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# Quantification of exchange processes between a bay and a river using a two-dimensional high-resolution flow and transport model

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**Abstract:** Hydrodynamics and transport simulations were conducted with the modeling software TELEMAC-2D (Hervouet, 2007) on Icó-Mandantes Bay, a branch of the Itaparica Reservoir, within the INNOVATE project. The bay has a seasonal water level variation of around 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 to  $y^{-1}$ , i.e. after 6 months simulation we obtained around  $8 \mu\text{g P L}^{-1}$  and  $6 \mu\text{g P L}^{-1}$  at the source of emissions, for low and high water scenario, respectively. Additionally, uniform distribution of a mass-conservative passive tracer in the whole bay was imposed as initial condition to quantify water retention times of the bay, which resulted higher for the high water level scenario compared to the low, and even higher when we took evaporation into account (around 725 days).

**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 and water harvesting (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 (around 2 m per year), 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 nitrogen and phosphorus dissolved ions emissions from an aquaculture system hypothetically located in the bay, to quantify the potential impacts on water quality. Additionally, we conducted a study about water residence times, imposing an initial uniform distribution of a mass-conservative passive tracer, classifying its spreading over time.

## 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 or 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).

### Preprocessing

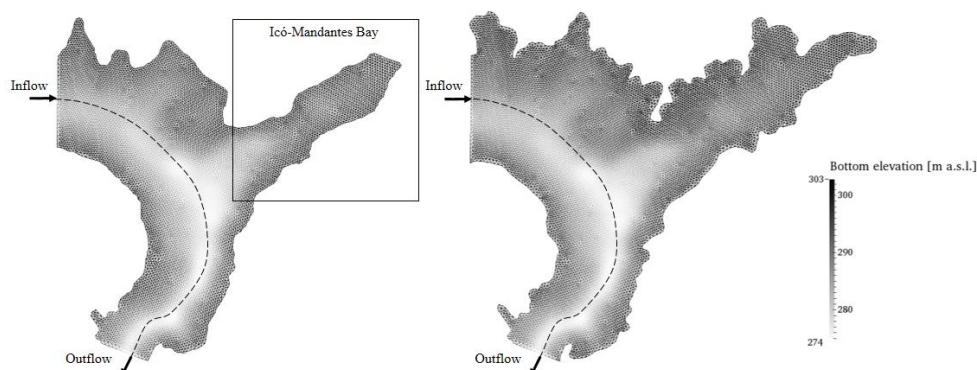
Water level fluctuations are common phenomena in semi-arid areas due to rain seasons, high evaporation rates and hydropower generation. These changes play an important role for water quality by aquatic biodiversity development, nutrient release from desiccated areas and therewith water quantity management 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<sup>2</sup>: 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<sup>2</sup>, with a regulated mean outflow of 2,060 m<sup>3</sup>s<sup>-1</sup> 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 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 m<sup>3</sup> s<sup>-1</sup> as boundary condition at the inflow from Itaparica. A mean wind of 5.5 m s<sup>-1</sup> blowing from South-East with an angle of 140° (Matta *et al.*, 2014) and a Strickler bottom friction coefficient of 30 m<sup>0.33</sup> s<sup>-1</sup> (Cirillo, 1991) were chosen for each case studied. We assumed velocity diffusivity and diffusion coefficient equal to 10<sup>-4</sup> m<sup>2</sup> s<sup>-1</sup>.

