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MODELING SEDIMENT TRANSPORT DYNAMICS FOR A SAND MINING AREA IN SANTOS BAY, BRAZIL

Mariana Coppedê Cussioli[1] and Eduardo Yassuda[2]

ABSTRACT

This paper presents the results of a modeling project that evaluates the hydrodynamics and sediment transport impacts of a sand mining area in the Santos Bay, Brazil. For this purpose, we carried out a comprehensive characterization of the study area which included hydrography, circulation, water level, wave climate and local bathymetry evaluation. We used these results to force the hydrodynamic and sediment transport model. We carried out two hydrodynamic and sediment transport scenarios: the 'present condition', which uses the present bathymetry as reference, and a 'future condition', which considers the deepening of 1 m in the sand exploitation area. The model results show that the sediment plumes, in general, remain near the dredged area or spread toward the inner shelf adjacent to the Santos Bay. In the latter case, the plumes present a shoreline parallel to the main direction of the sediment transport, following the local circulation. The results also show that the exploited area present a maximum accretion of 15 $cm \cdot yr^{-1}$ in the sediment deposition rates compared to the 'present scenario' and thereby, the estimated time to recover the previous sediment deposition equilibrium is 7 years.

1. INTRODUCTION

The study area is located in the Santos Bay, southeastern Brazil (Figure 1). The Santos Estuarine System is in the Inner Continental Shelf (ICS), in the central section of the Southeast Brazilian Continental Shelf (SBCS), bounded on the north by Cabo Frio (23º S) and on the south by Cabo de Santa Marta (28º40' S). It is influenced either by ocean waters (through its entry), as for continental waters (riverine waters). The most important river in the drainage basin of the Santos Estuarine System is the Cubão River, which presents maximum flow rate in March (21.5 $m^3 \cdot s^{-1}$), according to data from SigRH (Integrated System of Water Resources Management).

During high tides, the surface currents flow outward the bay through the central section. During low tides, there is evidence of an anti-clockwise movement within the bay, mainly due to the bottom geomorphology and dynamic effect of the Porto Channel flow (Fúlfaro & Ponçano, 1976). The tidal wave presents co-oscillation with semidiurnal period, propagating simultaneously by the Porto, São Vicente and Bertioga channels, with amplitudes ranging from 0.27 m during neap tide and 1.23 m during spring tide (Harari et al., 2000) and the main components for the region are M2 and S2.

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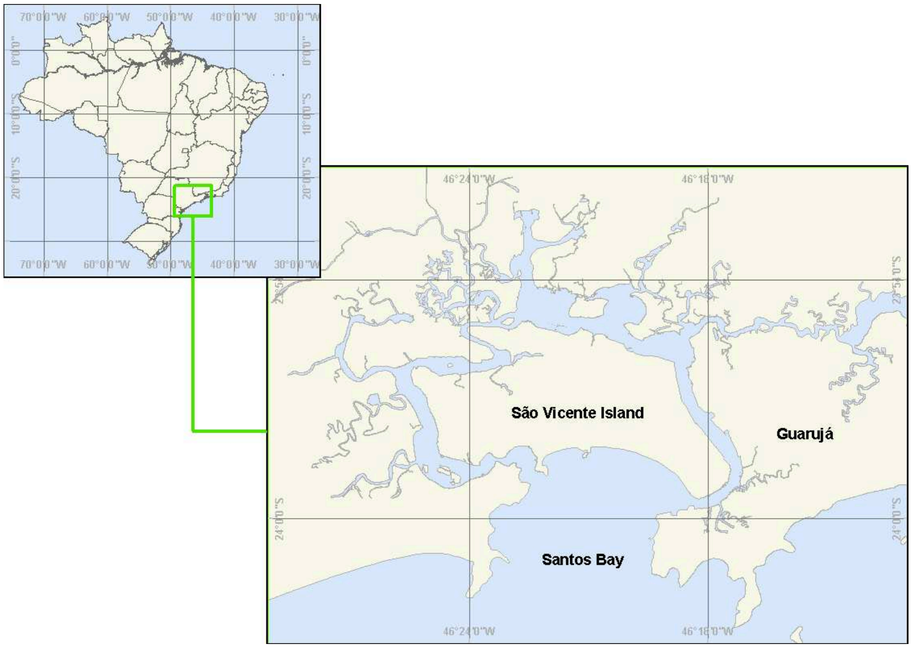

Figure 1 The Santos Estuarine System Study is located in southeastern Brazil.

