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SEDIMENT PLUME SIMULATION FROM BOTTOM-TRAWLED FISHERY AND DEPOSITION EFFECTS ON RHODOLITHS AND DEEP-WATER CORALS FROM CAMPOS BASIN, BRAZIL

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ABSTRACT: Extensive rhodoliths and deep-water coral has been described along the continental shelf and slope of the Campos Basin, but such environments can be highly vulnerable to the bottom trawling fishing. This study applied the MOHID software to simulate the sediment resuspension during the bottom trawling operation and to evaluate possible impacts of sediment deposition onto rhodoliths and deep-water coral. The sediment transport model was validated by field measurements of a bottom trawling operation and presented good accuracy. The results indicated that sediment resuspension by a double-rig trawling induced a 0.13 mm sediment layer deposition onto the rhodoliths from the continental shelf which has potential deleterious effects considered that such thickness is higher than the threshold proposed by the literature. On the contrary, a sediment resuspension/deposition by a single-rig trawling has no impact in the deep-water corals from the continental slope based on the thin layer deposition that was lower than the proposed tolerance limits.

Keywords: Computational modeling, Sediment transport, MOHID, Continental shelf, slope.

RESUMO: *O leito marinho da Bacia de Campos é caracterizado pela presença extensiva de rodolitos e corais de águas profundas ao longo da plataforma e talude continental, podendo ser esses ambientes sensíveis a pesca de arrasto. Este estudo utilizou o software MOHID para simular a sedimentação do material ressuspendido durante uma operação de pesca de arrasto na Bacia de Campos, avaliando possíveis impactos da disposição de sedimentos no rodolitos e corais de águas profundas. O modelo de transporte de sedimentos foi validado por medições de campo de uma operação de pesca de arrasto, apresentando boa acurácia. Os resultados indicaram que a ressuspensão de sedimentos pela pesca de arrasto de porta dupla tem um potencial de causar impactos a rodolitos, devido a deposição de uma camada de sedimentos de espessura superior a 0,13 mm, sendo esses valores acima dos valores de tolerância estabelecidos pela literatura. Por outro lado, não houve indicação de impactos aos corais de águas profundas do talude pela deposição de sedimentos ocasionada pela pesca de arrasto de porta simples.*

Palavras-chave: *Modelagem computacional, Transporte de sedimentos, MOHID, Plataforma continental, Talude.*

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1. INTRODUCTION

The bottom trawling is a fishing technique that induces physical effects in coastal sediment dynamic by scraping and ploughing the seabed, increasing turbidity by the sediment resuspension and enhancing the sediment deposition onto the seabed and associate biodiversity (Benn *et al*., 2010). The impacts caused by bottom trawling depends on the seabed features (e.g., grain size and benthic communities), oceanographic processes (e.g., current velocity and direction) and fishing technique (e.g., towing speed, gear feature) (Durrieu de Madron *et al*., 2005; Linders *et al*., 2018; O'Neill & Summerbell, 2011; Port *et al*., 2016). It is well recognized that bottom trawling disturbance is more intense in deep seabed than in the shallow coast where the influence of this fishing technique on the sediment dynamic may be similar to the coastal resuspension/deposition processes induced by waves and currents (Clark *et al*., 2016; Puig *et al*., 2012).

In the 1960's, the bottom trawling was introduced in the inner continental shelf of the Southern and Southeastern Brazilian coast (Port *et al*., 2016). Over the 1970's and 1980's, the bottom trawling expanded throughout the exclusive economic zone and increased the fish capture to supply the national and international markets (Arana *et al*., 2016). Continuous expansion of the bottom trawling fleet reached to more than 650 ships operating between 19°- 34°S degrees of latitude at depth from 20 to 800 m (Port *et al*., 2016). At this time, this fishing technique expanded to deeper waters of the continental shelf and slope, with unknow impacts on such pristine marine ecosystems (Perez *et al*., 2009; Sant Ana & Perez, 2016). Recent studies registered the bottom trawling in the continental shelf and slope of the Campos Basin in Brazil (Port *et al*., 2016; Tagliolatto *et al*., 2020)and estimated the direct initial mortality rate of these animals, in the industrial double-rig-bottom trawl fishery in south-eastern Brazil. This is also the first attempt to relate bycatch/at-sea mortality in bottom trawling to stranded turtles found along the adjacent coast. The fishery was monitored from October 2015 to April 2018 through data collected voluntarily by the captains of eight industrial double-rig trawlers. Two hundred and one sea turtles were captured during 9362 tows (43,657.52 trawling hours where extensive presence of rhodoliths and deep-water corals is also described (Cavalcanti *et al*., 2017; Curbelo-Fernandez *et al*., 2017). In addition, the Campos Basin hosts important offshore oil and gas fields, continuously explored since 1980's. Thus, this region is very vulnerable to anthropogenic activities such as the oil and gas exploration and bottom trawling, reinforcing the necessity for actions to preserve the rhodoliths and deep-water corals (Magris *et al*., 2021).

