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Simulations of nutrient emissions from a net cage aquaculture system in a Brazilian bay

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Abstract: Hydrodynamics and transport simulations were conducted with the modeling software TELEMAC-2D on Icó-Mandantes bay, a branch of the Itaparica reservoir. The bay has a maximal operational water level amplitude of 5 m and is suffering for eutrophication and algae bloom. Therefore, we investigated low and high water level scenarios with two different high resolution meshes, with the purpose to deeper understand their impact on transport of substances and to improve the watershed management. In particular, nutrient emissions from a hypothetical net cage aquaculture system located in the bay were investigated on half-year cycles. We observed a relevant impact on water quality for a tilapia production of 130 t y⁻¹, i.e. after 6 months simulation we obtained around 8 µgP L⁻¹ and 6 µgP L⁻¹ at the source of emissions, for low and high water scenario, respectively.

Keywords: Itaparica reservoir; water level change; transport; São Francisco River

Introduction

Many reservoirs in Brazil were built within the last 50 years, primarily for water storage and energy production, without a conscious consideration of the environment. As a general consequence, large-dam construction in the 1960s and 1970s strongly interfered with river functioning and the hydrological cycles, producing many changes in these cycles and in the biodiversity related to the rivers (Tundisi & Matsumura-Tundisi 2003). Human intervention affects irreversibly water flows natural state, with a huge social and ecological impact. In Itaparica reservoir, located in the semi-arid Pernambuco, Northeast Brazil, climate and land-use changes as well as multiple uses of water lead to water quality problems (Gunkel & Sobral 2013). Surface water conservation, both for water quality and quantity aspects, is strategic for the sustainable development of the region (Araújo *et al.* 2003). Therefore, it is necessary to face the social, political and ecological issues with the help of multi- and trans-disciplinary studies, in order to find enhanced management options for the future. This is one of the purposes of the INNOVATE project (Interplay among multiple uses of water reservoirs via innovative coupling of substance cycles in aquatic and terrestrial ecosystems), a joint research in collaboration between Germany and Brazil, which this work belongs to.

Object of the study is Icó-Mandantes bay, a shallow eutrophic bay, located approximately in the middle of Itaparica reservoir. A map of the study site can be found in Matta *et al.* (2014). Previous research in the area showed that exchange with the reservoir main stream hardly occurs, as long as wind is neglected (Özgen *et al.* 2013; Broecker *et al.* 2014; Matta *et al.* 2014). Water multiple uses (e.g. irrigation agriculture), water level fluctuations and shore's desiccation, caused by high evaporation rates (ca. 2,000 mm y⁻¹), are overstressing the bay, isolating it from the river (Selge *et al.* 2015). In this work, we simulated hydrodynamics and transport using TELEMAC-2D, in order to quantify the mechanisms and timescales of exchange between Icó-Mandantes bay and the

reservoir main stream, according to different water elevations. We investigated in particular nitrogen and phosphorus dissolved ions emissions from an aquaculture system hypothetically located in the bay, to quantify the potential impacts on water quality.

Material and Methods

Modeling tools

The bathymetry of the model was set up using measured data mapping, conducted by echo sounder profiling during different field campaigns, performed between 2012 and 2014 (Selge *et al.* 2015). The data were imported and elaborated with the help of Janet (Smile Consult GmbH), an efficient tool to generate and edit grids for numerical simulations. TELEMAC-2D, a module of the TELEMAC-MASCARET system (Laboratoire National d'Hydraulique et Environnement (LNHE), part of the R&D group of Électricité de France), was used as processor. It is a powerful integrated modeling tool for free-surface flows and it solves the two-dimensional shallow water and transport equations with complex algorithms mainly based on the Finite Element Method, computing the water depth, the two velocity components and the depth averaged concentration at each point of the mesh (Hervouet 2007). After each computation, the results were examined with the help of ParaView, an open-source multi-platform data analysis and visualization application (Ayachit 2015).

Governing equations

The governing equations are the two-dimensional depth-averaged shallow water and transport equations. The shallow water equations consist of the continuity and the momentum equations in x- and y-direction (Equation 1, 2, 3):

$$\frac{\partial h}{\partial t} + \frac{\partial uh}{\partial x} + \frac{\partial vh}{\partial y} = 0 \quad (1)$$

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

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

where u and v are the x- and y-component of the velocity vector, respectively, ν_t is the turbulent viscosity (assumed constant and equal to $\nu_t = 10^{-4} \text{ m}^2 \text{ s}^{-1}$), f_x and f_y are the shear stresses (at the bottom and at the surface) in x- and y-direction, respectively, h is the water depth, g is the gravity acceleration, ρ is the fluid density and z_b is the bottom elevation.