Our inhouse current meter dataset shows that the most common pattern at the surface (mean velocity of the most frequent direction) occurs in the ENE–WSW direction. At the surface, the current velocity is in the order of 0.30 $m \cdot s^{-1}$. The circulation pattern observed by Mazzini (2009) and Moreira (1998), in the ICS, indicate a predominance of NE currents. The current on the border between the middle and the inner shelf, on the Lage the Santos region, presents a diverse pattern, with influence of the Brazil Current and predominance of SW currents.

Regarding the wave climatology, in normal conditions the waves come from NE and E, with periods of 6 s and significant wave heights less than 1 m. In extreme weather conditions, the waves come from SW, with periods of 12 s and wave-heights of 2 m.

2. HYDRODYNAMIC AND SEDIMENT TRANSPORT MODELING

We used the three dimensional hydrodynamic and sediment transport model Delft3D in this study.The model simulates the hidrodynamic as the answer to the major baroclinic and barotropic forcings, as well as the momentum transfer into the hydrodynamic system resulting from the wind fields. Furthermore, the system updates every time step the bathymetry due to bottom geomorphologic changes (sediment erosion and deposition), besides the sediment transport (bed load and suspension).

We used a numerical grid with 249x191 horizontal points and 5 sigma vertical coordinates. The horizontal grid resolution varies between 3000 m and 90 m farther and closer to the area of interest, respectively. The bathymetry data is derived from nautical charts no. 1701 and 1711 of DHN (Directorate of Hydrography and Navigation). Inhouse measurements extend the bathymetry data.

Figure 2 shows the grid and the bathymetry for the Santos Bay and the adjacent continental shelf, for the ‘present condition’. At the open oceanic boundaries, the hydrodynamic model is forced with results from a regional model (Princeton Ocean Model - POM) forced with wind and pressure fields from the NCEP/NCAR reanalysis datasets. For the river flux rates we used monthly-averaged river discharge data.

