MODELLING AND VALIDATION OF THE SANTA CATARINA ISLAND BAYS HYDRODYNAMICS BASED ON ASTRONOMIC TIDES AND MEASURED TIDES

LUIS H P GARBOSSA (1), ARGEU VANZ (1), LUIS FERNANDES (2), ROBSON VENTURA DE SOUZA (1), LUIZ FERNANDO VIANNA (1), GUILHERME RUPP (1)
(1): EPAGRI, Santa Catarina Agricultural Research and Extension Corporation, Rod. Admar Gonzaga, 1347 - Itacorubi, Florianópolis, SC, 88034-901, Brazil
(2): Action Modulers, *Rua Cidade de Frehel, Bloco B, nº 12 A, 2640 – 469 Mafra, Portugal*

Santa Catarina Island bays (SCI bays) have a great economic and social importance in the region. With more than 700,000 habitants in its surroundings, besides touristic and fishery activities, it represents approximately 70% of the Brazilian bivalve shellfish production. In order to understand processes controlling the water quality and food availability, relevant for the shellfish production, it is unquestionably important to understand the main hydrodynamics patterns of SCI Bays. Thus, the first step was to characterize the hydrodynamics of the SCI bays via observations and using the numerical model MOHID. An acoustic Doppler current profiler (ADCP) was deployed in two different locations, during a period of one lunar cycle each, in order to obtain a time series of water level, currents velocity and direction, which were then used to validate the model. The model was forced with astronomical tides and measured tides to evaluate the meteorological tide influence. Results from the model using both, measured tides and astronomical tides, show index of agreement for water elevation of 0.98 and 0.88 for the month of May and 0.96 and 0.73 for the month of July, respectively. The best results for the relative mean absolute error and the index of agreement for velocity V were from the simulation forced with measured tides, in July, with results of 0.07 and 0.80, respectively. Based on the results, the hydrodynamic model forced with measured tide will be used to drive the water quality model for bacteriological dispersion and decay.

INTRODUCTION

The cultivation of shellfish in Brazil is concentrated in the southern coast, especially in the state of Santa Catarina where 98.45% of the national production is generated (MPA [8]). In this state 23,495 tons of mollusks were produced in 2012 (EPAGRI [2]), with, approximately, 73% of this amount cultivated in the limits of the Santa Catarina Island (SCI) Bays. These two bays, located between the mainland and the SCI, have great importance for aquaculture production in Brazil and are also used for tourism (bathing and navigation) and fishing. In the central area of the island, there is a strait, where the downtown of the Florianópolis city is located. The surrounding area is the largest population cluster in the state of Santa Catarina where more than 700,000 people live.

Data from the Brazilian Federal Government indicate that only 21% of the population from the state of Santa Catarina lives in areas covered by sewage collection and treatment systems (SNSA [11]). This scenario is quite worrying from the point of view of public health when one considers that the Santa Catarina Island Bays compose the most important Brazilian production center of marine mollusks, filter feeding organisms capable of bioaccumulate existing pathogens in the water they are grown in. Thus information on the hydrodynamics are mandatory for public health control measures, especially those addressing the dispersion of pollution into these bays and the influence of city sewage on the bay area. Preliminary hydrodynamic studies on the SCI Bays are available (Melo *et al.* [6] and Carvalho *et al.* [1]).

Hydrodynamic numerical models offer wide scope of uses in environmental and water management projects and can provide valuable and extensive information for scientists and engineers. Hydrodynamic modeling have been used as a tool for evaluation of dispersion of contaminants of faecal origin with public health purposes, especially for determination of condition of bathing waters. However, it is important to consider the limitations of these numerical models and carefully evaluate the accuracy of the results obtained (Harris *et al*. [4]).

Our research group intend to model the dispersion of contaminants of faecal origin in the SCI Bays and use the model outputs as a risk assessment tool for decision making in the Brazilian shellfish sanitation program. This paper describes the first step of this work, which is to model the hydrodynamics of the SCI Bay using different tide data sources and to evaluate the models performances with measured tides and astronomical tides.

METHODS

The study consisted of implementing a hydrodynamic model with two simulations for the SCI Bays, one was forced with astronomic tides (FAT) and the other was forced with measured tides (FMT). The simulations were run for two periods of 30 days and the outputs (currents direction, speed and water level) were compared with the hydrodynamic data collected in field. Based on the results of these comparisons, the meteorological tide influence in the results was evaluated and the most indicated tide data series to be adopted was determined.