To evaluate the physical impacts of the bottom trawling on rhodoliths and deep-water corals, it is important to quantify the sediment resuspension and deposition onto seabed. Coarse and fine sediments may be differently resuspended and deposited, depending on the influence of currents, and consequently, such impact on the seabed can be variable (Linders *et al*., 2018; Mengual *et al*., 2016; O'Neill & Summerbell, 2011). For example, an exclusion zone to protect coral reefs from trawling operation may has about 10 to 100 m when coarse sediment is resuspended by the trawling operation. On the contrary, when such fisheries resuspended fine sediments, a restriction zone of one kilometer or more is necessary to protect corals (Diesing *et al*., 2013; Linders *et al*., 2018; Port *et al*., 2016). However, field measurements of such sediment plumes may be difficult in deeper waters and the sediment modelling is an alternative tool to provide preliminary data about the impact of the bottom trawling in benthic organisms (Mengual *et al*., 2016; Payo-Payo *et al*., 2017). Thus, this study aimed to apply the MOHID software to simulate the sediment resuspension and deposition during the bottom trawling operation and evaluate possible impacts of the sediment deposition onto rhodoliths and deep-water coral in the Campos Basin.

2. MATERIALS AND METHODS

2.1 Study area

The study site is contained on the continental shelf and slope of the Campos Basin, located at the southern Brazilian coast (Figure 1). Two main distinctive sedimentary domains were characterized: (1) terrigenous mud to gravel in the inner shelf and (2) carbonate sediments in the outer shelf with mud and, rarely sand, composed typically by bioclastic and biolitoclastic material (Castro & Picolini, 2015; Rezende *et al*., 2017). Extensive rhodolith banks and deep-water corals spread throughout the seabed of the continental shelf and slope, respectively (Amado-Filho *et al*., 2012; Cavalcanti *et al*., 2017)150 m depth. Rhodoliths are located at 150 m depth and originated from the association of the free-living red calcareous algae species (*Rhodophyta*, *Corallinales*, *Sporolithales* and *Peyssonneliales*) (Curbelo-Fernandez *et al*., 2017). Growth, sensitivity to impacts, and ecological importance of rhodolith communities is very scarce in the literature (Henriques *et al*., 2014). Deep-water corals are also distributed along the Campos Basin. They feed zooplankton, phytodetrite and suspended organic matter particles in the water column (Cavalcanti *et al*., 2017). Deep-water corals are particularly vulnerable to impacts because of their slow growth (Ramirez-Llodra *et al*., 2011). In the Campos Basin, deep-water corals were found in the middle slope from 500 to 1,200 m (Cavalcanti *et al*., 2017).

Figure 1. Study area, located at Campos Basin. The Red rectangle represents the region of interest that was modelled.

The Figure 2 shows the presence of rhodoliths banks and deep-water corals, the bottom trawling fishing areas that can occur until 800 m depth, and the transects of the case studies proposed by the present work. The data referring to the study area (rhodoliths and deep-water corals distribution, silt and clay content of the bottom sediments, and bathymetry of the Campos Basin) were available by Petrobras, within the scope of the Campos Basin Regional Characterization Project (PCR-BC), and are consolidated in a georeferenced database (PETROBRAS, 2014).

