ICHE 2014, Hamburg - Lehfeldt & Kopmann (eds) - © 2014 Bundesanstalt für Wasserbau ISBN 978-3-939230-32-8

Simulation of Wind-Induced Flow and Transport in a Brazilian Bay

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ABSTRACT: Wind-induced flow and transport processes were investigated in Icó-Mandantes bay, a branch of the São Francisco river, Brazil. Aim of the study was to analyze the effects of the wind on the water body and on the interaction between the São Francisco river and the bay, for different scenarios and different wind conditions. It was found out that while the velocities in the bay remained relatively small (mm/s), they were significantly increased by the wind shear stress. Additionally, a tracer was injected at different locations in the area to simulate the spreading of a contaminant. An increase of tracer exchange between the river and the bay was observed.

Keywords: Wind-induced flow, 2D shallow water model, Parameter study

1 INTRODUCTION

Turbulent mixing in reservoirs and lakes is primarily caused by wind which is the principal source of the required mechanical energy. Wind-induced flow was an object of a wide range of studies, on the field and in laboratory experiments (Tsanis, 1989). Facing the complexity in studying water flow and circulations in bays, nowadays the aid is found in numerical models, which simulate shallow water and transport.

In this work a two-dimensional shallow water model was used in order to investigate wind-induced flow in Icó-Mandantes bay, North-East Brazil. The model is implemented in the Hydroinformatics Modelling System (HMS), a Java-oriented software framework, developed at the Chair of Water Resource Management and Modeling of Hydrosystems, Technische Universität Berlin. Previous research on Icó-Mandantes bay showed that no significant exchange of water and matter between the bay and the São Francisco river occurred and that the water in the bay was almost stagnant (Özgen et al., 2013). The study was conducted without considering the influence of the wind. In this regard a method was implemented in HMS, in order to consider the wind shear influence on the water body and to analyze the interactions between the bay and the main stream.

The study area is located in the Itaparica reservoir in the state of Pernambuco, North-East Brazil. The reservoir is upstream the Louis Gonzaga dam, formerly known as Itaparica dam, built with the purpose of water storage, mainly for power generation. Nowadays it also serves to develop large areas of irrigation agriculture, abstraction of drinking water, fishery and aquaculture. Over the past twenty years, the demand for energy has increased and the uses of water are multiple. This, combined with the climate change, is leading 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 (Gunkel and Sobral, 2013). The INNOVATE project (INterplay among multiple uses of water reservoirs via inNOVative coupling of substance cycles in Aquatic and Terrestrial Ecosystems) was born in this context. It is funded by the BMBF (Federal Ministry of Education and Research), with the aim to develop a sustainable reservoir management for the region and to find suitable solutions for the conflicts about the multiple uses of the basin.

As part of the INNOVATE project, this work investigates the interaction of Icò Mandantes bay and São Francisco river with a numerical model which simulates flow and transport processes. This model should help to get deeper insight into the relevant parameters and processes and into water reservoir eutrophication and its nutrient concentration limits as well as to determine mitigation measures.

2 MATERIAL AND METHODS

2.1 *Governing Equations and Modeling System*

The model is based on the depth-averaged two-dimensional shallow water and transport equations. The equations are derived from the principles of conservation of mass and conservation of momentum and they are non-linear and hyperbolic. These equations are applicable only to free surface flows. The other underlined assumptions are hydrostatic pressure in gravity direction, slow bottom inclinations and depth-averaged variables. Physical and turbulent viscosity are neglected in this work. At right hand side of the momentum equation there are both the bottom friction and the surface friction terms. The first is computed with the Strickler Law, with a roughness coefficient of 50 $m^{1/3}/s$, which is kept constant for every simulation run. The Flather's approach was used to compute the wind stress. The determination of the wind coefficient depends on the intensity of the wind velocity. The 2D shallow water equations in the conservative form can be written as:

$$\partial \boldsymbol{q}/\partial t + \nabla \boldsymbol{f} = \boldsymbol{s} \tag{1}$$