Study site

The SCI bays (lat. 27° 36'S; long. 48° 34'W – Datum SAD 69) (Figure 1) are two adjacent bodies of water located between the mainland and the SCI, also called South Bay and North Bay. They cover a total area of 340 km^2, 50 km long in Northward direction and 12 km in Eastward direction. Both bays communicate with the Atlantic Ocean: the North Bay through its north extreme and the South Bay through the south extreme. A narrow channel named *Estreito* is located in the central area of the SCI bays and links them. The bays shores are composed of small coves, sand beaches, mangroves and promontories. The average depth inside the SCI bays is 3.4 m, with depths of more than 25 m in the narrowest areas, such as the central channel. The calculated average water volume in the bays is 2.2E10^9 m^3. The SCI bays receive freshwater inputs from more than 49 drainage basins. A study estimated that three of them input 65% of all the fresh water (Garbossa *et al*. [3]). The three most important rivers have together a reference discharge value of, approximately, 22 m^3.s^{-1} during dry weather. The sum of the discharges in the bays varies from a minimum of 10 m^3.s^{-1} in dry periods to a maximum of, approximately, 700 m^3.s^{-1}.

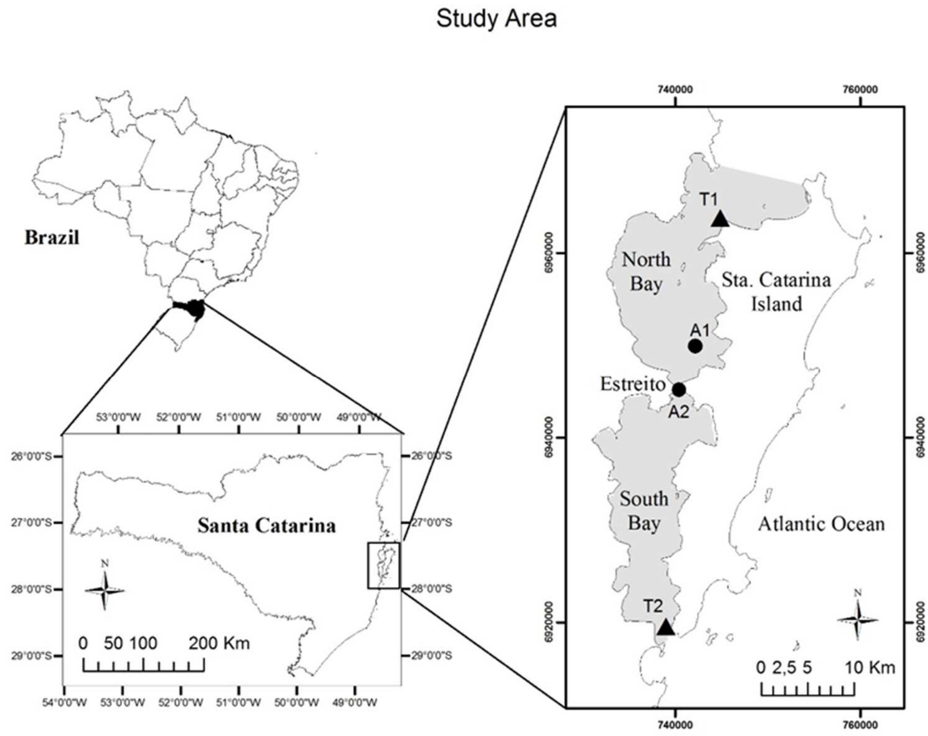

Figure 1. SCI Bays domain of the study with the tide gauges T1 (North gauge) and T2 (South gauge) and ADCP deployment location A1 (May/2013) and A2 (July / 2013)

Model description

The three-dimensional (3D) water modelling system MOHID was developed by Marine and Environmental Technology Research Center / Instituto Superior Técnico, from the Technical University of Lisbon and is based on the Navier-Stokes equations including the Boussinesq and hydrostatic approximations. The basic equations are integrated numerically using the finite volume method taking into account appropriate boundary and initial conditions. Several studies are reported in the last years using the model (Mateus & Neves [5]).

Data collection

For modelling purposes, meteorological, river flow and tide data were generated during different periods and with different frequencies. Bathymetry was based on the existing data for the SCI bays. For validation purposes, current velocity and direction were registered for determined periods. The details are described below:

Meteorological data - collected for a two-year period, from January 2012 to December 2013, from two different weather stations located near the central area of the SCI (Figure 1). The following parameters were collected: wind speed and direction, temperature, solar radiation and precipitation.

