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Simulation of Flow and Transport Processes in a Brazilian Reservoir

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ABSTRACT: This work presents various simulations of flow and transport processes for the Itaparica Reservoir in northeast of Brazil. Flow conditions and spreading of tracer were simulated for mean flow conditions as well as for a drought and a flood case using the TELEMAC-2D model. The simulations indicate that the stream in the main river dominates the flow field for mean flow as well as for the drought, while in the bays the water is almost stagnant and a tracer injected at the inflow boundary is mainly transported downstream without entering the bays. For the flood case, the flow velocities considerably increased in the whole reservoir. Therefore, a tracer injected at the inflow boundary enters parts of bays. It was found out that in the flood case the friction coefficient is very sensitive.

Keywords: Numerical modeling, Parameter study, TELEMAC

1 INTRODUCTION

The Luiz Gonzaga Dam dam in northeast Brazil was built between 1979 and 1988 to generate renewable energy and to provide water to the drier region in the north (Horgan 1999). In addition to the environmental impact through this dam, the soil and water quality became worse and algae blooms occurred (Gunkel and Sobral, 2013). Focusing on the Itaparica Reservoir, the objective of the INNOVATE project is to achieve a sustainable watershed management. Previous hydraulic studies which helped to get a better understanding of the present hydraulic conditions were mainly concerned with the Icó Mandantes bay which is located in the middle part of the Itaparica Reservoir. Özgen et al. (2013) investigated flow and transport processes in this bay for mean discharge and for a moderate flooding event. The simulations showed no significant exchange of matter between the main stream and the Icó Mandantes bay for both cases. Moreover, Özgen et al. (2013) observed that the water inside the bay is almost stagnant. During the regarded flood event the flow velocities inside the Icó Mandantes bay increased but remained small compared to the main stream. While Özgen et al. (2013) neglected the interaction of wind, Matta (2013) introduced wind-induced flow for the same domain. As a result the flow velocities inside the bay increased significantly. For the transport simulations, mean wind conditions as well as extreme wind conditions were considered. A tracer was injected upstream and along the northern boundary. Under mean wind conditions the tracer did not enter the bay, whereas for extreme wind the concentrations were much higher. For both study researches the Hydroinformatics Modelling System (HMS), an object-oriented framework, developed at the Chair of Water Resources Management and Modeling of Hydrosystems (Technische Universität Berlin) was used.

In this contribution flow and transport processes of the whole reservoir are investigated, applying the modeling system TELEMAC-2D. The investigations should help to get a deeper understanding of the relevant parameters and processes of the Itaparica Reservoir as a base for further studies which address water quality and adaptation measures (Broecker 2014).

2 METHODS AND MATERIAL

2.1 *TELEMAC*

The modeling system TELEMAC-2D has been chosen for the simulations. Applying the Finite Element Method, TELEMAC-2D solves the two-dimensional Saint-Venant equations for open channel flow. The computed variables are the water depth, the velocity and the tracer concentrations which are averaged over the vertical (Hervouet 2007). Amongst others, the system provides several stabilization methods and solvers as well as various laws of friction. As stabilization method the narrow (N) distributive scheme was used for the velocity, the Positive Streamline Invariant (PSI) distributive scheme for the advection and the method of characteristics for the transport. Since the generalized wave equation has been applied, the conjugate gradient method was chosen as solver in this research (Hinkelmann 2005). TELEMAC-2D has been used for several studies in the research group at TU Berlin concerning fluvial and estuarine hydraulics (e.g. Jourieh et al. 2009, Mahgoub et al. 2012 and Hinkelmann 2005).