$$\boldsymbol{q} = \begin{bmatrix} h \\ uh \\ vh \end{bmatrix}, \quad \boldsymbol{f} = \begin{bmatrix} \boldsymbol{v}h \\ \boldsymbol{v}uh + \frac{1}{2gh^2} - \nu_t \nabla(uh) \\ \boldsymbol{v}vh + \frac{1}{2gh^2} - \nu_t \nabla(vh) \end{bmatrix}, \quad \boldsymbol{s} = \begin{bmatrix} r \\ -\frac{\tau_{Bx}}{\rho} - C_D \rho_a u \sqrt{u^2 + v^2} - gh\frac{\partial z_B}{\partial x} \\ -\frac{\tau_{By}}{\rho} - C_D \rho_a v \sqrt{u^2 + v^2} - gh\frac{\partial z_B}{\partial y} \end{bmatrix} \tag{2}$$

where $\boldsymbol{q}$ = storage vector, $\boldsymbol{f}$ = flux vector, $\boldsymbol{s}$ = source vector, $\boldsymbol{v}$ = velocity vector, ν_t = turbulent viscosity (assumption: $\nu_t = 0$), τ_B = bottom shear stress, h = water depth, r = mass sink/source term (e.g. rainfall, infiltration), g = gravity acceleration, ρ = fluid density, ρ_a = air density, C_D = wind coefficient and z_B = bottom elevation. The depth-averaged transport equation as follows:

$$\boldsymbol{q} = [ch], \quad \boldsymbol{f} = [\boldsymbol{v}c - D\nabla(ch)], \quad \boldsymbol{s} = r_t \tag{3}$$

with r_t= tracer mass sink/source term, D = turbulent diffusion and c = concentration. The wind coefficient necessary to compute the shear stress in Equation (2) can be calculated by Flather's approach as:

$$C_D = (0.63 + 0.066 \cdot v_w) \cdot 10^{-3}, \quad \text{if } v_w < 5 \text{ m/s}$$

$$C_D = (-0.12 + 0.137 \cdot v_w) \cdot 10^{-3}, \quad \text{if } 5 \le v_w \le 19.22 \text{ m/s}$$

$$C_D = 2.513 \cdot 10^{-3}, \quad \text{if } v_w > 19.22 \text{ m/s} \tag{4}$$

with v_w = intensity of the velocity of the wind, at 10 m above the surface level.

The modeling system used was Hydroinformatics Modelling System (HMS), a Java-oriented software framework, developed at the Chair of Water Resource Management and Modeling of Hydrosystems, Technische Universität Berlin. In HMS the two-dimensional shallow water and transport equations are discretized with a cell-centered finite volume method using a high resolution scheme in space (Hou et al. 2012, 2013) and an explicit forward Euler method in time. An overview of the software architecture and model concepts can be found in Busse et al. (2012) and Simons et al. (2012, 2014).

2.2 *Study site and Computational Domain*

Icò-Mandantes bay is located in the Itaparica reservoir, in the semi-arid State of Pernambuco. The area is crossed by the São Francisco river, the longest of Brazil, about 2,914 km, damed up by the Louis Gonzaga dam, built around the 80s. The Itaparica reservoir is a large basin of about 828 km^2. It has a regulated mean outflow of 2,060 m^3/s and a mean water elevation of 302.8 m (source of the hydrological data: CHESF, Companhia Hidro Elétrica do São Francisco). For sake of simplicity the Icò-Mandantes bay will be further referred to as "the bay" and the São Francisco river as "the main stream".

Wind data from May 2002 until May 2013 were provided by a weather station in the city of Floresta, with an approximate distance of 30 km to the study site. The source was a database (SINDA, Sistema