River flow - inferred through hydrological calculus, based on four measurements performed during one year in 26 streams and in measurements performed in an hourly basis for the largest river in the region (Garbossa *et al*. [3]).

Tides - obtained during two years from two tide gauges installed in the two extremes of the study area (Figure 1). The north one is a mechanical sensor gauge, buoy and counterweight system inside an equilibrium shaft and the south is a radar level sensor gauge. The north gauge registered instantaneous readings of the sea level while the south gauge registered an average of 30 seconds of the sea level readings. A harmonic analysis was made based on the generated data using the T-Tide tool (Pawlowicz *et al*. [10]), in order to obtain the harmonic constituents for the North and South gauge.

Bathymetry –chart from the Brazilian Navy – Directorate of Hydrography and Navigation, chart numbers 1904 and 1902 from years 1977 and 2003, respectively. Considering the age of the information, four transects off the bays were performed to verify its consistence. The bathymetry for shallow areas seemed to be reliable; however, differences up to 10 meters were found in the narrow communication of south bay with the Atlantic Ocean and in the central channel. Despite the inconsistences, this database was adopted for the model because is the only available dataset.

Current velocities and directions - generated by an Acoustic Doppler Current Profiler (ADCP). The equipment was deployed twice, in different locations (Figure 1). The first deployment (A1) was performed in May of 2013, in the limits of the North Bay, in a 4.07 m depth site with an eastward distance (U direction; shore to shore) of 9,000 m. The second deployment (A2) was performed in July of 2013 in the channel between the North and South Bays, at 11.60 m depth site with an eastward distance of 750 m. In both deployments the ADCP were set to log the currents and tide with a frequency equal to the tide gauges frequency, a 15 minutes interval. The equipment was anchored using a specifically designed bottom bracket. Given to the bracket structure and the blanking distance of the ADCP sensor, data from the first 1 m from the bottom were not registered. The results from the measured currents profiles where vertically integrated in order to compare the results of the measured data with the model depth integrated simulations.

Modelling procedures

The area was discretized with a Cartesian grid, resulting in approximately 55,000 cells with a spatial step of 90 x 90 m. The bathymetry was linearly interpolated for the grid and, as first step, the simulation was setup in a depth integrated model, by defining only one vertical layer. A total of 49 points of fresh water discharge were created. Three time series were provided for each of the three largest rivers, in an hourly basis. A specific constant river discharge was used as input data for the other 46 smaller watersheds. The Table 1 describes the parameters used in the model calculations.

Table 1. Parameters used in the simulations

Physical parameter	Used values
Time step	9 s
Grid	90 m x 90 m
Horizontal cells (i,j)	270 x 600
Open cells / Area	55,268 / 447 km^2
Vertical coordinate	Sigma – 1 layer
River discharges	Measured and estimated
Wind rugosity	2.5 E^{-3}
Bottom rugosity coefficient	2.5 E^{-3}
Open boundary temperature	Measured
Open boundary salinity	36 psu

Both simulations (FAT and FMT) were run specifically for the periods when the ADCP was deployed (May of 2013 and July of 2013). A warm up period of seven days of simulation were adopted prior to the ADCP dataset availability. The tide data was used to force the simulation FMT. The simulation FAT used 20 tidal constituents. The five constituents with more than 4 cm of amplitude were SA, O1, M2, S2 and K2. The other tidal constituents' amplitudes varied from 3.9 cm until 0.79 cm.

Model calibration and validation

For validation purposes, the modelled direction and speed of currents were compared with data obtained in field. For direction of currents, the comparison was performed visually through graphical analysis. To compare the current velocity, the model outputs for speed in U (east-west) and V (north-south) directions were related with the readings from the Acoustic Doppler Current Profiler (ADCP). The following parameters were generated: coefficient of determination (R^2), relative mean absolute error (RMAE) and Index of Agreement (IA) Navas *et al.*, [9]. The parameters were calculated as shown:

$$RMAE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{(Ci-Mi)}{Mi}\right| \tag{1}$$

$$IA = 1 - \frac{\sum_{i=1}^{n}(Mi-Ci)^2}{\sum_{i=1}^{n}(|Ci-\bar{M}|+|Mi-\bar{M}|)^2} \tag{2}$$

Where Ci and Mi are the computed and measured values, respectively, and M is the measured mean value. The best results are when IA is close to 1. The classification of the simulation results for RMAE are presented in Table 2 (Navas *et al.*, [9]).