### Aquaculture nutrient emissions

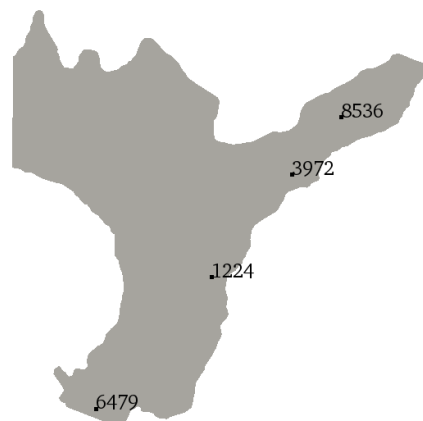
Tilapia production in Itaparica Reservoir amounts to 20,000 tons per year. In Brazil, 1% of the lake surface is allowed to host aquaculture (43,267 t y<sup>-1</sup>), but there are concerns about the sustainability to this regulation (Gunkel *et al.*, 2013). Net cage fish culture brings a desirable economic 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<sup>-1</sup>, which means that Dissolved Nitrogen (DN) and Dissolved Phosphorus (DP) are equal to around 17.359 kg d<sup>-1</sup> and 1.302 kg d<sup>-1</sup>, 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 [ $\mu\text{gL}^{-1}$ ] 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 [ $\mu\text{gL}^{-1}$ ]	DP [ $\mu\text{gL}^{-1}$ ]	Observation points	DN [ $\mu\text{gL}^{-1}$ ]	DP [ $\mu\text{gL}^{-1}$ ]
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 [ $\mu\text{gL}^{-1}$ ]	DP [ $\mu\text{gL}^{-1}$ ]	Observation points	DN [ $\mu\text{gL}^{-1}$ ]	DP [ $\mu\text{gL}^{-1}$ ]
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).

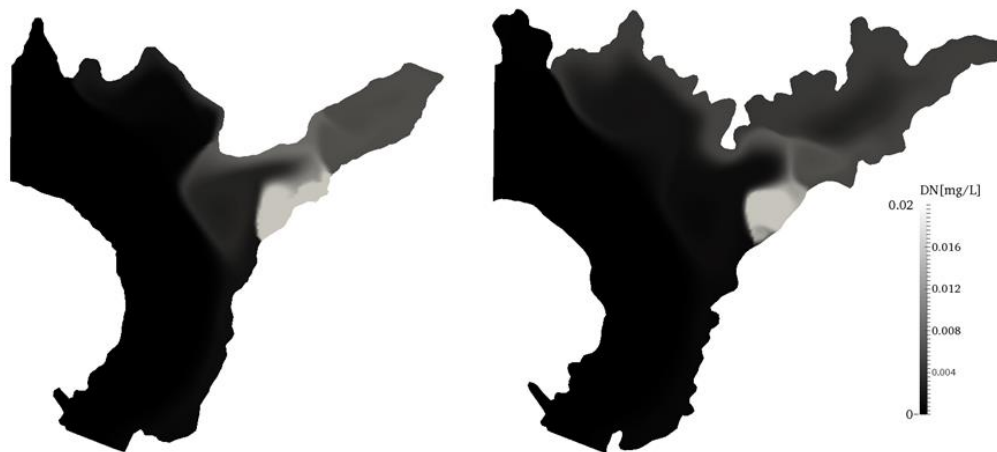
Considering a critical DP concentration of  $25 \mu\text{g L}^{-1}$  (Selge *et al.*, 2015), the accumulation of nutrients inside the bay is considered relevant: after 6 months simulation we obtained around  $8 \mu\text{g L}^{-1}$  and  $6 \mu\text{g L}^{-1}$  at the source of emissions (3972), while 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.