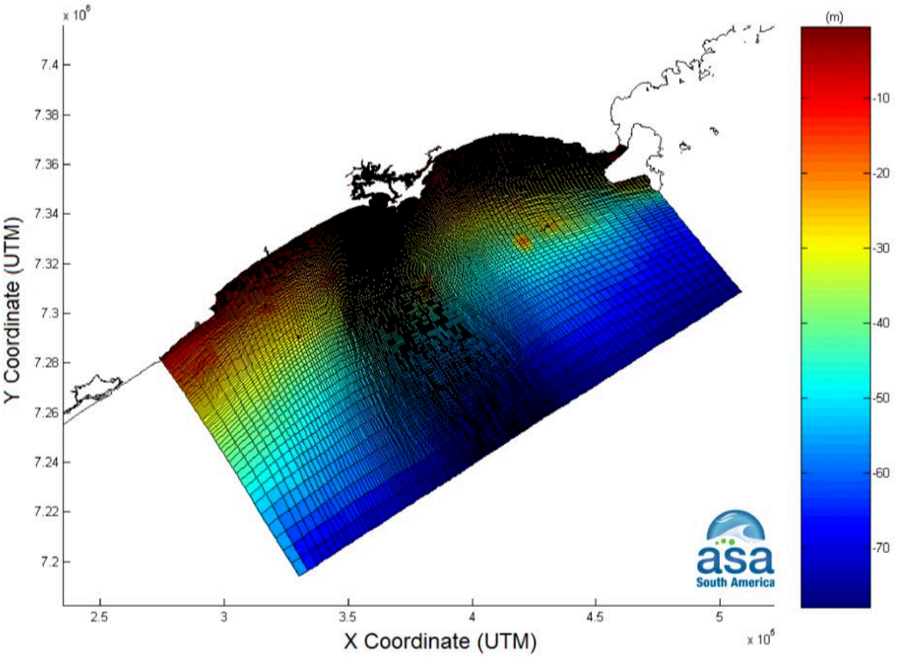

Figure 2 Bathymetry of the Santos Bay and adjacent shelf ('present condition') and the numerical grid used for the Delft3D modeling suite.

2.1. The Impact of Sand Mining on the Sediment Transport

The purpose of this part of the study is to evaluate changes in the sediment transport dynamics in the area after the sand exploitation.With the calibrated and validated model, we carry out and analyse two hydrodynamic and sediment transport scenarios: the 'present condition', which uses the current bathymetry as reference, and a 'future condition', which considers the deepening of 1 m in the sand exploitation area.

Figure 3 shows the sand mining area, in blue. For both scenarios, the simulations are carried out for a period of one year, between March 2010 and April 2011. We compared the final results of both simulations to evaluate the impact of the deepening of the dredged area in the local hydrodynamics and sediment transport.

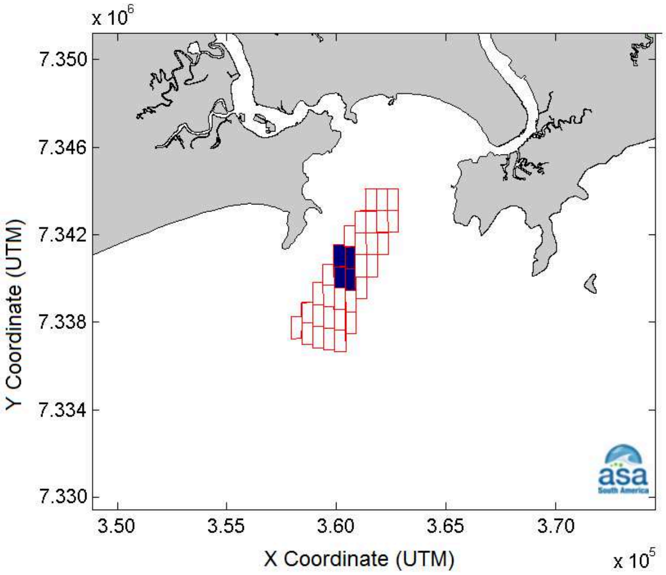

Figure 3 Sand mining area with the exploited deposit rectangles in blue. In the ‘future condition’ scenario, this area is considered 1 m deeper regarding the ‘present condition’.

Figure 4 shows the result of one year simulation regarding bathymetric change for the ‘present condition’ (before dredging). In this case we observe only positive values, indicating a tendency of sediment deposition in the coastal region and in the Santos Bay. Note that the deposition of sediments occurs with higher intensity in the channels, both the Porto Channel and São Vicente Channel, with maximum values of about 5 cm·yr^{-1}.