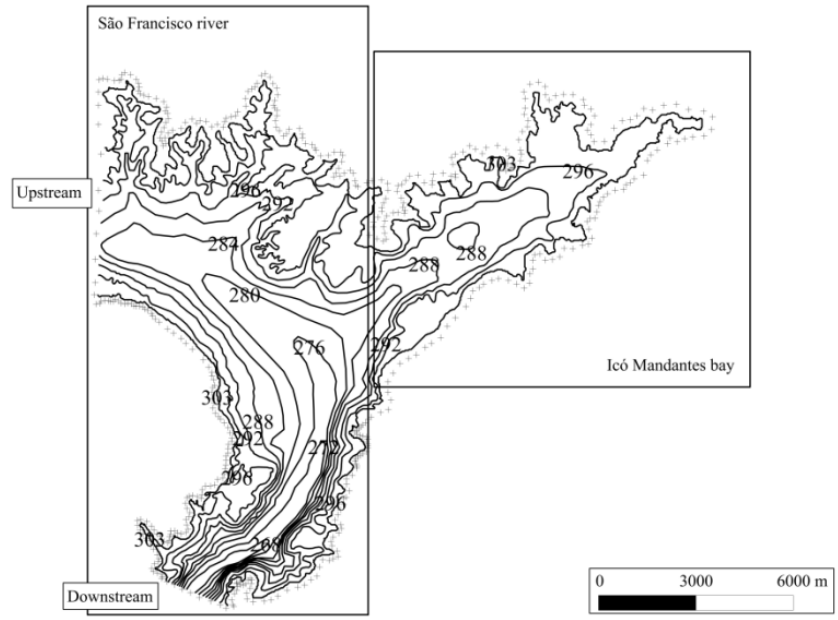

Figure 1. Computational domain of Icò Mandantes bay, Itaparica reservoir.

Integrados de Dados Ambientais), an integrated system of environmental data, available by the Brazilian Ministry of Science and Technology. A mean wind velocity of 5.5 m/s and a maximal wind velocity of 20 m/s were determined through statistical evaluation of the data. On the Beaufort scale the mean wind velocity corresponds to a gentle breeze and the maximal wind velocity is listed as a gale.

The computational domain of the study area is the same as in (Özgen et al., 2013) and is illustrated in Figure 1. For the boundary of the numerical domain, the 305 m isoline was chosen because the operation level of the reservoir changes between 299 m and 304 m (Gunkel and Sobral 2009). The upstream and the downstream boundary are open. The rectangles show the location of the bay and the main stream in the domain. The bottom elevation was interpolated between the isolines with an inverse distance weighting method. The domain was discretized with an unstructured mesh of about 40,000 triangular cells. An average element length is 100 m.

3 RESULTS AND DISCUSSION

The simulations were conducted for different flow and wind scenarios. Mean and extreme wind cases were considered both for mean flow and for a moderate flood, with several wind directions, varying from 30° to 315°. The results were observed with the main focus on the velocity for surface flow simulations and on the concentration of the tracer for transport simulations.

A constant mean water elevation of 302.8 m, a zero initial flow velocity and a zero tracer concentration in the whole domain were imposed as initial conditions for every case. The inflow boundary conditions were set depending on the case studied and they are specified in each case. For the outflow a Dirichlet boundary condition with a constant mean water elevation of 302.8 m along the open boundary was imposed for every case. As mentioned above, the bottom friction was computed considering a Strickler coefficient of 50 $m^{1/3}/s$ and this value was never changed during the analyses. The time step is an adaptive time step and the duration of the simulations depends on the case under consideration.

At first, the water flow was simulated without considering the wind influence, in order to compare the further cases with it. This is called the *reference case.* Upstream the boundary condition was imposed variable in time, to reach the steady state faster, with an inflow velocity. The function started from zero, then it increased up to the value that corresponds to the mean flow discharge (2060 m^3/s) within 12 hours and then was kept constant for times higher than 12 hours. The results of the reference case showed that the water inside the bay was almost stagnant, while the mean flow velocity along the main stream was ca. $1.4 \cdot 10^{-2}$ m/s and the maximum ca. $1.5 \cdot 10^{-1}$ m/s.

The cases further investigated considered the wind in several wind directions. In this paper only the wind direction of 140° is presented because it is most frequently occurring in the region.