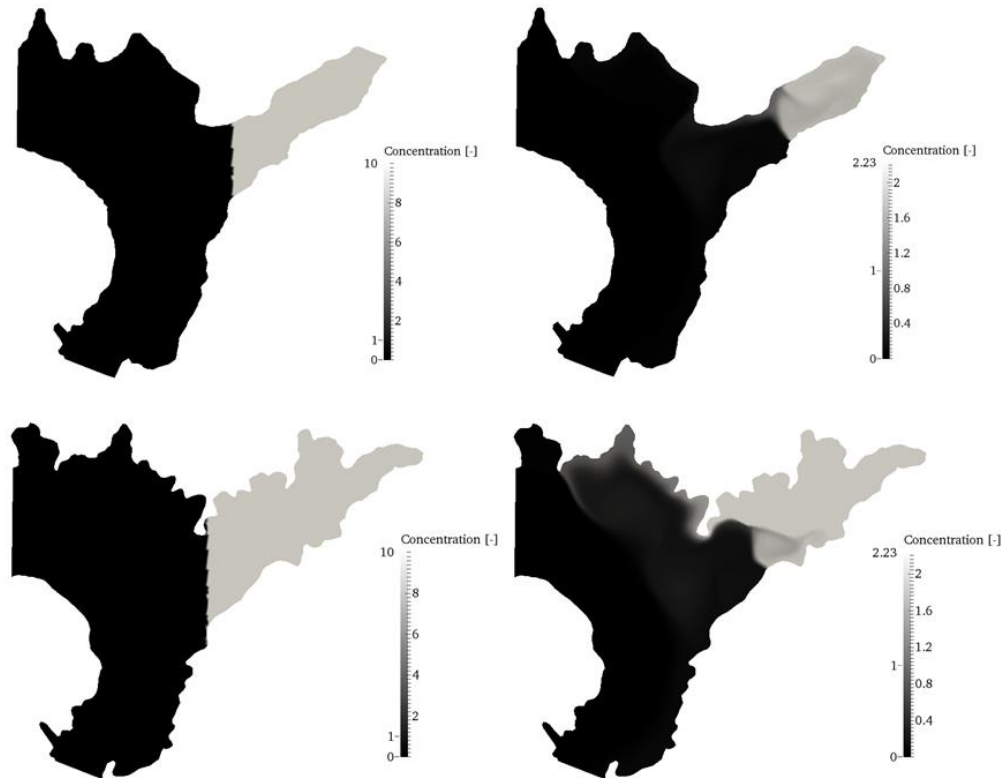


**Figure 3** Spreading of DN concentrations [ $\text{mgL}^{-1}$ ] inside Icó-Mandantes Bay, after a computation of 6 months for LWL (*left*) and HWL (*right*).

### Mass-conservative tracer uniform distribution

Hitherto, modeling studies to define retention times in Icó-Mandantes Bay have not yet been conducted. In general, residence time for a natural river flow can be simply determined after Chapra (1997). In more complex cases, as our study area, no constant flow through is ensured and the problem depends on many variables. Several methods can be used, as Lagrangian Particle Tracking (Banas *et al.*, 2005).

In this study, a mass-conservative passive tracer with concentration equal to 10 was set as initial condition ( $t = 0$ ) in the whole bay, while zero concentration in the rest of the domain. More specifically, the value of 10 was assigned to each point of the mesh, which had the x- coordinate higher than 560,157 m (Fig. 4, *left*). Both LWL and HWL were examined, considering alternatively zero evaporation or evaporation equal to  $5.479 \text{ mm day}^{-1}$  (Selge *et al.*, 2015). We run the simulations for 2 years, assuming a constant water elevation for the whole computation.