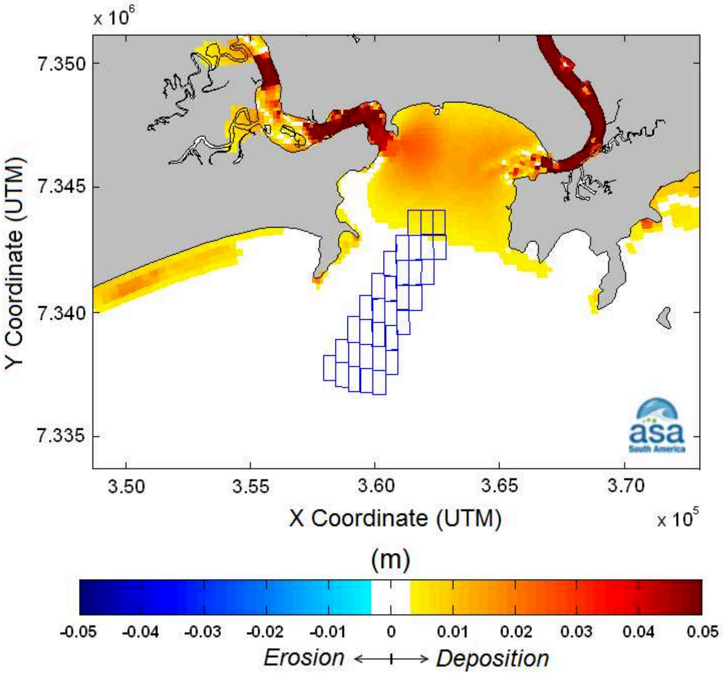

Figure 4 Annual bathymetry change (in meters) as a result of numerical simulation considering the ‘present condition’ (prior to sand exploitation). Positive values indicate deposition and negative values erosion.

After one year of simulation under the new bathymetry condition ('future condition'), we evaluate the impact calculating the difference between the erosion/deposition rates of the 'future condition' and the 'present condition', as illustrated in Figure 5. The analysis of the simulated scenarios indicates three preferred regions of sedimentation after the sand exploitation. The first region, with more significant rates, is located directly in the dredging area. In this area the maximum estimated deposition rate is 15 cm·yr^{-1}. Two other regions of lower intensity, located from Itararé Beach to Jose Menino Beach (northeast of the dredged area) and the coastal region northwest of the dredged area. It is worth pointing out that in these two locations, the observed deposition rates are less than 3 cm·yr^{-1}, in agreement with the magnitude of depositional processes observed in the region prior to dredging (see Figure 4). We consider in our analysis the 'present condition' as reference and assuma that, in this case, a state of dynamic equilibrium. According to the numerical results, the exploited area presents an additional maximum sediment deposition rate (relative to the current condition) of approximately 15 cm·yr^{-1}. Therefore, considering the dredged scenario, the equilibrium condition might be reached again in approximately 7 years.

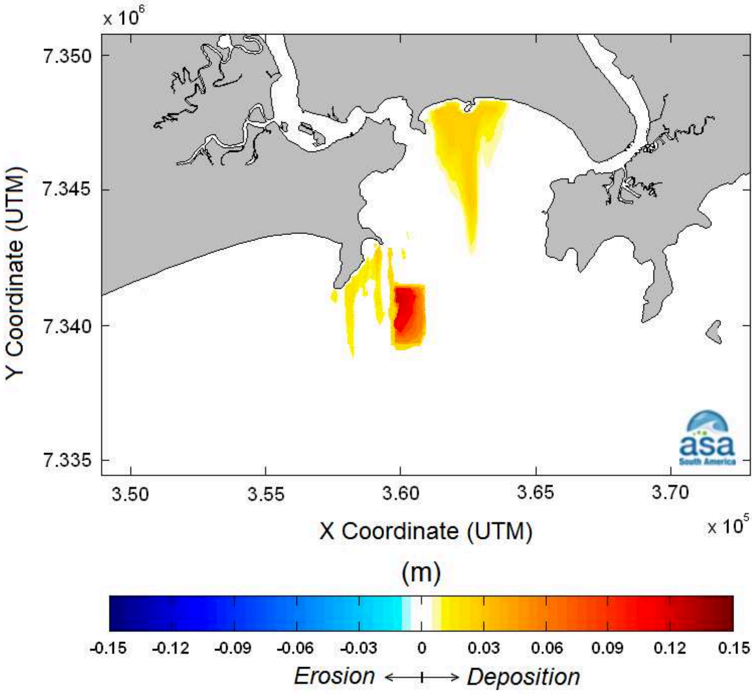

Figure 5 Bathymetric variation (in meters), as a consequence of the deepening of 1 m in the exploited sand deposit, after one year simulation. Positive values indicate deposition and negative values, erosion.