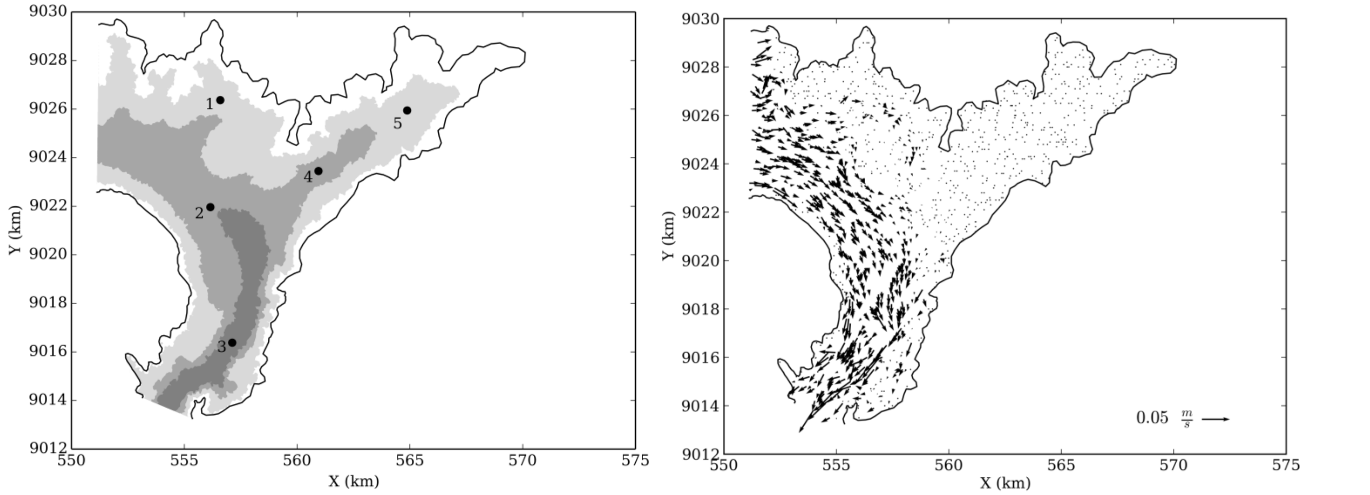

Figure 2. Surface flow simulation for mean flow conditions: control points (left); surface flow simulation without the action of the wind, reference case (*right*).

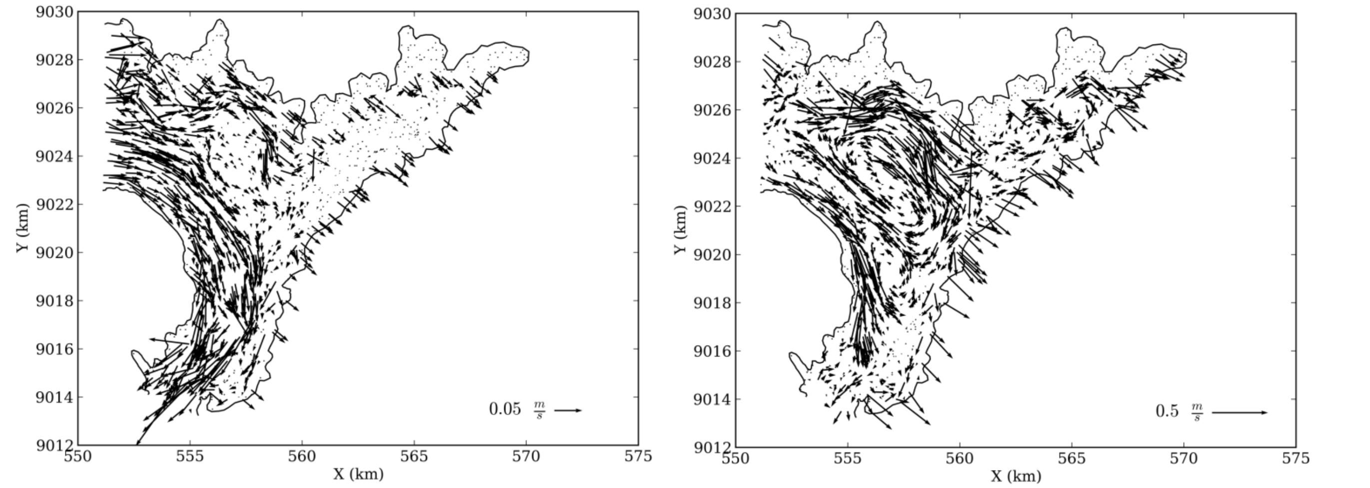

Figure 3. Surface flow simulation for mean flow conditions: flow velocity for mean wind (*left*) and for extreme wind conditions (*right*).