2.2 MOHID model and the sediment transport validation

The MOHID hydrodynamic model developed by the MARETEC research center (Marine and Environmental Technology Research Center, IST-Lisbon) was applied to simulate sediment resuspension and deposition onto seabed (Leitão *et al*., 2008). The simulation of cohesive sediment transport processes is performed solving the 3D- advection-diffusion equation, in the same grid used by the hydrodynamic model (Cancino & Neves, 1994). The governing equation can be written as:

$$\frac{\partial(C)}{\partial t} + \frac{\partial(uC)}{\partial x} + \frac{\partial(vC)}{\partial y} + \frac{\partial((w+W_s)C)}{\partial z} = \frac{\partial}{\partial x}(\varepsilon_x \frac{\partial C}{\partial x}) + \frac{\partial}{\partial y}(\varepsilon_y \frac{\partial C}{\partial y}) + \frac{\partial}{\partial z}(\varepsilon_z \frac{\partial C}{\partial Z}) \quad (1)$$

where C is the suspended sediment concentration, t is time, x, y are the horizontal co-ordinates, z is the vertical co-ordinate, ε_x, ε_y, ε_z are the sediment mass diffusion coefficients, W_S the sediment fall velocity and u, v w the flow velocity components in x, y, z directions.

The hydrodynamics of the south-eastern Brazilian coast has already been explored with MOHID (Franz *et al*., 2016), including in oil drift studies (Juliano *et al*., 2012; Paiva *et al*., 2017). The MOHID is widely used for sediment transport modeling in the ocean (Cho *et al*., 2013; Coelho *et al*., 2002; Paiva *et al*., 2020; Park *et al*., 2015; Santos *et al*., 2002), lakes/lagoons (Costa *et al*., 2018; Olsson *et al*., 2011; Vaz *et al*., 2019), estuaries (Angeletti *et al*., 2019; Franz *et al*., 2014, Franz *et al*., 2017), fjords (Marín *et al*., 2013) and bays (Restrepo *et al*., 2017). The model is also capable to reproduce the morphological changes of the seabed caused by sediment dynamics (Franz, *et al*., 2017; Silva *et al*., 2012). MOHID was recently used in a study in Cartagena Bay (Tosic *et al*., 2019), Colombia, to explore the tolerance limits of suspended sediment concentration in coral reefs of shallow water when exposed to river discharges.

Before simulating the Campos Basin case studies proposed in the present work, in order to validate the sediment transport model, we applied the MOHID to the field measurements of the sediment resuspension from a bottom trawling operation in the Bay of Biscay (Mengual *et al*., 2016), which allowed to evaluate and compare the results simulated by the present work with the field measurements carried out by Mengual *et al*. (2016).

To simulate the bottom trawling movement, the sediment discharge was imposed at a constant height of the seabed, changing its position in the horizontal plane along the transects, considering the speed of the boat during the operation. The bottom currents of the present study, which influence the transport of cohesive sediments, were imposed on the model, since field current measurements were available, both in the Bay of Biscay and in the Campos Basin. The total volume of sediments considered in the model discharge depends on the volume disturbed by trawling equipment on the seabed, but also on the silt and clay content, since only this fraction forms the sediment plume after disturbance (Mengual *et al*., 2016).

Therefore, input data included: the initial plume height after sediment discharge (3 m) and the boat speed (1.6 m/s) (Mengual *et al*., 2016); the oceanic bottom current imposed on the model with a value of 10 cm/s (Lazure & Dumas, 2008) and the sediment settling velocity, also imposed, with a value of 0.7 cm/s; and the total volume of 21.3 kg per meter of trawl