Table 2. Classifications for RMAE

RMAE value	Classification
Excellent	< 0.20
Good	0.20 – 0.40
Reasonable	0.40 – 0.70
Poor	0.70 – 1.00
Bad	> 1.00

RESULTS AND DISCUSSION

The results from the measured currents profiles where vertically integrated in order to compare the results of the measured data with the model depth integrated

The currents directions were predominantly northward distributed for both A1 and A2 deploys, probably due to the bays morphology. The vectors directions were discretized in 16 cardinal directions of the wind rose (Figure 2). It was possible to observe that almost 100% of the measures in A2 are NNW-SSE direction, while in A1 there is a more distributed pattern. These differences are an effect of the narrow shape of the channel between the North and South Bay. Whenever the measured and computed vectors of direction were within $\pm$ 11.25° of the cardinal direction it was considered as an adequate agreement of the model.

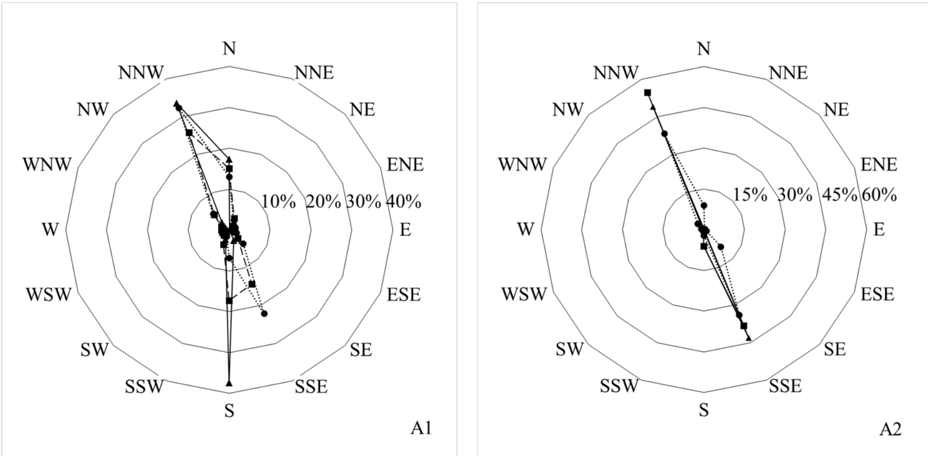

Figure 2. Frequency of occurrence of vectors direction for the ADCP deployments A1 and A2. ADCP measurements are in dotted line, results of simulation FAT are solid lines with triangles and results from simulation FMT are dashed lines with rectangles

The model results seem to be very consistent with the ADCP data, in general, the model can predict the current direction adequately. The simulation FAT presents a direction agreement of 70% in A2 and the simulation FMT an agreement of 80% in A1.

The speed of currents in the V are presented in Figure 3 because they are more significant than U due to the bays morphology. The speed in V direction were higher in the deploy A2 than in A1. The higher speeds in the deploy A2 were expected because of the deployment of the ADCP in a narrow region. The average velocity modulus for speed V was underestimated for A1 in 2.7 cm.s^{-1}, while it was overestimated in 2.6 cm.s^{-1} for A2 with the simulation FMT.

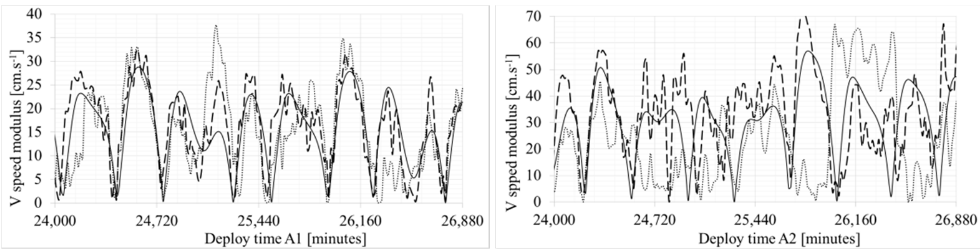

Figure 3. Partial time series for V speed for both deploys A1 and A2. ADCP measurements are in dotted line, simulation FAT are solid lines and simulation FMT are dashed lines

The RMAE results (Table 3) show that the current V velocity was more precise for the FMT simulation than for the FAT. The RMAE for V velocity from FMT simulation was considered excellent (0.07) in the deploy A2 and reasonable (0.57) in A1. The FAT simulation data resulted in poor RMAE results for both deploys (0.76 and 0.96). This tendency was also noted for IA and R^2 results, with results slightly higher for the FMT simulation.