3.1 *Surface Flow*

3.1.1 *Mean and Extreme Wind with Mean Flow Conditions*

The simulations were conducted for mean flow conditions, with a mean discharge of 2060 m^3/s (CHESF, São Francisco's Hydroelectric Company), imposing the same inflow boundary conditions of the *reference case*. The mean wind case is characterized by a value of the wind velocity equal to 5.5 m/s. For the direction of 140° the x- and y- component are respectively -4.2 m/s and 3.5 m/s. The duration of the simulations was 12 hours until steady state conditions were reached. The resulting mean value of the flow velocity was about $1.4 \cdot 10^{-2}$ m/s, approximately equal to the *reference case*. In order to analyze the differences in more detail, values were taken in 5 control points inside the computational domain (1, 2, 3, 4, 5), reported in Figure 2 (*left*): 1 near the inflow boundary, 2 in the middle of the domain along the main stream, 3 in proximity of the outflow boundary, 4 along the interface between the main stream and the bay, 5 inside the bay. The results in the selected points were reported in Table 1. Comparing the flow field with the *reference case* respectively reported in Figure 3 (*left*) and in Figure 2 (*right*), the bay was no longer stagnant, but the velocities increased to the order of 10^{-3} m/s, which is still particularly low. Two main trends are observed: one is the main current, that flows along the main stream with velocities higher than 10^{-2} m/s, where the bottom elevations are lower; the other follows the northern boundary of the domain and enters the bay (order of 10^{-3} m/s). Along the boundaries, where the water depth is lower than 4 m, a high increase of the flow velocities occurred, with a maximum value inside the bay of $1.4 \cdot 10^{-2}$ m/s.

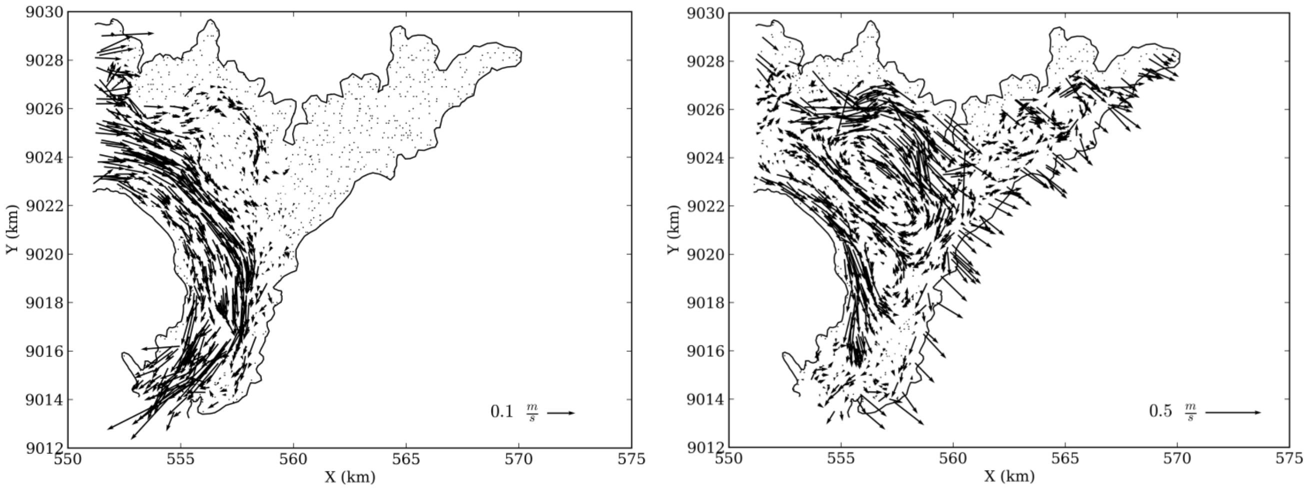

Figure 4. Surface flow simulation for a moderate flood event (Q_{max}=4688m^3s^{-1} at t=18h): flow velocity for the case without wind (*left*) and for extreme wind conditions (*right*).