3. SEDIMENT FATE AND DISPERSION MODELING

We use the Dredgemap/SSFATE model to simulate the dispersion of the resuspended material during dredging activities. This model has characteristics used exclusively for studies involving dredging activities, with the ability to simulate real scenarios. The model calculates resuspension based on the granulometry of the dredged material and the types of dredging vessels (Cutterhead, Clamshell or Hopper), which defines the percentage of material resuspended to the water column.

The sediment characteristics used in the dredging simulations are obtained from bottom sediment samples. Table 1 shows the average grain size considered for the Dredgemap/SSFATE model.

Table 1 Granulometry data from bottom sediment samples in the study area.

Sediment classes	%
Clay	0,6
Fine Silt	3,0
Coarse Silt	3,4
Fine Sand	84,0
Coarse Sand	9,0

We used four rectangles to simulate the resuspension caused by dredging activities (blue area in Figure 3). We considered a Hopper dredger, 144 m long and 28 m wide, with 17,000.0 m³ capacity. Table 2 presents the Hopper characteristics and Table 3 presents the dredging operations characteristics, with and without overflow rates.

Table 2 Dredge characteristics.

Equipment	Hopper
Capacity	17,000.0 m³
Length overall	144.0 m
Breadth	28.0 m
Speed during dredging operation	1.9 knots

Table 3 Dredge operations characteristics.

Amount of sediment per dredge cycle	5,734.0 m³ without overflow rate/ 7,032.0 m³ with overflow rate
Total cycle duration (h)	4.40 without overflow rate / 5.02 with overflow rate
Load time (h)	0.62 without overflow rate / 1.12 with overflow rate
Hours of operation per week	145 without overflow rate / 149 with overflow rate
Number of cycles to dredge 2,000,000 m³	349 without overflow rate / 284 with overflow rate
Overflow rate	without overflow rate / 32% with overflow rate

We consider 2,000,000 m³ total dredged volume. Four simulations were carried out: with and without overflow rates, for summer and winter periods. For the scenarios considering overflow, a 32% overflow rate was adopted. Table 4 lists these scenarios.

Table 4 Scenarios characteristics.

Scenarios	Volumes (m³)	Depth (m)	Overflow rate	período	Length (days)
1	2.000.000	1.0	with	summer	67
2				winter	
3	2.000.000	1.0	without	summer	74
4				winter	

3.1 Results of Dredgemap/SSFATE Model

The results obtained for each of the simulated scenarios show the dispersion of dredging plumes. Table 5 show the total area of the plume trajectories generated during dredging operations. The largest plume area occurs during the winter scenario with overflow rate. The sediment plumes, in general, either remain near the dredged area or spread toward the inner continental shelf, and follow the local circulation patterns

Table 5 Total area (km²) of plume trajectories generated during dredging operations, for each scenario.

Scenarios	Area (km²)
1	25.3
2	35.5
3	11.3
4	11.6

The following figures show the total area of suspended sediment plume trajectories generated during dredging activities, and the occurrence frequency within these areas. All cycles required to dredge the volume of 2,000,000 m³ are being considered. We first present the scenarios considering overflow rate for summer and winter and then the scenarios without overflow rate for summer and winter.

Figure 6 and

Figure 7 illustrate the total area of plumes trajectories and their occurence frequency of occurrence for the scenario considering overflow rate during summer and winter, respectively. As specified in Table 5, the total area is 25.3 km² during summer and 35.5 km² during winter. The maximum occurrence frequency is observed within the dredged region and the difference between summer and winter is only represented in the area ranged by frequencies between 0 and 10%. In winter this area becomes greater due to the main circulation patterns. The stronger ICS currents during winter transport the plume outside the Santos Bay.