2.2 *Study site*

The considered area of this work is the Itaparica Reservoir which is part of the river São Francisco having a length of 2914 km. The river flows from its source mainly into northern direction along the border of the states Bahia and Pernambuco. The Itaparica Reservoir, which has a surface area of about 828 km², is limited by the Luiz Gonzaga Dam. The mean flow is regulated to 2060 m³/s (Operador Nacional do Sistema Elétrico 2012). The width of the reservoir varies between 1400 and 7000 m and the length amounts approximately 140 km. The bottom topography was determined through 93 elevation measurements in the reservoir which were reported by Cirilo (1991). Due to the lack of further measurements, suitable idealized channel cross-sections were assumed at the measurement points in form of parables. The bathymetry was generated by interpolating with an inverse distance weighting method between these parables. The result is shown in Figure 1. The maximum water depth is 42.8 m. The generated mesh is unstructured and consists of 30986 triangular elements with element lengths between 8 m and 632 m (Storck 2013). The mean water elevation in the reservoir is 302.8 m (Operador Nacional do Sistema Elétrico 2012).

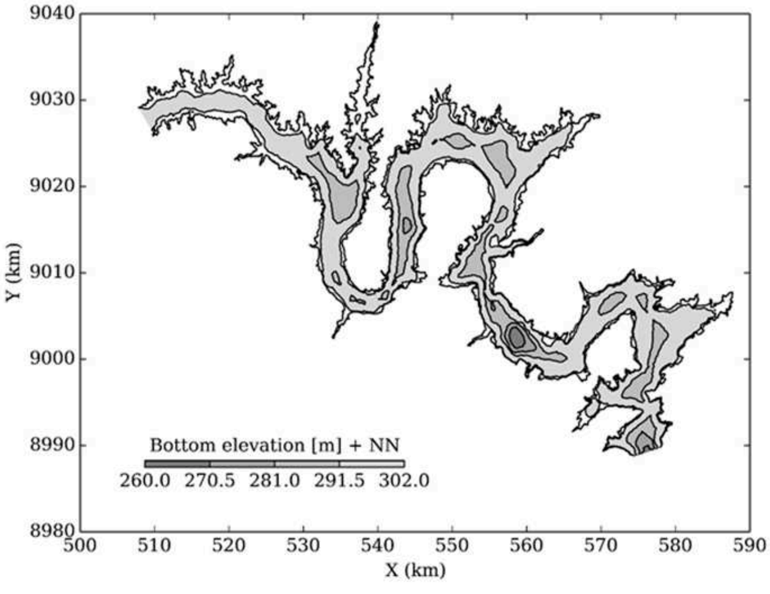

Figure 1. Bottom elevation

3 RESULTS

3.1 *Mean flow conditions and tracer transport*

For the first simulation the mean water elevation of 302.8 m is imposed as downstream Dirichlet boundary condition. A constant water elevation of 302.8 m is initially defined for the whole reservoir.

The regulated mean discharge of the Itaparica Reservoir of 2060 m³/s is set as upstream boundary condition. To avoid oscillations, the discharge is linearly increased from 0 m³/s within a day. The Strickler roughness coefficient is set to 50 m1/3/s. The time step size was 30 s. Under these conditions a steady state is reached after approximately 4 days. The simulation shows that the stream in the main river dominates, whereas the flow velocities in the bays are very small. Figure 2 indicates that big velocities occur especially in the entrance area of the considered domain, where the water depth is very low and where the river is narrow. The maximum velocity is around 0.592 m/s.

