixing of water at the local scale and be a positive side effect on water quality, as pollution will be diluted faster. Model scenarios investigating the impacts of water diversion channels, to improve lakes' dynamics and thus water quality, can be found, for example in Li *et al.* (2013), and specifically for Itaparica Reservoir in Melo *et al.* (2012). Further studies in this direction are needed and must be adapted to each specific case.

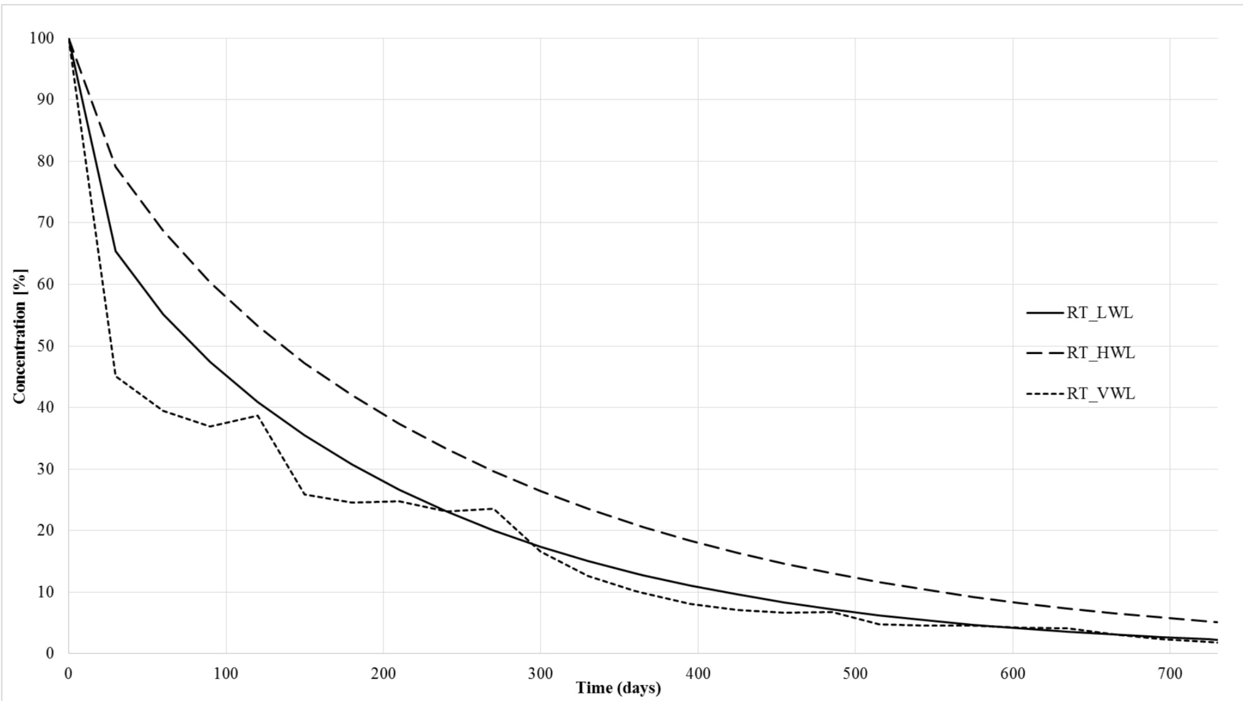

Fig. 5 Evolution of the mean tracer concentration inside the bay vs. time.

CONCLUSIONS

Given the prolonged drought affecting Northeast Brazil, the new water diversion project and the physical complexity of the system investigated, managing the multiple uses of water in the Itaparica Reservoir is becoming more and more challenging. The objective of this research was to provide a first numerical modeling tool for the Icó-Mandantes Bay, a branch of the reservoir, capable of simulating 2D flow and transport scenarios, in order to support water management in the region and integrate the hydrological models at the basin scale (e.g. Koch *et al*. 2018) with local studies (e.g. Gunkel *et al*. 2018).

The impacts of the eastern channel of the water diversion project and of a flood with mass-conservative transport from the intermittent tributary Riacho dos Mandantes were investigated, considering the reservoir operating under variable conditions, to take into account the water level variations due to HPP. The results showed that the 2D effects of the intake and the tributary on the hydrodynamics are negligible, except for the near field. In the case of intense rain events, the management of the intakes for irrigation agriculture and of the water diversion needs to be adapted. In the northeastern tip of the bay, high concentrations and long residence times were observed: higher values on the shorter term for drought scenarios and longer tracer retention for the high flow scenarios. Furthermore, an alternative method for estimation of water residence times of the bay was developed and tested. The results indicated high tracer retention times (> 1 year), alarming for the long-term stagnation of contaminants. First exploratory studies showed that withdrawal by the eastern channel of the water diversion is able to significantly reduce water residence times of the bay and thus potentially improve water quality. Nevertheless, further investigations in this direction are needed.

The 2D hydrodynamic and transport modeling framework developed for Icó-Mandantes Bay and described in this paper is of great importance for the Brazilian actors engaged in the water-related field. These are principally the Committee of the São Francisco River Basin (i.e. CBHSF), the water managers (i.e. CHESF), the Brazilian agencies ANA and IBAMA (i.e. Brazilian Institute of Environment and Renewable Natural Resources), who take decisions about flow regulation, as well as smallholders and universities (e.g. the Federal University of Pernambuco, UFPE). Since the model was implemented through open-source tools, it can be further applied for specific studies aiming to improve the knowledge of this complex water system as well as water management. The methodology and the outcomes of this work can be transferred to other reservoirs in semi-arid areas facing similar issues, where peripheral bays are isolated and used for multiple purposes. Water quality issues such as the development of harmful algae blooms in lentic areas, and their interactions with the reservoir main stream and the water withdrawals should be assessed in future research, coupling the existent model with a water quality module (e.g. with the recently released WAQTEL software of the open TELEMAC-MASCARET suite of solvers).

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