The bottom and the surface friction (i.e. wind) are respectively determined through the Strickler law and the empirical Flather's approach, where the relevant parameters are the Strickler coefficient for the first, the wind velocity and a wind shear stress coefficient, dependent on wind velocity and direction, for the second. More information about the consideration of wind forcing in the TELEMAC system may be found in (Hervouet 2007). A mean wind of 5.5 m s^{-1} blowing from South-East with an angle of 140° (Matta *et al.* 2014) and a Strickler bottom friction coefficient of $30 \text{ m}^{0.33} \text{ s}^{-1}$ (Cirilo 1991) were chosen for each case studied.

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

$$\frac{\partial c}{\partial t} + u \frac{\partial c}{\partial x} + v \frac{\partial c}{\partial y} - \frac{\partial}{\partial x} \left(\nu_{t,t} \frac{\partial c}{\partial x} \right) - \frac{\partial}{\partial y} \left(\nu_{t,t} \frac{\partial c}{\partial y} \right) = 0 \quad (4)$$

where c is the concentration and $\nu_{t,t}$ is the turbulent diffusivity (assumption: $\nu_{t,t} = 10^{-4} \text{ m}^2 \text{ s}^{-1}$).

We considered only conservative transport in our study, simulating phosphorus and nitrogen emissions. This means that biological or chemical reactions and feedback effects of the transport with the flow are not taken into account. The evolution in time of the transported substances depends on advection (most relevant) and diffusion, whose terms are shown in Equation 4.

Further, two-dimensional simulations are carried out, i.e. vertical variations of the velocity or concentration are also not considered.

Preprocessing

Water level fluctuations are common phenomena in semi-arid areas due to rain seasons, high evaporation rates and hydropower generation. These changes play an important role for water quality by aquatic biodiversity development, nutrient release from desiccated areas and therewith water quantity management becomes a major tool for aquatic ecosystem control in these regions. Therefore, the study cases were investigated according to high and low water levels, in order to compare the respective results. Two unstructured triangular grids with high resolution were set up with the software Janet, one for low water level (LWL) and one for high water level scenarios (HWL) (Tab. 1).

Table 1 Characteristic parameters of the grids

High resolution models with unstructured mesh			
Water level	Maximum bottom elevation (m a.s.l.)	Prescribed water elevation (m a.s.l.)	Number of triangular cells (-)
LWL	299.5	300.0	17,000
HWL	302.8	304.0	23,000

The computational domain has an area of around 100 km^2 : it covers Icó-Mandantes bay and it includes a part of São Francisco River, concerning the inflow and the outflow (Fig. 1). São Francisco river, the longest in Brazil with about 2,914 km length, crosses the area and it is interrupted in its flow by the Luiz Gonzaga dam, forming the Itaparica reservoir: a large basin of about 828 km^2 , with a regulated mean flow of $2,060 \text{ m}^3 \text{ s}^{-1}$ and a mean water elevation of 302.8 m a.s.l.

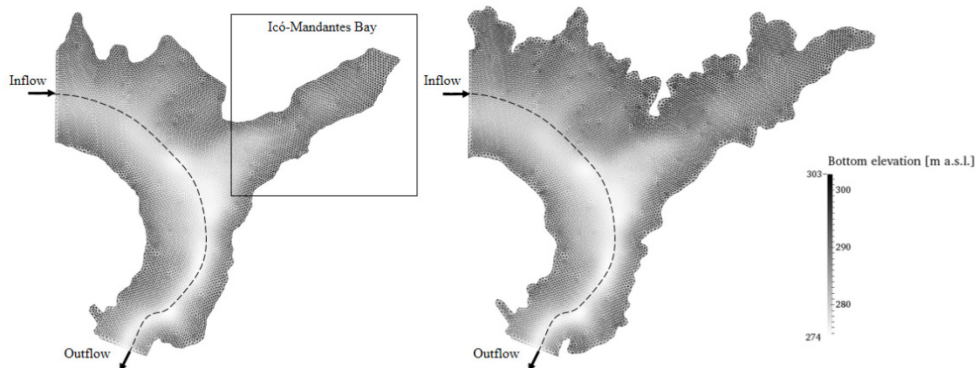


Figure 1 Unstructured high resolution grid for LWL (*left*) and for HWL (*right*). The black frame in the LWL grid (*left*) highlights Icó-Mandantes bay.