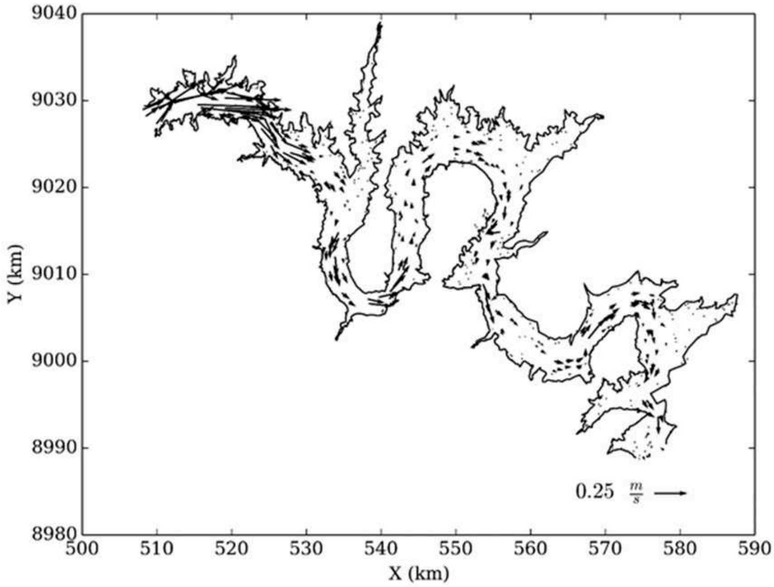

Figure 2. Velocity field under mean flow conditions

After steady state is reached, a tracer concentration of 100 % is injected at the upstream boundary for two different cases:

1. The tracer is continuously injected for 50 days.
2. The tracer is injected for one day and the transport is simulated for further 50 days.

The diffusion coefficient is set to 0.001 m²/s. The spreading of the tracer was observed at five cross-sections as presented in Figure 3. Moreover, results were observed in control points of four large bays.

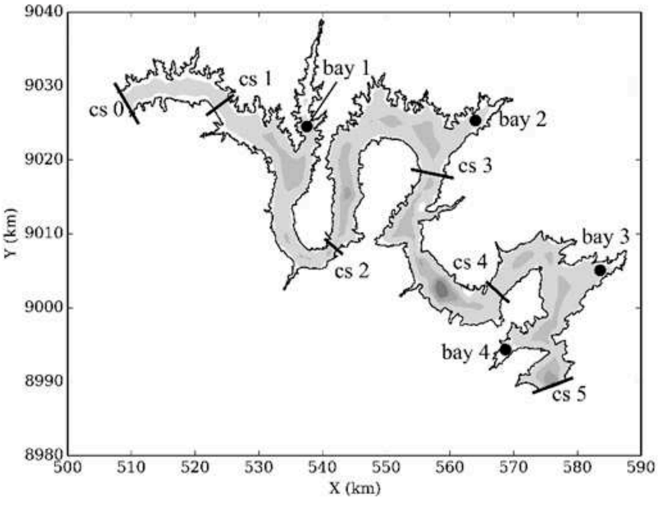

Figure 3. Control points and cross-sections

Figure 4 shows the results after 50 days for the continuous injection. The spreading of the tracer mainly occurs in the main stream. Almost no exchange of tracer in the four bays was observed. Table 1 shows the maximum tracer concentrations for the control points in the bays.

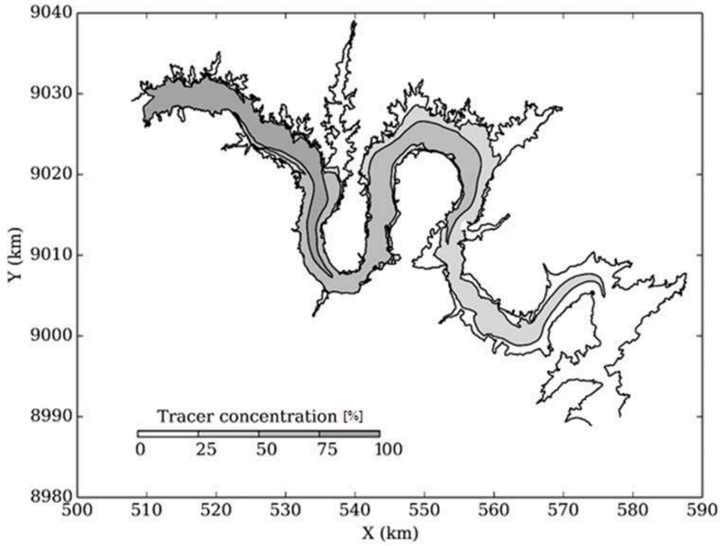

Figure 4. Tracer distribution in the reservoir after 50 days

Table 1. Tracer concentrations in the bays for mean flow conditions

Maximum concentration at control points [%]			
bay 1	bay 2	bay 3	bay 4
2.70E-9	3.44E-14	2.80E-05	1.32E-05