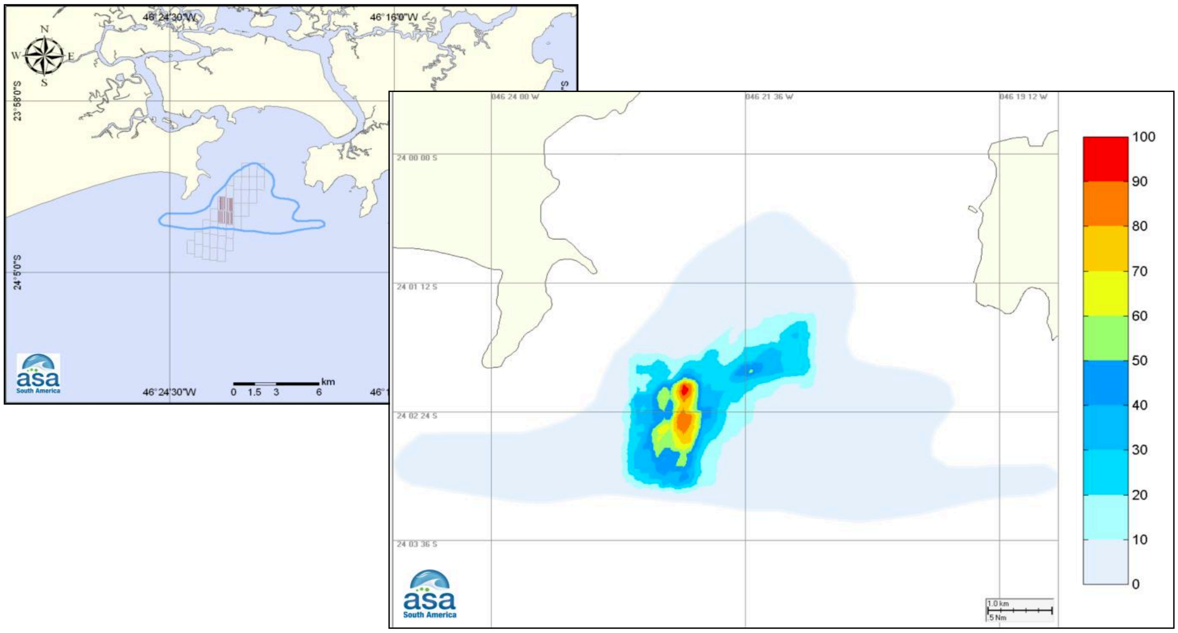

Figure 6 Total area of suspended sediment plume trajectories generated by dredging activities after 67 days, and the occurrence frequencies (%), during the summer scenario, and considering overflow rate.