The extreme case is characterized by a value of the wind velocity equal to 20.0 m/s. For the direction of 140° the x- and y- component are respectively -15.3 m/s and 12.9 m/s. The duration of the simulations was 12 hours until steady state was reached. The resulting mean value of the flow velocity was about $2{\cdot}10^{-2}$ m/s in the whole computational domain, while inside the bay the mean and the maximum values were $7{\cdot}10^{-3}$ m/s and $7{\cdot}10^{-2}$ m/s, respectively. The exact values taken in the control points were reported in Table 1. Observing the flow field in Figure 3 (*right*), the trend is similar to the mean case, but much more intense and characterized by circular currents and horizontal vortexes, both in the main stream and in the bay. A significant increase of the velocities inside the bay occurred, that reached at least 10^{-2} m/s.

3.1.2 *Mean and extreme wind with a moderate flood event*

For the flood case a moderate flood with a return period of 1 year (4688 m^3/s) was considered and set as inflow boundary condition. A curve was created, representing a typical flood hydrograph. The starting point was chosen to the mean value of the discharge: 2060 m^3/s. The peak of 4688 m^3/s is reached after 36 hours and then it decreases in the successive hours. The duration of the simulations was approximately 3 days. With these flow conditions a case without wind and successively the mean and extreme wind were simulated in the area, to analyze the combination between a moderate flood and wind effects. The results were reported in Figure 4, taken in proximity of the flood peak (t = 1.5 days). The exact values of the flow velocities taken in the control points were reported in Table 1.

The trends in the water field were similar to the mean flow condition, but more intense. The flood without the influence of the wind was reported in Figure 4 (*left*). The results showed that the velocity along the main stream increased, while the bay was almost not affected by the flood. When the wind was taken into account, the mean wind case showed an intense water flow along the river and the extreme wind case presented more circular currents and vortexes. The mean value of the flow velocity of the flood case without the wind was about $3.2{\cdot}10^{-2}$ m/s, for the mean wind $3.8{\cdot}10^{-2}$ m/s and for the extreme wind $1.1{\cdot}10^{-1}$ m/s. It was observable that the mean value changed by about $6{\cdot}10^{-3}$ m/s when a gentle breeze is simulated. If a gale (extreme wind) occurred, the mean velocity reached 10^{-1} m/s.

Table 1. Results at t = 12 h for flow velocities in m/s at the control points 1–5

Flow conditions	mean flow			moderate flood		
v_W [m/s]	0	5.5	20.0	0	5.5	20.0
Point 1	0.005	0.023	0.242	0.019	0.030	0.243
Point 2	0.016	0.048	0.200	0.104	0.095	0.162
Point 3	0.036	0.082	0.017	0.150	0.148	0.082
Point 4	0.001	0.004	0.032	0.002	0.005	0.033
Point 5	0.000	0.002	0.040	0.000	0.001	0.040

3.2 *Mean and Extreme Wind for Tracer Transport*

A tracer with a concentration of 1 [-] was injected in order to simulate the spreading of a contaminant in the study area and the exchange of water and matter between the main stream and the bay. Previous research, which had the aim to analyze the same concept without considering the action of the wind, stated that the tracer did not enter the bay for both mean flow conditions and the flood event (Özgen et al., 2013).