Figure 5 shows the breakthrough curves of the tracer concentrations at the cross-sections. At cross-section 0 the tracer was injected. The tracer concentration amounts up to 100 %. Cross-section 1 shows a big gradient at the beginning. After 10 days the gradient becomes much lower and the concentration remains at around 80 %. The tracer reaches cross-section 2 after 3 days. The gradient is also big at the beginning and becomes flatter after a while. The tracer had to pass from cross-section 1 to cross-section 2 through deep and wide bathymetry (for instance around the first bay) which increased the spreading. Therefore the maximum concentration is only around 57 %. The last cross-section shows a tracer concentration of less than 10 % after 50 days. It took almost 20 days till the tracer reached this cross-section and at that time the tracer considerably diffused into the surrounding water.

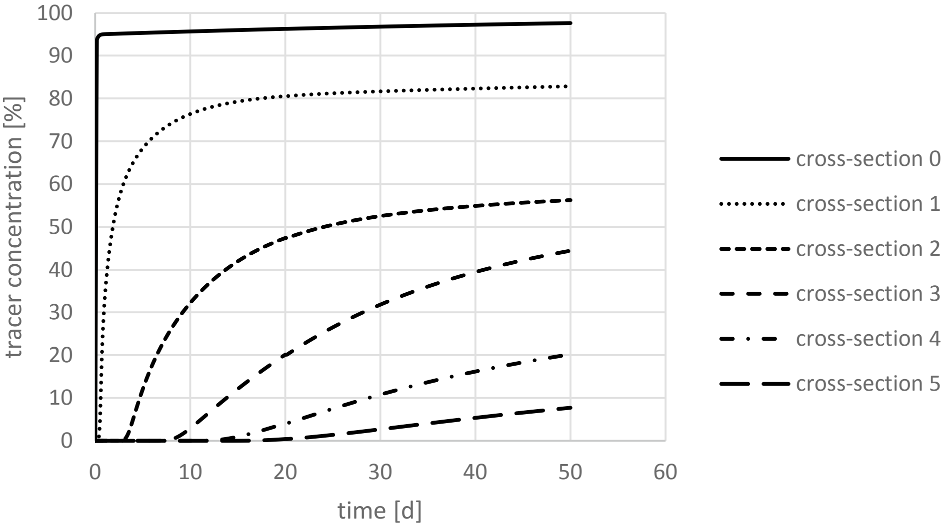

Figure 5. Breakthrough curves for a continous tracer injection under mean flow conditions

As a second case the tracer is injected only for one day at the upstream boundary. Figure 6 shows the breakthrough curves of four cross-sections. Cross-section 1 reaches a maximum concentration of 41.6 % after 1.3 days. It takes 10 days until the concentration in this cross-section is lower than 1%.
Cross-section 2 indicates a maximum concentration of 6.7 % and it takes 18 days until the concentration is less than 1%. For the following cross-sections the peaks of the tracer decrease significantly and therefore all concentrations are very low.