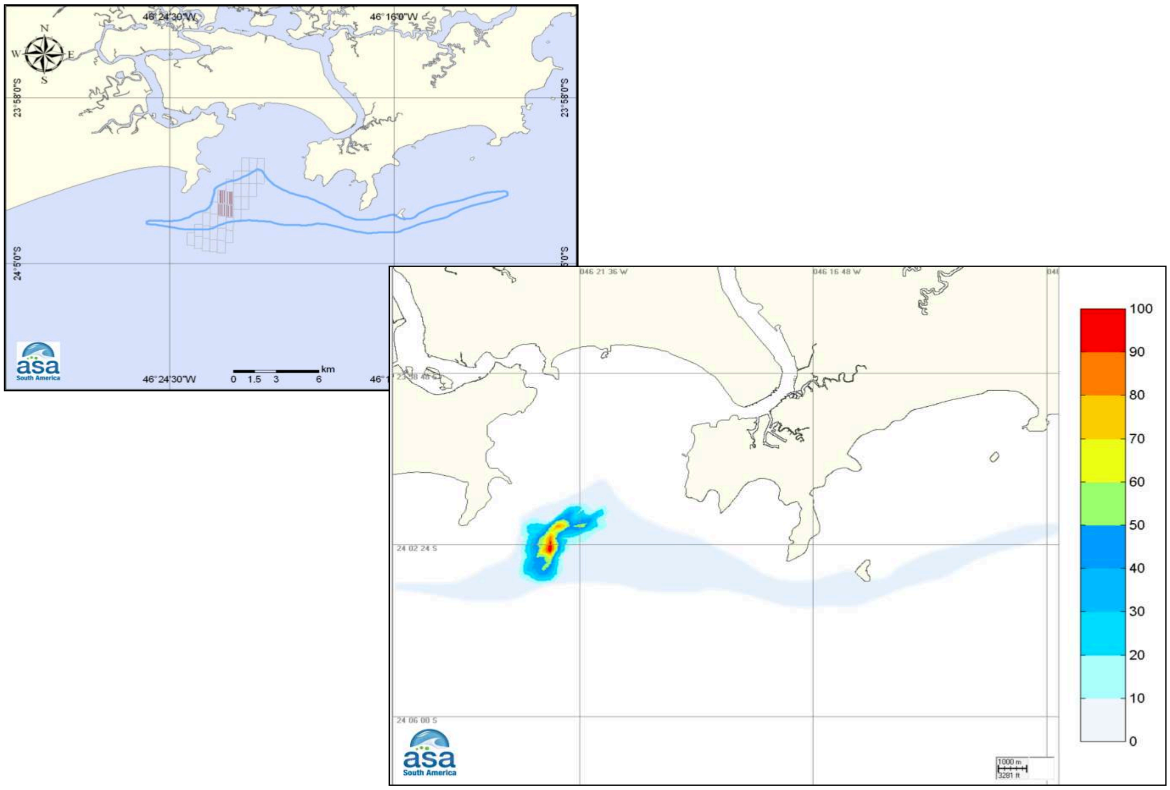

Figure 7 Total area of suspended sediment plume trajectories generated by dredging activities after 67 days, and the occurrence frequencies (%), during the winter scenario, and considering overflow rate.

We now consider the total areas of the plume trajectories and their occurrence frequency, for the scenarios without overflow rate, during summer and winter. The plume areas for these scenarios are 11.3 km² during summer (Figure 8) and 11.6 km² during winter (Figure 9). Both scenarios show similar surface and as the results above, the maximum occurrence frequency is observed within the dredged area. At the surroundings, the occurrence frequencies are below 10%.