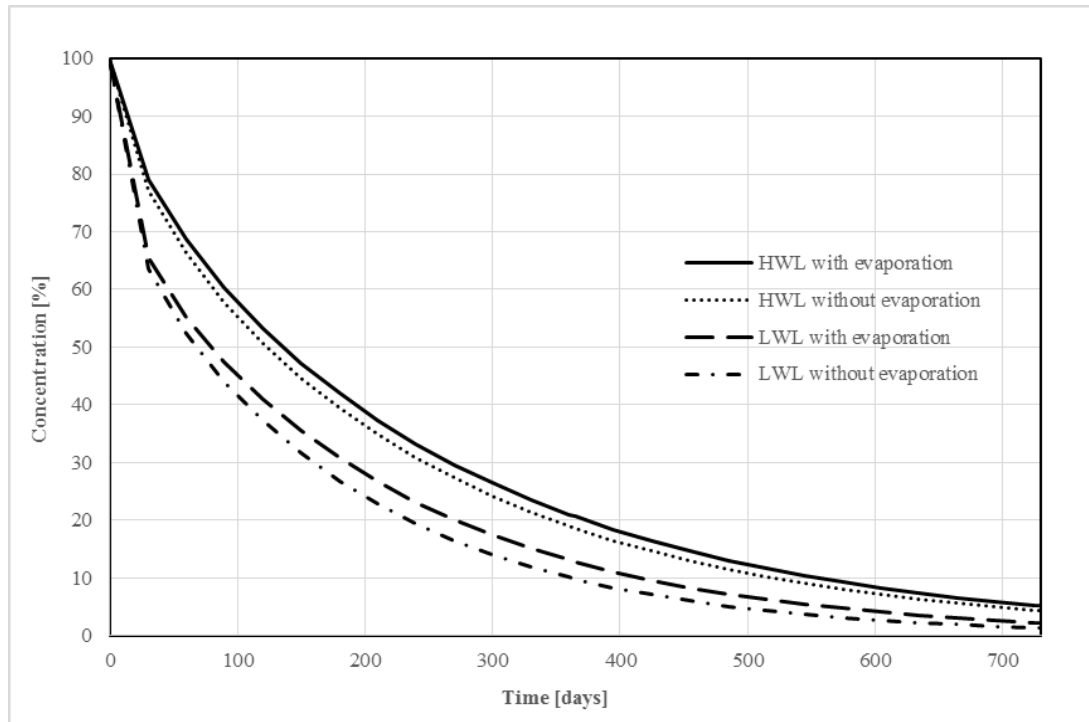
**Figure 4** Spreading of the mass-conservative passive tracer concentration at zero time (*left*) and after 1 year simulation (*right*) for LWL (*above*) and HWL (*below*), considering evaporation.

The limitation applied to the grid points for the initial conditions ( $x > 560,157$  m) was used as well to distinguish the results related only to the bay. This means that the number of nodes belonging to the bay are 1,383 and 2,932 for LWL and HWL, respectively. In order to provide an approximated value of residence time for each scenario, the results were divided in different intervals. In particular, if the initial value at  $t = 0$  was  $c = 10$ , we counted how many nodes fit to a certain concentration interval after each saved time step, i.e. concentration higher than 9, between 8 and 9, between 7 and 8, between 6 and 7, including the extremes of the interval, and coming with this procedure until the interval of concentration lower than 1. The time at which all points of the bay belonged to this latter interval, was defined as the approximated water residence time. It means that after that time, all points of the bay have a concentration lower than 10 % of the initial value. The results are reported in Table 4.

**Table 4** Approximated values of water residence time, modeling a uniform distribution of mass-conservative passive tracer as initial condition in Icò-Mandantes Bay. The values indicate the time at which each point of the bay has a concentration lower than 10 % of the initial one.

	Water residence time [days]	
	zero evaporation	evaporation of $5.479 \text{ mm d}^{-1}$
LWL	485	545
HWL	695	725

Finally, retention graphs for each scenario are shown in Figure 5, until time equal to 730 days, i.e. 2 years. We can observe that evaporation has an influence on the results, higher for HWL, compared to the LWL.



**Figure 5** Decrease of tracer concentration inside the bay [%] vs. time [days].

## 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 processor. 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).

Additionally, we tried to quantify water residence times of the bay, subjected to evaporation or not, under low and high water levels, in order to improve future management decisions of the reservoir. We simulated the spreading of a mass-conservative passive tracer uniform distribution, imposed as initial condition with concentration 10, just inside the bay. As we observed studying aquaculture impacts, substances were retained longer for HWL compared to LWL. After 2 years of computation, assuming constant water elevation for the whole time frame and considering evaporation, we still registered 5 % of the initial value inside the domain for HWL and 2 % for the LWL. Slightly lower values occurred when evaporation is neglected (4 % and 1 %, respectively).