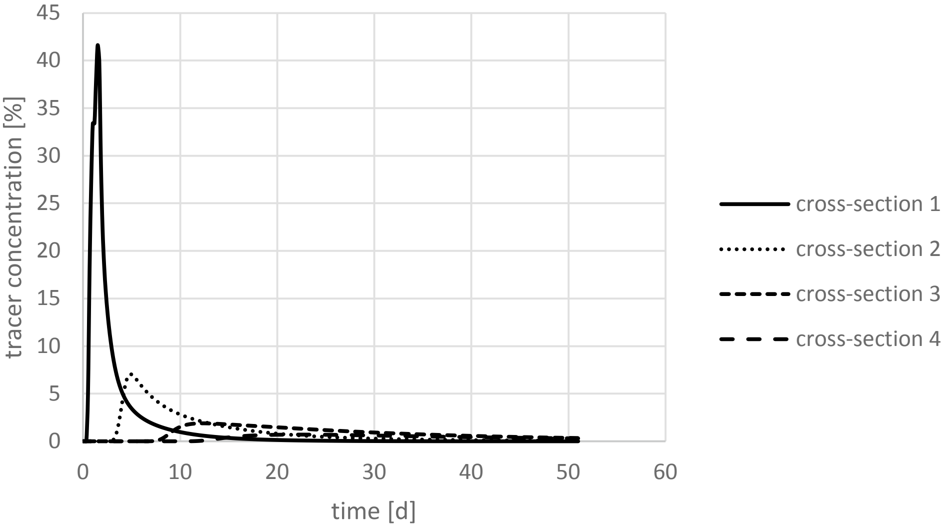

Figure 6. Breakthrough curves for a one day tracer injection under mean flow conditions

3.2 *Drought*

Statistical analysis of field measurement data concluded that a drought with a statistical recurrence of ten years corresponds to a minimum discharge of 442 m³/s. To simulate a realistic case which approximately reflects this event, daily measured discharges from 14th May, 2008 to 30th November, 2008 with a minimum discharge of 436 m³/s are investigated. The measured discharges (see Figure 7a) of this period are chosen as inflow boundary condition. The simulation starts with mean flow conditions. As downstream boundary condition the mean water elevation of 302.8 m is chosen. The same Strickler roughness coefficient as in the previous simulations is imposed. A maximum decrease of the water level is calculated at the inflow with a magnitude of 0.246 m. Figure 7b shows the velocity field after 180 days. The maximum velocity is 0.136 m/s at this time. The velocities in the bays are not affected by the drought.

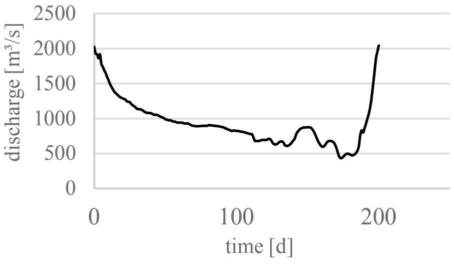

Figure 7a. Inflow boundary condition for a drought with a minimum discharge of 436 m³/s