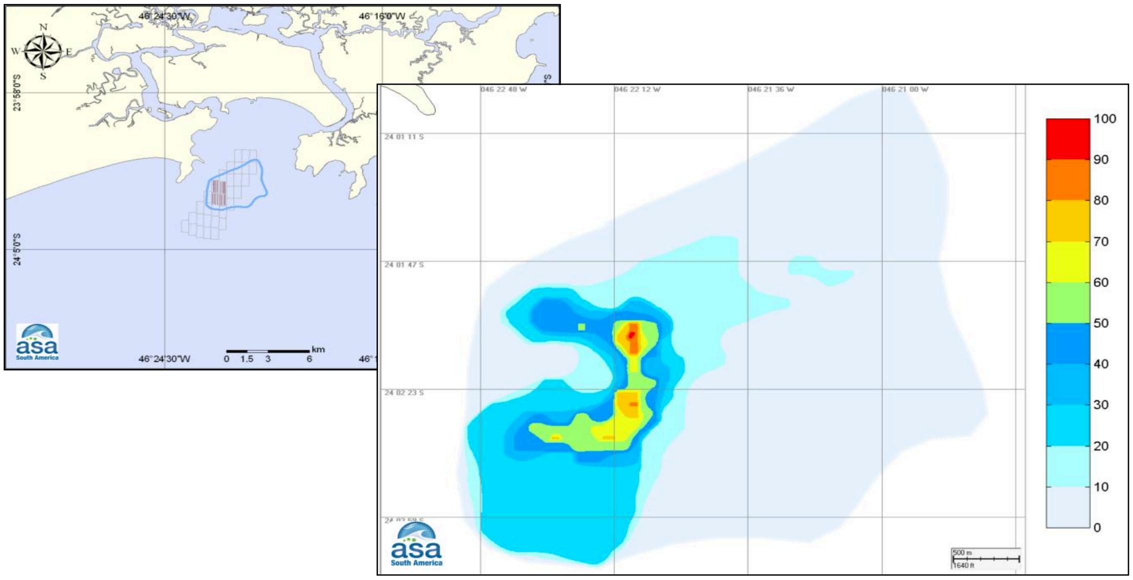

Figure 8 Total area of suspended sediment plume trajectories generated by dredging activities after 74 days, and the occurrence frequencies (%), during the summer scenario, without overflow rate.

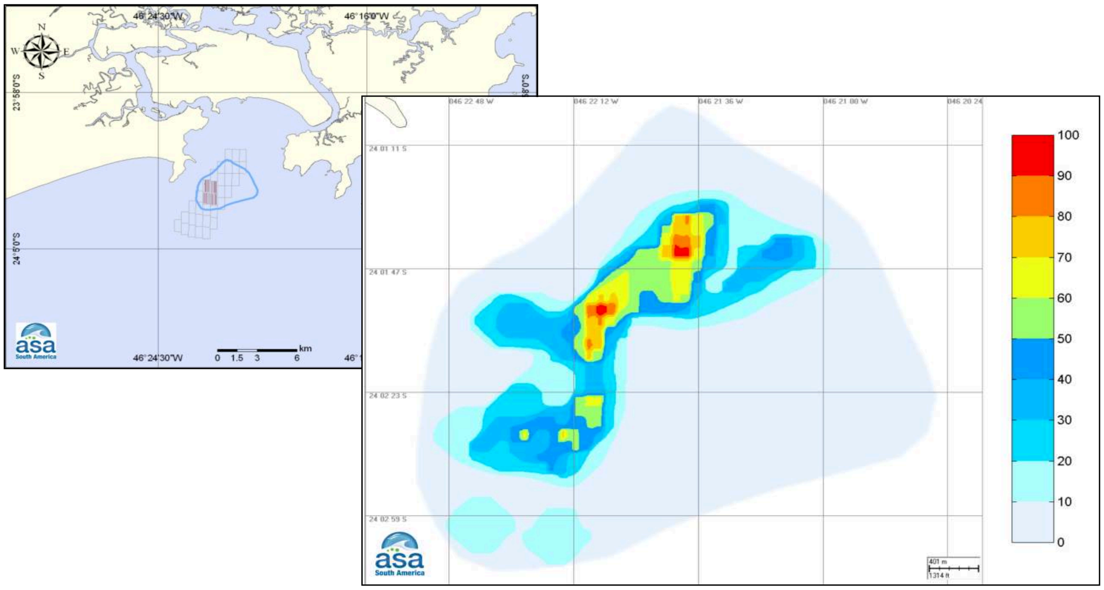

Figure 9 Total area of suspended sediment plume trajectories generated by dredging activities after 74 days, and the occurrence frequencies (%), during the winter scenario, without overflow rate.

4. CONCLUSION

We consider the simulations of the ‘present condition’ scenario as the state of dynamic equilibrium. According to the numerical results, the exploited area presents an additional maximum sediment deposition rate (relative to the current condition) of approximately 15 $cm \cdot yr^{-1}$. Considering the dredged scenario, the equilibrium condition might be reached again in approximately 7 years.

For assessment of sediment plumes arising from dredging operations, we elaborated four scenarios by selecting the most critical conditions. The results show total surface areas of the suspended plumes trajectories ranging from 11.3 km^2 to 35.5 km^2. The largest area is observed during the winter scenario with 32% overflow rate. The sediment plumes, in general, either remain near the dredged area or spread toward the inner continental shelf, and follow the local circulation patterns. The maximum occurrence frequency is observed within the dredged region. At the surroundings, the occurrence frequencies are below 10%.

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