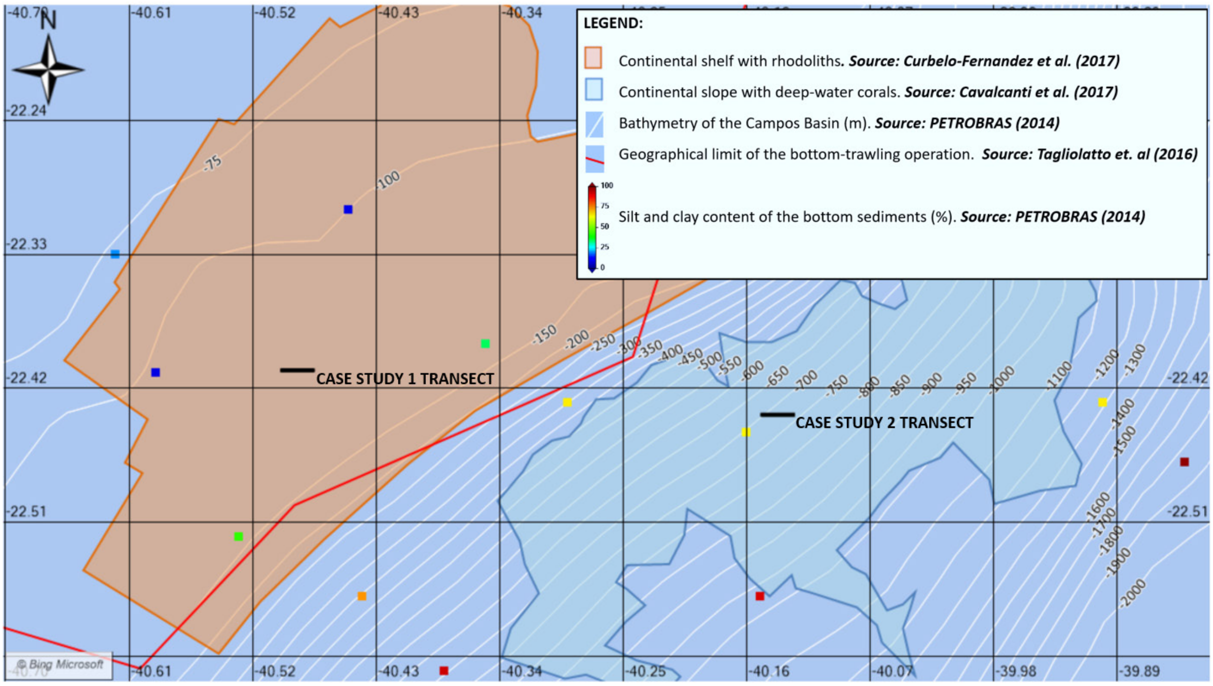

Figure 2. Rhodoliths and deep-water corals distribution (Curbelo-Fernandez *et al.*, 2017); bathymetry with silt and clay content of the bottom sediments (PETROBRAS, 2014), geographical limit of the bottom-trawling operation areas (Tagliolatto *et al.*, 2020)and estimated the direct initial mortality rate of these animals, in the industrial double-rig-bottom trawl fishery in south-eastern Brazil. This is also the first attempt to relate bycatch/at-sea mortality in bottom trawling to stranded turtles found along the adjacent coast. The fishery was monitored from October 2015 to April 2018 through data collected voluntarily by the captains of eight industrial double-rig trawlers. Two hundred and one sea turtles were captured during 9362 tows (43,657.52 trawling hours and transects of the case studies proposed by the present work.

per door (O'Neill & Summerbell, 2011), considering 15% mud content of the Bay of Biscay region (Mengual *et al*., 2016).

The non-parametric Mann-Whitney U was applied to compare the measured (Mengual *et al*., 2016) and simulated (present work) suspended sediment concentrations and sediment resuspension heights of the sediment plume from the trawling operation. The software GraphPad Prism 5.0 was used for all analyses (GraphPad Software Inc., San Diego, CA, EUA). A significance level (p-value) of 0.05 was applied for all analyses ($p < 0.05$).

2.3 Simulation of the sediment resuspension and deposition onto the seabed in the Campos Basin

We simulate the sediment plume resuspension from bottom-trawled fishery and deposition effects on rhodoliths and deep-water corals from Campos Basin. The first case study simulated a double-dig trawling operation in the continental shelf, on a transect from position (22.41° S, 40.47° W) to position (22.41° S, 40.50 W), at a depth of 115 m where rhodoliths colonized the seabed. The second case study simulated a single-dig trawling operation in the continental slope, on a transect from position (22.44° S, 40.12° W) to position (22.44° S, 40.15 W), at depth of 717 m. The Table 1 shows the input data for the MOHID model, obtained from field measurements performed by Petrobras (mud content and bottom current velocity) and from the study of O'Neill & Summerbell (2011) (resuspended sediment mass by trawling distance).

Table 1. Input data for the MOHID simulation of sediment plume dynamic and deposition onto the seabed from the two case studies.

Case study	Mud content	Trawling configuration	Resuspended sediment mass by trawling distance	Bottom current velocity
Continental shelf with rhodoliths	41%	Double-rig trawling	51.84 kg/m	22.5 cm/s
Continental slope with deep-water corals	62%	Single-rig trawling	38.82 kg/m	12.5 cm/s