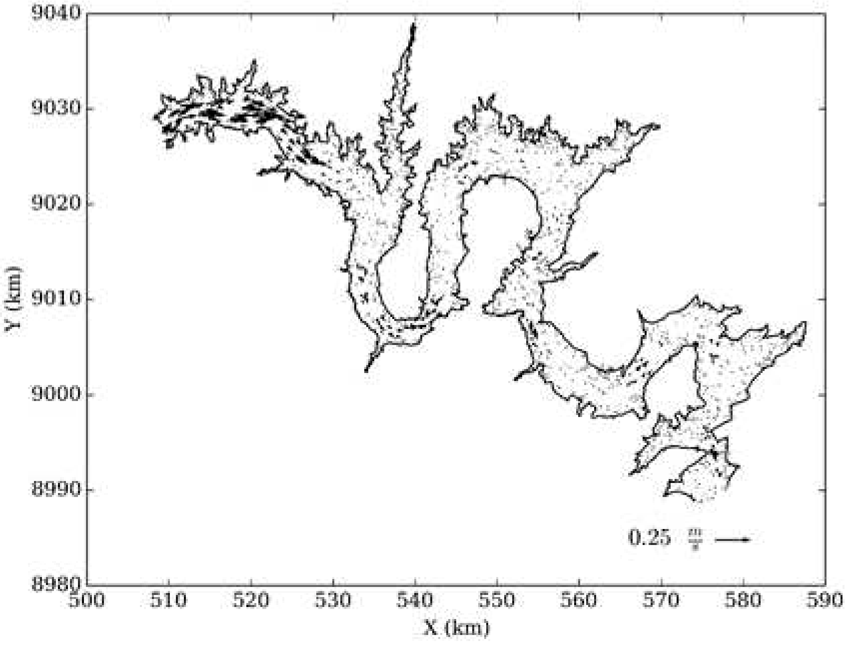

Figure 7b. Velocity field drought after 180 days

3.3 *Flood event and tracer transport*

A flood event with a maximum discharge of 12194 m³/s was measured between 11th January, 2004 and 24th May, 2004. This event approximately corresponds to a flood with a statistical recurrence of 10 years and is used in the following.

Figure 8a shows the daily measured discharges which were imposed as upstream boundary condition. The simulation starts under mean flow conditions with a discharge of 2060 m³/s. For the boundary condition downstream, the water elevation of 302.8 m is set again. The friction coefficient is varied between 10 $m^{1/3}/s$ and 75 $m^{1/3}/s$. The velocity and water depth are investigated. A maximum velocity of 0.587 m/s and an average velocity of 0.432 m/s is calculated for a roughness coefficient of 10 $m^{1/3}/s$. The velocity with a friction coefficient of 75 $m^{1/3}/s$ amounts 1.793 m/s in maximum and 1.238 m/s in average. Figure 8b shows the water elevation for various Strickler roughness coefficients for a control point situated near cross-section 1. For a roughness coefficient of 10 $m^{1/3}/s$ the maximum water elevation is 310.54 m. Compared to a roughness coefficient of 75 $m^{1/3}/s$ the maximum difference amounts 6.02 m. Consequently the bottom roughness coefficient has considerable influence on the flow in the main stream for flood events.

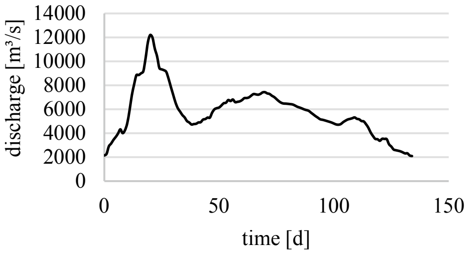

Figure 8.a. Inflow boundary condition for a flood event with a maximum discharge of 12194 m³/s

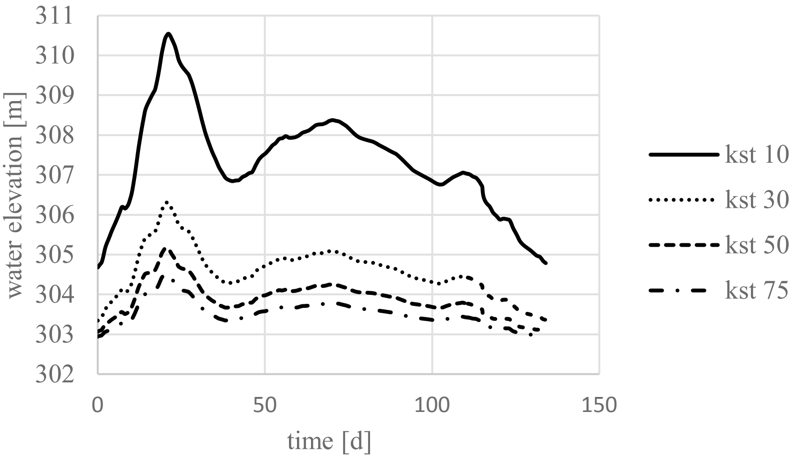

Figure 8b. Water elevation for different Strickler roughness coefficients

A tracer concentration of 100 % is injected at the inflow boundary. The Strickler roughness coefficient is 50 $m^{1/3}/s$ and the diffusion coefficient is 0.001 m²/s. The concentrations of the cross-sections are illustrated in Figure 9. Compared to mean flow the advective spreading is much faster and diffusion is of minor importance. The concentrations of the cross-sections are higher compared to Figure 5 (under mean flow conditions). Through the bigger discharge more tracer mass enters the reservoir.