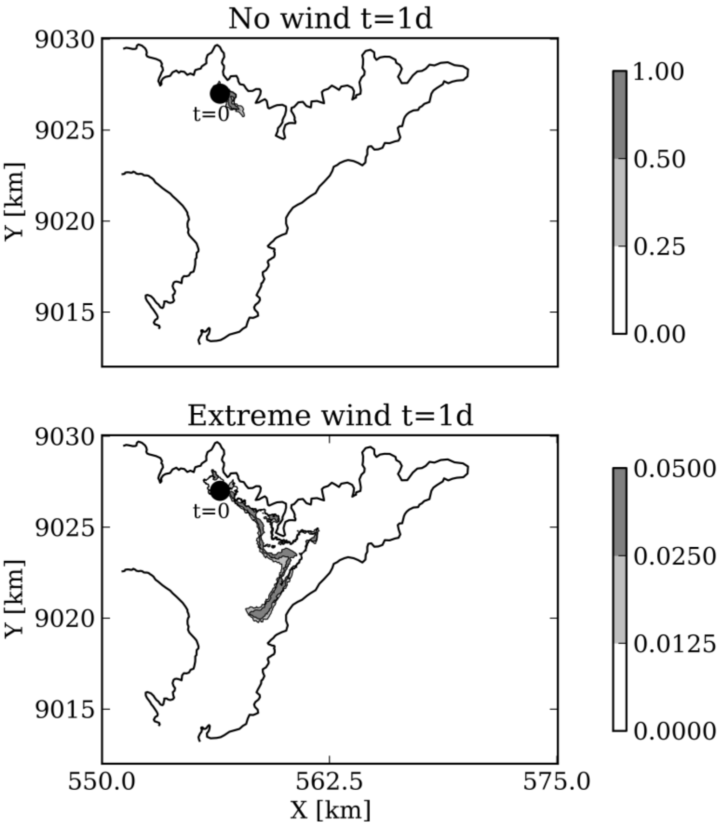

Figure 5. Transport simulation for mean flow conditions: concentration of the tracer for the case without wind (*up*) and for extreme wind conditions (*down*).

The same boundary conditions of the *reference case*, the mean and the extreme wind cases were set: upstream zero concentration and downstream zero gradient of concentration. Simulations with a turbulent diffusion of 10^{-3} m^2/s and 10^{-5} m^2/s showed that it had an impact on the results. No data about its value were available, so it was set to 10^{-3} m^2/s. The tracer was injected in two different points: along the upstream boundary and along the northern boundary.

The first injection point (x = 552.31 km; y = 9024.02 km) was the same used in (Özgen et al., 2013), without taking the wind into account. In this work the action of the wind was simulated in the same case and the results showed no interaction between the main stream and the bay. It could be stated that, when a loss of a pollutant occurs near the upstream boundary, it probably will not cause big issues to the bay.

Successively the tracer was injected along the northern boundary (x = 556.477 km; y = 9026.99 km), inside the current that was possible to observe when surface flow was simulated (Figure 3). The duration was set to around 9 days, because the spreading of a contaminant is a slow process in a big reservoir, where the flow velocities are low. First the case without taking the wind into account was simulated. The results were shown in Figure 5 (*up*). The tracer entered the bay after ca. 6 days with concentration of ca. 4 % of the initial value. After 8 days the concentration reached the value of 8 % and then started to decrease slowly. The spreading of the substance remained limited on the interface between the bay and the main stream. This simulation served as comparison for the cases which considered the influence of the wind. For the mean wind case the tracer entered the bay after 3.5 days with a maximum concentration of ca. 1.6 % of the initial one, affecting just the boundary between the river and the bay. There it reached a maximum of 8 % after 4 days and since then it started to decrease slowly. After 6 days the concentration was still around 4 % and after 9 days around 3.0 %. The concentrations remained low and the spreading did not affect the entire length of the bay, but just the southern-western part of it. For the extreme wind case the process was faster. The tracer entered the bay after ca. 12 hours with concentrations lower than

1 % of the initial value (ca. 0.6 %), then reached a maximum of 10 % after 1 day and then started to decrease. After ca. 1.5 days the tracer spread widely inside the bay with concentrations between 2.0 and 4.0 %. It can be seen in Figure 5 (*down*) that it was also transported in percentages lower than 1 % inside the circular currents of the main stream. Since then, the concentrations inside the bay decreased quickly. The spreading affected the whole bay, but after less than 2 days the concentrations were already much lower than 1 %.

4 CONCLUSIONS AND OUTLOOK

Wind shear stress induced flow and transport processes in Icó-Mandantes bay were simulated with the shallow water flow and transport model HMS.