3. RESULTS AND DISCUSSION

3.1 MOHID modeling validation

The Figure 3 shows the simulated and measured aspects of the sediment plume originated from the bottom trawling operation. Along the proposed transect at Bay of Biscay, from position (47.30ºN, 4.10ºW) to position (47.30ºN, 4.13ºW), the measured (Mengual *et al*., 2016) and simulated (present work) average sediment plume height reached 3.41 and 2.78 m, respectively, which was statistically different ($p < 0.0068$). Maximum values of 6 and 4 m were measured and estimated, respectively, for the sediment plume resuspension. For the suspended sediment concentrations, maximum measured and simulated values were 33 and 43 mg/L, respectively, which cannot be statistically differentiate ($p > 0.05$). Maximum values of 91 and 97 mg/L were measured and estimated, respectively, for the sediment plume resuspension. At the end of the transect, the sediment plume height was measured at 1.4 m and the simulated at 0.80 m. The suspended sediment concentrations at the end of the operation were similar for the measured and simulated results (10 mg/L). These results suggested good agreement between the measured (Mengual *et al*., 2016) and simulated (present work) suspended sediment concentration. Besides, the sediment plume height simulation presented an error of 6.7% relative to the field measurements, that is also considered good for our objective.

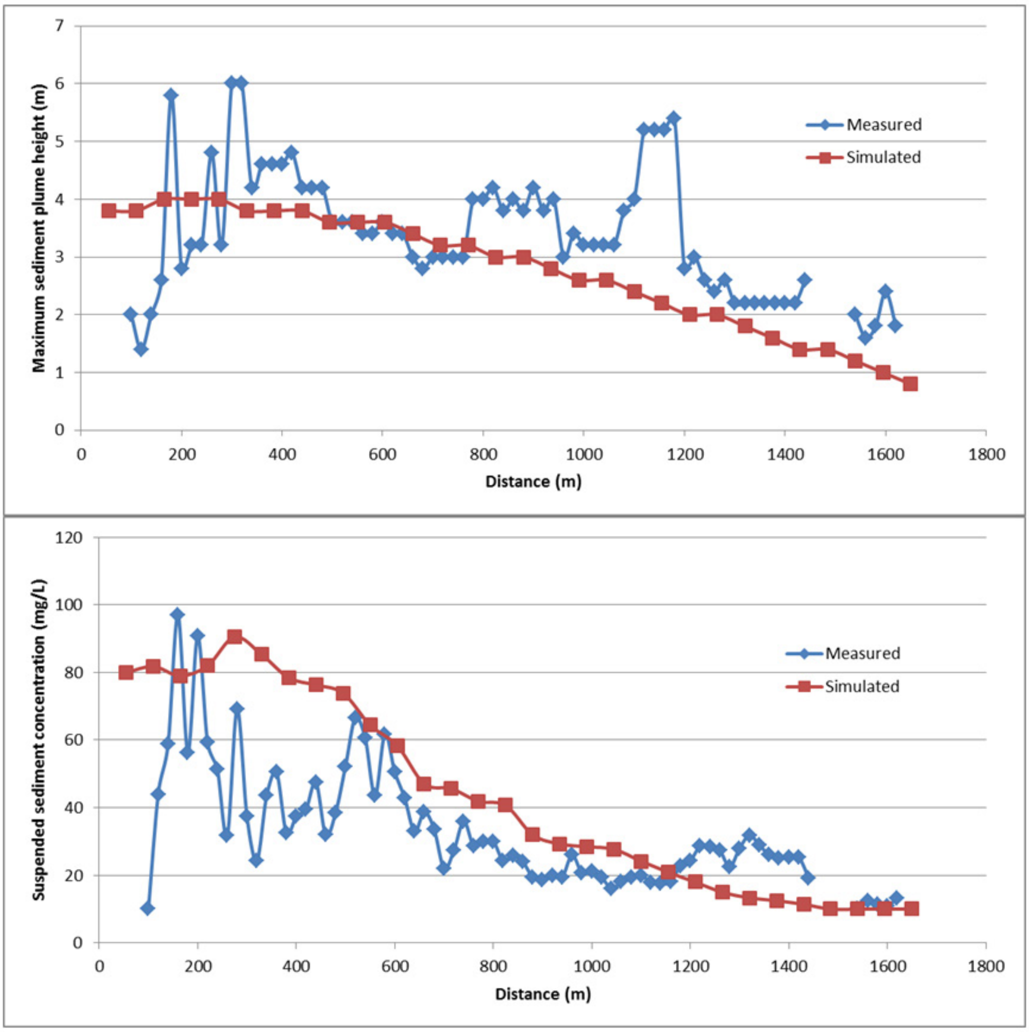

Figure 3. Measured and simulated longitudinal maximum sediment plume height (up) and suspended sediment concentrations in the water column (down) originated by the bottom trawling operation (Mengual *et al*., 2016).