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.

## Acknowledgements

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## References

- Araújo J. C., Fernandes L., Machado J. C. J., Lima Oliveira M. R. and Cunha Sousa T. (2003). *Sedimentation of Reservoirs in Semiarid Brazil*. In: Global Change and Regional Impacts: Water Availability and Vulnerability of Ecosystems and Society in the Semiarid Northeast of Brazil, Springer eds., pp 205-216.
- Ayachit U. (2015). *The ParaView Guide: A Parallel Visualization Application*. Kitware, ISBN 978-1930934306.
- Banas N. S., Hickey B. M. (2005). *Mapping exchange and residence time in a model of Willapa Bay, Washington, a branching, macrotidal estuary*. Journal of Geophysical Research, Vol. 110, Issue C11011.
- Broecker T., Özgen I., Matta E., Cabral J., Candeias A. L. and Hinkelmann R. (2014). *Simulation of Flow and Transport Processes in a Brazilian Reservoir*. Lehfeldt, R. & Kopmann, R. (eds): International Conference on Hydrosience & Engineering (ICHE) 2014, Hamburg, Germany, © 2014 Bundesanstalt für Wasserbau ISBN 978-3-939230-32-8.
- Chapra S. (1997). *Surface Water Quality Modeling*. McGraw-Hill, New York, USA.
- Cirillo J. A. (1991). *Análise dos processos hidrológico – Hidrodinâmicos na bacia do Rio São Francisco*. PhD Thesis, Universidade General do Rio do Janeiro, Brazil.
- Gunkel G. and Sobral M. C. (2013). *Re-oligotrophication as a challenge for tropical reservoir management with reference to Itaparica Reservoir, São Francisco, Brazil*. Water Sci. Technol., Vol. 67, No. 4, pp. 708-714.
- Gunkel G., Steemann J. and Sobral M. C. (2013). *Carrying capacity limits in net cage fish production in water reservoirs*. In: Sustainable Management of Water and Land in Semiarid Areas. ed. G. Gunkel, J.A. Silva & M.C. Sobral, Editora Universitária UFPE, Recife. ISBN 978-85-415-0259-7, pp. 99-117.
- Gunkel, G., Matta, E., Selge, F., Nogueira da Silva, G. M. & Sobral, M. (2015). *Carrying capacity limits of net cage aquaculture for Brazilian reservoirs*. Revista Brasileira Ciências Ambientais, subm.
- Hervouet J. M. (2007). *Hydrodynamics of free surface flows: modelling with the finite element method*. Wiley, 360 p.
- Matta E., Özgen I., Cabral J., Candeias A.L. and Hinkelmann R. (2014). *Simulation of Wind-Induced Flow and Transport in a Brazilian Bay*. Lehfeldt, R. & Kopmann, R. (eds): International Conference on Hydrosience & Engineering (ICHE) 2014, Hamburg, Germany, © 2014 Bundesanstalt für Wasserbau ISBN 978-3-939230-32-8.
- Selge F., Matta E., Hinkelmann R. & Gunkel G. (2015). *Nutrient load concept- reservoir vs. bay impacts*. Proceedings 17th IWA DIPCON Conference, Berlin, Germany.
- Özgen I., Seeman S., Candeias A. L., Koch H., Simons F. and Hinkelmann R. (2013). *Simulation of hydraulic interaction between Icó Mandantes bay and São Francisco river, Brazil*. Sustainable Management of Water and Land in Semiarid Areas. Gunkel G., da Silva J. A. A., Sobral M. Editors, pp. 28-38.
- Tundisi J. G. and Matsumura-Tundisi T. (2003). *Integration of research and management in optimizing multiple uses of reservoirs: the experience in South America and Brazilian case studies*. Hydrobiologia 500: 231–242.