When wind effects were not taken into account, the water in the bay was stagnant and along the main stream the velocities assumed the order of cm/s. The influence of the wind affected the velocities and the currents inside the bay, with an increase of about 1 order of magnitude for the mean wind and of about 2 - 3 orders of magnitude for the extreme wind. A moderate flood seemed to not relevantly affect the interaction between the main stream and the bay and the velocities in the study site, compared to the effect of the wind, also because the value of 4688 m^3/s is moderate for a big reservoir as the Itaparica. The spreading of a substance in the area was simulated injecting a tracer in two different points and observing the results in terms of concentration and width of spreading. Only when the injection point was chosen along the northern boundary, directly inside the distinct flow that enters the bay, the interaction occurred, with different timing and intensities, depending on the case under consideration. It was observed that turbulent diffusion had an impact on the results. No certain information about its value were available, therefore other diffusion coefficients (e.g. 10^{-4}) could be further investigated.

The eventual uncertainty of this work is due to the lack of data. The wind data were available just from one station (Floresta, ca. 30 km from the bay) and only for the last 12 years. Despite that, the results could help the other sub-project partners of the INNOVATE, the stakeholders (as CHESF, Hydroelectric Company of São Francisco), the Brazilian partners and others to better understand the behaviour of Icó- Mandantes bay and the interaction with the main stream. In future work a 3D model of the Icò-Mandantes bay and a water quality model will be set up. Further, climate and land use change as well as stakeholder-defined scenarios will be investigated.

NOTATION

$\boldsymbol{q}$	storage vector
$\boldsymbol{f}$	flux vector
$\boldsymbol{s}$	source vector
$\boldsymbol{v}$	velocity vector
u, v	x- and y- components of the velocity [m/s]
v_w	intensity of the velocity of the wind, at 10 m above the surface level [m/s]
ν_t	turbulent viscosity [m^2/s]
τ_B	bottom shear stress [N/m^2]
r	mass sink/source term [m/s]
r_t	tracer mass sink/source term [m/s]
z_B	bottom elevation [m]
ρ	fluid density [kg/m^3]
ρ_a	air density [kg/m^3]
C_D	wind coefficient [-]
D	diffusion coefficient [m^2/s]
c	concentration [-]
h	water depth [m]

ACKNOWLEDGMENT

This work was financially supported by the Federal Ministry of Education and Research (BMBF) in the framework of the INNOVATE project. We specially thank Dr. G. Gunkel and F. Selge (Technische Universität Berlin), Dr. H. Koch and Dr. F. Hattermann (Potsdam-Institut für Klimafolgenforschung) for the fruitful collaboration.

REFERENCES

Busse, T., Simons, F., Mieth, S., Hinkelmann, R., Molkenthin, F. (2012). HMS: a generalized software design to enhance the modelling of geospatial referenced flow and transport phenomena. Understanding Changing Climate and Environment and Finding Solutions, Proceedings of the 10th International Conference on Hydroinformatics – HIC 2012, Hamburg, Hinkelmann, R., Nasermoaddeli, M.H., Liong, S.Y., Savic, D., Fröhle, P., Daemrich, K.F. Editors.

Gunkel, G., Sobral, M. (2009). Management of river basins under water stress – exchange of experiences from Brazil and Germany. Proceedings of the SLB/DAAD Workshop "German-Brazilian Limnology", Macaé.

Gunkel, G., Sobral, M. (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.

Hou, J., Liang, Q., Simons, F., Hinkelmann, R. (2013). A 2D well-balanced shallow flow model for unstructured grids with novel source term treatment. Adv. Water Resour., Vol. 52, pp. 107-131.

Simons, F., Busse, T., Hou, J., Özgen, I., Hinkelmann, R. (2014). A model for overland flow and associated processes within the Hydroinformatics Modelling System. J. Hydroinform., Vol. 16, No. 2, pp. 375-391.

Simons, F., Busse, T., Hou, J., Özgen, I., Hinkelmann, R. (2012). HMS: Model concepts and numerical methods around shallow water flow within an extendable modeling framework. Understanding Changing Climate and Environment and Finding Solutions, Proceedings of the 10th International Conference on Hydroinformatics – HIC 2012, Hamburg, Hinkelmann, R., Nasermoaddeli, M.H., Liong, S.Y., Savic, D., Fröhle, P., Daemrich, K.F. Editors.

Tsanis, I.K. (1989). Simulation of wind-induced water currents. J. Hydraul. Eng., Vol. 115, pp. 1113-1134.

Özgen, I., Seeman, S., Candeias, A. L., Koch, H., Simons, F., 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.