3.2 Case Study 1: Double-rig trawling in the continental shelf of the Campos Basin and effects in rhodoliths

This case study evaluated the sediment resuspension and deposition caused by a double-rig trawling operation in the continental shelf of the Campos Basin. In such region, 41% of the seabed is composed by silt and clay and this region is colonized by rhodoliths. The MOHID simulation indicated that the double-rig trawling resuspended a 4 m height sediment plume that produced a maximum suspended sediment concentration of 150 mg/L (Figure 4). Such value is similar to field measurements of suspended sediment resuspension of 200 mg/L from bottom trawling in the continental shelf of the Bay of Biscay (France) (Mengual *et al*., 2016). Rhodoliths can be more resilient to the increasing turbidity because it is more affected by frequent coastal resuspension/deposition processes induced by waves and currents (Reynier *et al*., 2015; Rogers, 1990) respectively. Chronic rates and concentrations above these values are 'hlgh'. Heavy sedmentation is associated with fewer coral species, less live coral, lower coral growth rates, greater abundance of branching forms, reduced coral recruitment, decreased calcification, decreased net productivity of corals, and slower rates of reef accretion. Coral species have different capabilities of clearing themselves of sediment particles or surviving lower light levels. Sedlment rejection is a function of morphology, orientation, growth habit, and behavior; and of the amount and type of selment. Coral growth rates are not simple indicators of sediment levels. Decline of tropical fisheries is partially attributable to deterioration of coral reefs, seagrass beds, and mangroves from sedimentation. Sedimentation can alter the complex interactions between fish and their reef habitat. For example, sedimentation can lull major reef-building corals, leading to eventual collapse of the reef framework. A decline in the amount of shelter the reef provides leads to reductions in both number of individuals and number of species of fish. Currently, we are unable to rigorously predict the responses of coral reefs and reef organisms to excessive sedimentation from coastal development and other sources. Given information on the amount of sediment which will be introduced into the reef environment, the coral community composition, the depth of the reef, the percent coral cover, and the current patterns, we should be able to predict the consequences of a particular activity. Models of physical processes (e.g. sediment transport. The photosynthesis efficiency reduction by increasing suspended particles and turbidity has been described for calcareous algae. However, many works evidenced the survival rhodoliths capacity under a wide range of luminosity by photo-acclimation, as strategy to reduce the stress caused by turbidity waters and lower sunlight absorption (Harrington *et al*., 2005; Littler *et al*., 1985, 1991; Villas-Bôas *et al*., 2014).

From the simulated suspended sediment resuspension, the particle deposition onto continental shelf seabed and rhodoliths was calculated (Figure 5). The results indicated that the double-rig trawling operation created a 400 m width corridor in the seabed where take place the sediment deposition. Within the 100 m area was calculated the maximum sediment layer with thickness estimated at 0.13 to 0.15 mm deposited onto the rhodoliths. This simulated sediment layer deposited onto the rhodoliths can cause deleterious effects, considering that values was higher than the burial threshold for rhodoliths estimated at 0.13 mm (Table 2). This burial threshold is sufficient to reduce the oxygen and nutrient exchange and reduce the sunlight absorption (Figueiredo *et al*., 2015; Riul *et al*., 2008; Wilson *et al*., 2004).

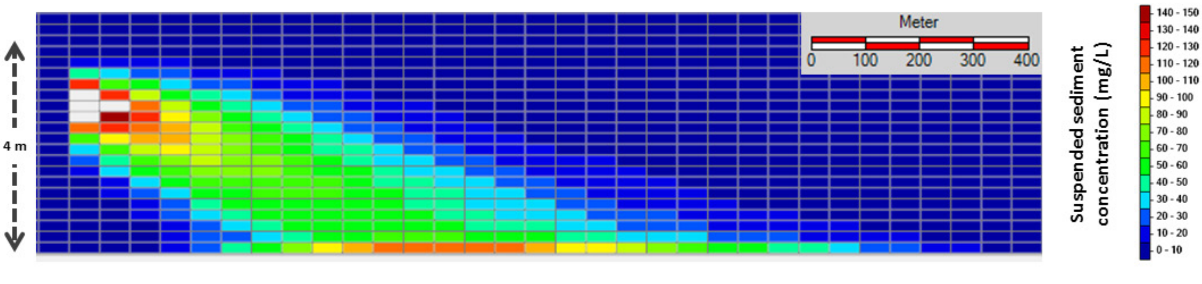

Figure 4. Vertical cut along Case Study 1 transect: simulated suspended sediment concentration from the double-rig trawling operation in the continental shelf of the Campos Basin.