Results and Discussion

A low water level of 300 m a.s.l. and a high water level of 304 m a.s.l. were imposed as constant water elevation for low water level (LWL) and for high water level (HWL) at the outflow boundary, respectively, and a controlled discharge of $2,060 \text{ m}^3 \text{ s}^{-1}$ as boundary condition at the inflow from Itaparica.

Aquaculture nutrient emissions

Tilapia production in Itaparica reservoir amounts to 20,000 tons per year. In Brazil, 1% of the lake surface is allowed to host aquaculture ($43,267 \text{ t y}^{-1}$), but there are concerns about the sustainability to this regulation (Gunkel *et al.* 2013). Net cage fish culture brings a desirable economic development, but can also contaminate water bodies with eutrophication and sediments leading to anoxic conditions (Gunkel *et al.* 2015). Thus far, Icó-Mandantes bay is not yet interested by any aquaculture system, although it is used e.g. for fishery, irrigation agriculture. Therefore, we thought to model the accumulation of nitrogen and phosphorus dissolved ions emissions from a hypothetical location inside the bay. Their spreading, as well as their retained mass quantities, were observed in time and space.

The choice of the emissions site required a specific care. Since it is necessary to guarantee enough space to allow translocation and dilution of particulate organic material to avoid an extreme sediment increase beneath the cages (*Resolução CONAMA 413*, 2009; Gunkel *et al.* 2015), we adopted a point of 5 m and 9 m water depth for LWL and HWL respectively, near the southeastern shore of the bay. We assumed a productivity of 130 t y^{-1} , which means that Dissolved Nitrogen (DN) and Dissolved Phosphorus (DP) are equal to around 17.359 kg d^{-1} and 1.302 kg d^{-1} , respectively. The emissions were simulated as a daily accumulation of nutrients, implementing a tracer source in TELEMAC-2D. The results were observed after 1 week and 6 months computation. In Table 2 we reported the values of DN and DP in 4 observation points chosen inside the domain (Fig. 2), considering the modeled aquaculture impact for LWL and HWL.

Table 2 DN and DP concentrations [μgL^{-1}] at 4 observation points chosen inside Icó-Mandantes bay after 1 week and 6 months simulation.

LWL 1 week			HWL 1 week		
Observation points	DN [μgL^{-1}]	DP [μgL^{-1}]	Observation points	DN [μgL^{-1}]	DP [μgL^{-1}]
1224	0	0	1224	0	0
3972 – source point	103.120	7.735	3972 – source point	53.164	3.988
6479	0	0	6479	0	0
8536	0	0	8536	0	0
LWL 6 months			HWL 6 months		
Observation points	DN [μgL^{-1}]	DP [μgL^{-1}]	Observation points	DN [μgL^{-1}]	DP [μgL^{-1}]
1224	0.683	0.051	1224	0.403	0.030
3972 – source point	110.575	8.294	3972 – source point	74.815	5.612
6479	0.012	0.001	6479	0.008	0.001
8536	7.497	0.562	8536	4.580	0.344

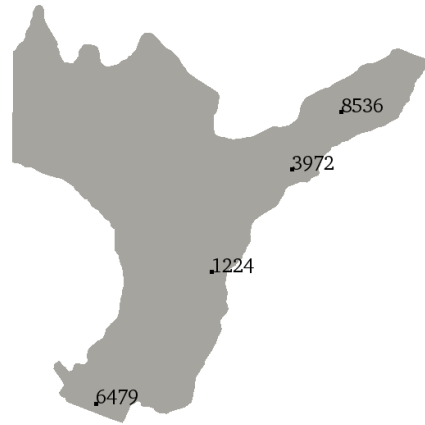


Figure 2 Observation points shown for the LWL grid (3972 is the source of nutrient emissions).