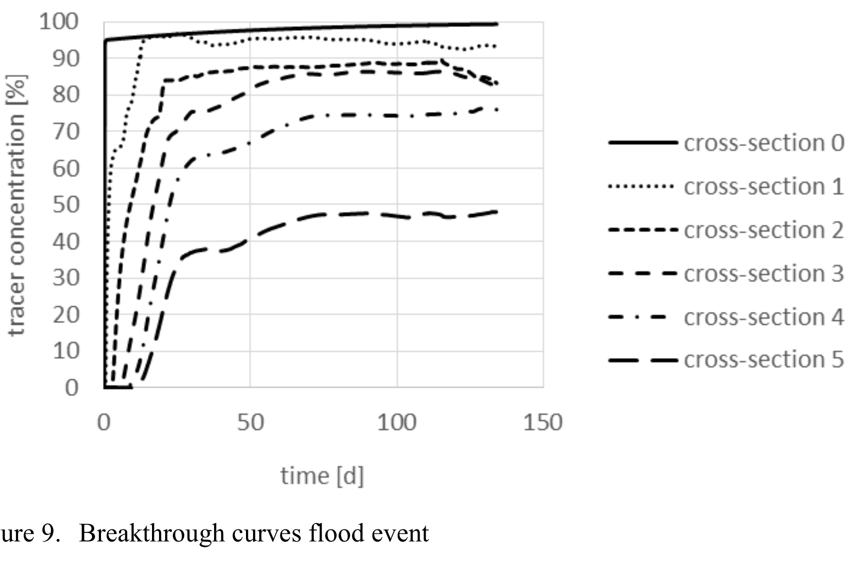

Figure 9. Breakthrough curves flood event

Table 2 shows the tracer concentrations at the control points in the bays. Compared to Table 1 (tracer injection under mean flow conditions) the concentrations in the bays are considerably higher. The water level as well as the velocities increase.

Table 2. Tracer concentrations in the bays during a flood event

Maximum concentration at control points [%]			
bay 1	bay 2	bay 3	bay 4
14.9481	0.0417	1.0748	0.2698

4 DISCUSSION

A Strickler roughness coefficient of 50 m1/3/s was chosen for mean flow conditions and the droughts. This value is very sensitive for the flood case (see sec 3.3), however it is less sensitive for the lower flow conditions and the drought. Due to much vegetation in various parts of the reservoir, the friction coefficient is probably smaller than 50 m1/3/s and field measurements are desirable.

Matta (2013) has shown that mean as well as extreme wind have considerable influence on the hydrodynamics in Icó Mandantes bay. Therefore, wind should also be taken into account for the reservoir in future simulations.

The lateral (impermeable) boundaries of the domain were determined from the zero water level line for mean discharge. A further lateral spreading of the water will occur in the flood case if the domain is extended. However, this effect is small for the considered case here.

The discharge boundary conditions can be changed in such a way that it is imposed through sink terms at the outflow boundary which represent the conditions in a more realistic way at the dam.

Finally, tracer measurements are desirable to determine the diffusion coefficient.

5 CONCLUSIONS AND OUTLOOK

For mean flow and the drought the mean stream and the bays show very different flow conditions: clear flow in the main stream and almost stagnant water in the bays, a tracer injected at the inflow boundary did not enter the bay and is mainly transported downstream. In the flood case the velocities are considerably increased in the main stream as well as in the bays. Therefore, a tracer injected at the inflow boundary also reaches parts of bays. It was found out that the friction coefficient is very sensitive in the flood case.

In future work, a 3D model of Icó Mandantes bay and a water quality model will be set up. Further, climate and landuse change as well as stakeholder-defined scenarios will be investigated.

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