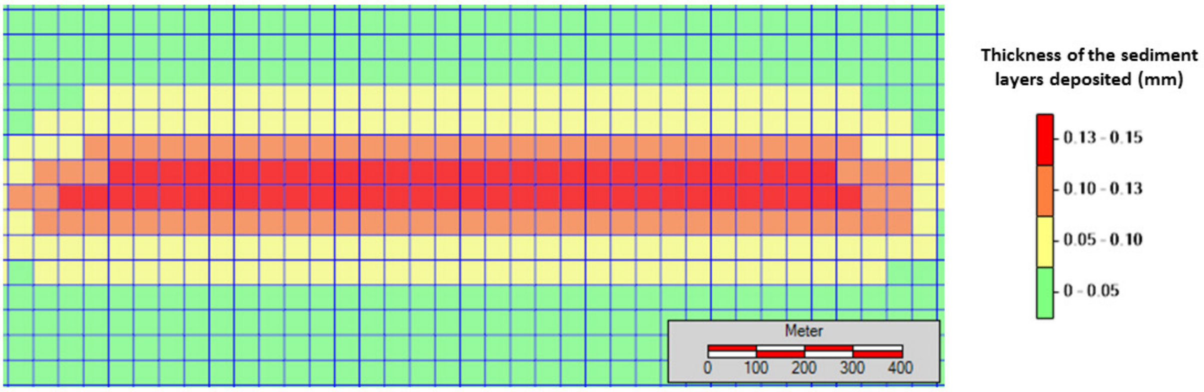

Figure 5: Seabed top view in the Case Study 1 transect region: simulated sediment layer deposited in the continental shelf by the double-rig trawling operation in Campos Basin.

Table 2. Tolerance limit of the sedimentary layer deposition onto rhodolith and deep-water corals.

	Sediment thickness layer	Suspended sediment concentration and exposition time
Rhodoliths	0.13 mm (Riul *et al.*, 2008)	Not applicable
Deep-water coral	6.3 mm (Larsson & Purser, 2011; Smit *et al.*, 2008)containing both chemicals and suspended solids (e.g., drilling discharges to the marine environment	10 mg/L during 9 hours (Baussant *et al.*, 2018; Brooke *et al.*, 2009)peak concentrations: 2–50 mg/L, mean concentrations: 1–25 mg/L

3.3 Case Study 2: Single-rig trawling operation in the continental slope of the Campos Basin and effects in the deep-water corals

Sediment resuspension and deposition were evaluated considering the single-rig trawling operation in the continental slope of the Campos Basin. In this region, 62% of the seabed is composed by silt and clay particles and is colonized by deep-water corals. The simulation showed that the trawling operation resuspended particles at a maximum concentration of 70 - 80 mg/L along a sediment plume of 4 m depth (Figure 6). Differently to the sedimentation effects on rhodoliths, the deep-water corals are not photosynthetically affected by the increased particle resuspension caused by bottom trawling, because such corals are azooxanthellate organisms (Larsson *et al*., 2013). The maintenance of high turbidity with suspended particle concentrations from 10 to 54 mg/L during the time period of 4 to 14 days may impaired different aspects of the deep-water corals such particle accumulation onto coenosarc and polyps, causing the epithelial tissue loss (Larsson & Purser, 2011), reducing the skeleton growth (Larsson *et al*., 2013) and impairing the larval ciliate movements (Järnegren *et al*., 2017).

The particle deposition onto the seabed of the continental slope of the Campos Basin and consequently the deep-water corals was calculated (Figure 7). The results indicated that the single-rig trawling operation created a 300 m width area where sediment was deposited. However, only across a 50 m area that sediment deposition produced a 0.13 - 0.15 mm layer. This sediment layer deposited onto the deep-water corals apparently did not cause deleterious effects, considering such values are lower than the burial threshold for corals estimated at 6.3 mm (Larsson & Purser, 2011) (Table 2).

In general, silt-clay plumes present higher risk to rhodoliths and deep-water corals (Lepland *et al*., 2000). Such particles remained suspended in the water column for a long time period, being transported by oceanic currents and deposited away from the original discharge, with possible long-term impacts in benthic organisms (Figueiredo *et al*., 2015; Harrington *et al*., 2005; Riul *et al*., 2008; Smit *et al*., 2008; Wilson *et al*., 2004)/PSIImax. Thus, the laboratory experiments define conservative tolerance limits for sediment deposition effects in benthic organisms. Such studies provides limits based on the worst-case scenarios that don't consider the biological and oceanographic aspects that can attenuate the deleterious effects (Larsson & Purser, 2011; Reynier *et al*., 2015).