For U velocity there was not a clear pattern of performances between the RMT and FAT simulations. Excellent RMAE results were obtained for both simulations in the deploy A1 and poor results for both simulations in A2. The RMAE was worse for the FMT simulation, the IA somewhat higher for the FAT simulation and R^2 was slightly higher for FAT simulation in the A1 deploy and the inverse occurred in A2.

Table 3. Statistical coefficients results for current velocity

Parameter	Deploy A1 – May / 2013					
	Measured tide			Astronomic tide		
	RMAE	IA	R^2	RMAE	IA	R^2
U velocity	0.17	0.65	0.21	0.04	0.58	0.27
V velocity	0.57	0.78	0.40	0.76	0.75	0.35
	Deploy A2 – July / 2013					
U velocity	2.45	0.76	0.43	1.85	0.71	0.32
V velocity	0.07	0.80	0.41	0.96	0.75	0.31

The water elevation results showed that both simulations are precise when simulating tides (Table 4). In general, the simulation FMT was more precise than the FAT. RMAE values for the FMT simulation water elevation were close to zero and the IA were higher than 0.96. Similar results were obtained for RMAE when using the simulation FAT. However, the IA results for the FAT simulation were not as high as the FMT and the differences are even higher in relation to the R^2.

Table 4. Statistical coefficients results for water level

Parameter	Measured tide			Astronomic tide		
	RMAE	IA	R^2	RMAE	IA	R^2
Deploy A1 – May / 2013	< 0.01	0.98	0.95	< 0.01	0.88	0.67
Deploy A2 – July / 2013	< 0.01	0.96	0.91	< 0.01	0.73	0.42

The consistence of the model for water elevation can be also noted observing the data temporarily distributed (Figure 4). Navas *et al.*, [9] obtained similar results for elevation and considered as good agreement between the predictions of the model and the observations. Menendez *et al.*, [7] simulated the region of Plata River and made a graphical comparison between simulated, and predict elevations and water velocities to assess the model efficiency.

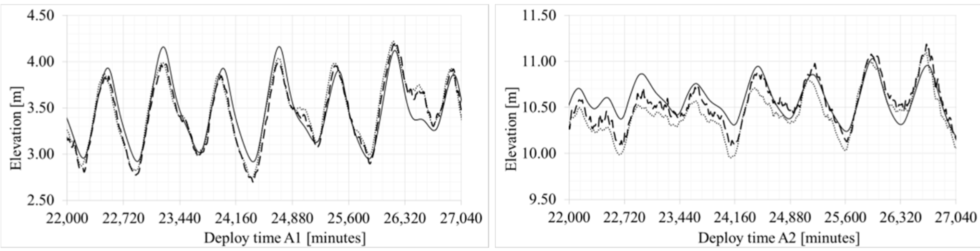

Figure 4. Partial time series for sea elevation for both deploys A1 and A2. ADCP measurements are in dotted line, simulation FAT are solid lines and simulation FMT are dashed lines

Considering the limitations of the Bathymetry, mainly in the two deepest locations, with errors larger than 10 m. Considering that the comparison of the vectors were made for a vertically integrated water column and that the ADCP measurements are punctual and each cell grid represents an area of 8,100 m^2. The results obtained in the effort of modelling the SCI Bays demonstrate adequate representation of the Bays. The simulations FMT, in general, presented a better representation of the bays hydrodynamics because they are under to micro-tidal influence and the wind forcing in the shallow waters are important in the region. Based on the results, simulations FAT can be used, but the degradation of the simulation quality should be considered.

CONCLUSIONS

Both simulation, FAT and FMT, presented adequate results for currents speeds, directions and water elevation. As expected, the FMT model showed a more precise representation of the SCI Bays and is more suitable to be used as reference for environmental studies, when tide datasets are available. Although, based on the results it is possible to identify that, in case the measured values are not available, the astronomic tides can be used with adequate representation of the SCI bays hydrodynamics.

The results of this study show the great potential of the model to be used as a tool for decision support in the SCI Bay region and the problems concerning the water use.

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