Considering a critical DP concentration of $25 \mu\text{g L}^{-1}$ (Selge *et al.* 2015), the accumulation of nutrients inside the bay is relevant: after 6 months simulation we obtained around $8 \mu\text{g L}^{-1}$ and $6 \mu\text{g L}^{-1}$ at the source of emissions (3972), while about $0.6 \mu\text{g L}^{-1}$ and $0.3 \mu\text{g L}^{-1}$ in point 8536, for LWL and HWL respectively. We can notice that the former gained higher concentrations in all observation points compared to the latter. We can state that with low water conditions, nutrients reached higher concentrations inside the bay and they spread faster. For high water conditions, the accumulation lasted longer and substances flew harder out of the bay. The final quantities [kg] that remained inside the bay after 1 week, 1 month and 6 months computation are reported in Table 3.

Table 3 DN and DP mass quantities [kg] still retained inside Icó-Mandantes bay after 1 week, 1 month and 6 months simulation.

	1 week		1 month		6 months	
	DN [kg]	DP [kg]	DN [kg]	DP [kg]	DN [kg]	DP [kg]
Source	121.513	9.114	520.770	39.060	3176.697	238.266
LWL	121.504	9.114	502.092	37.663	1385.204	103.908
HWL	121.504	9.114	519.644	38.980	2037.925	152.870

After 1 week, the entire quantity created by the source term is still inside the domain (s. Fig. 1). After 6 months, 56 % of the initial quantity left the domain for LWL, while for HWL only 36 %. Spreading and exchange processes inside Icó-Mandantes bay are slow, given to the extreme slow flow velocities, mainly driven by wind (Matta *et al.* 2014). The study conducted shows that installation of a net cage aquaculture system inside Icó-Mandantes bay would affect more the water quality of the area under low water conditions on a shorter term, but under high water conditions on a longer term. We can add that concentrations reached higher values for LWL, because water depths and surface are smaller, compared to HWL ($\text{Volume}_{\text{LWL}} = 66 \% \text{Volume}_{\text{HWL}}$). Figure 3 shows the spreading of DN in the computational domain after 6 months simulation.

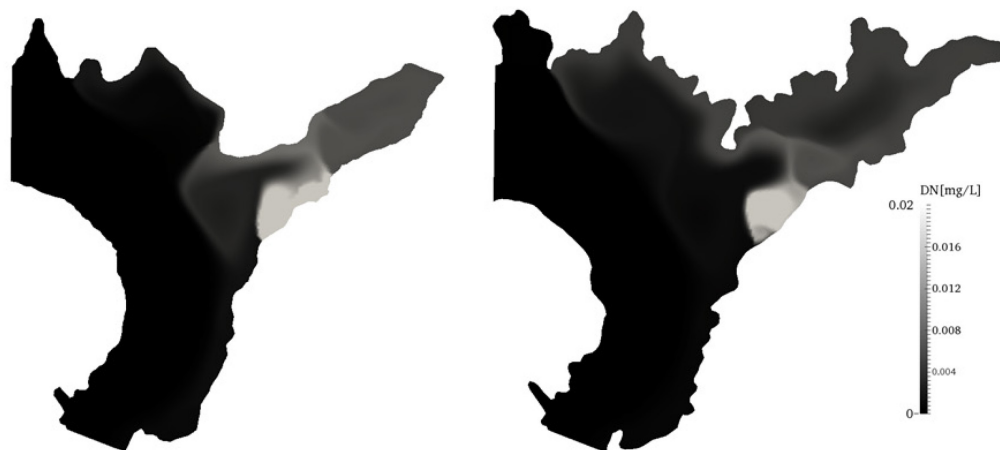


Figure 3 Spreading of DN concentrations [mgL^{-1}] inside Icó-Mandantes bay, after a computation of 6 months for LWL (*left*) and HWL (*right*).

Conclusions

Exchange processes between Icó-Mandantes bay and Itaparica reservoir main stream, Northeast Brazil, were investigated for low and high water conditions (abbreviated as LWL and HWL, respectively) using the TELEMAC-2D modeling system. Nutrient emissions were simulated on the long term (6 months), in order to understand the potential impacts of a hypothetical net cage aquaculture system inside the bay. The results showed that concentrations of DN and DP reached higher values for LWL and they spread faster inside the bay, while for HWL the mass quantities [kg] are retained longer in the area (56 % left the domain after 6 months for LWL and only 36 % for HWL).

The results of this study are an additional tool for local companies and decision makers, which can be particularly helpful regarding water quality control, water level regulation of the reservoir, placements of new pumps for irrigation agriculture or of a new net cage aquaculture system. In further work, also 3D effects (e.g. wind, stratification) will be investigated to observe hydrodynamic changes over the vertical, fulfilling the lacks of 2D modeling.

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