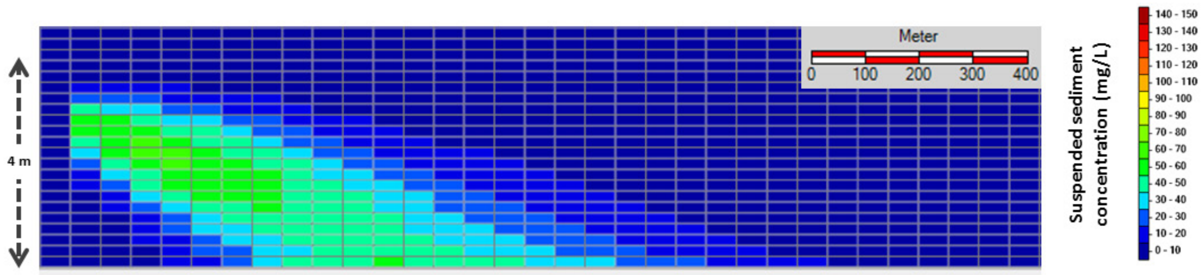

Figure 6. Simulated suspended sediment concentration from the single-rig trawling operation in the slope of the Campos Basin. Vertical cut along Case Study 2 transect.

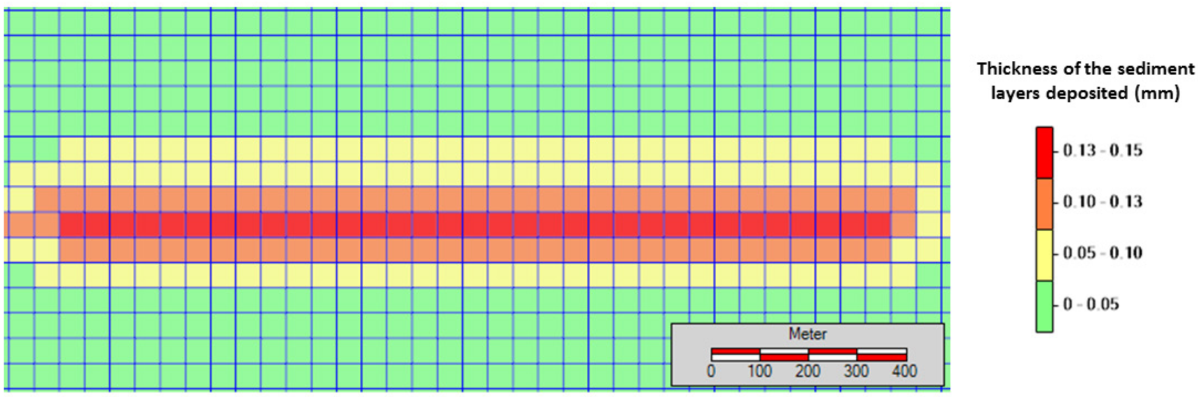

Figure 7. Seabed top view in the Case Study 2 transect region: simulated sediment layer deposited in the continental slope by the single-rig trawling operation in Campos Basin.

4. CONCLUSIONS

The MOHID model was validated by field measurements from the literature and presented a good agreement between the measured and simulated suspended particle concentration and plume height. The simulation of the double-dig trawling operation in the seabed of the continental shelf indicated a sediment resuspension plume of 4 m that produced a maximum suspended sediment concentration of 150 mg/L. In addition, such trawling configuration created a 400 m width corridor with a maximum sediment layer of 0.13 to 0.15 mm onto rhodoliths. Such sediment layer deposited onto rhodoliths can cause deleterious effects, considering that such values were higher than the burial threshold for rhodoliths. The single-trawling operation was simulated for the continental slope and such configuration resuspended particles at a maximum concentration of 70 - 80 mg/L across a sediment plume of 4 m depth. This fishing operation also created a 300 m width area where sediment was deposited at 0.13 - 0.15 mm onto the deep-water corals. However, such values were lower that the burial threshold for deep-water corals (6.3 mm) and thus it apparently did not suffer deleterious effects from the thickness layer deposition by the single-trawling operation.

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