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Decommissioning of subsea oil and gas production pipelines: hydrodynamic modeling for preliminary assessment of sediment resuspension and burial onto benthic organisms

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ABSTRACT: Many offshore oil and gas fields in Brazil are reaching the end of their economic productive life, which has increasing the demand for decisions about decommissioning of the offshore exploration structures such as subsea pipelines. However, removing, retaining or relocating subsea infrastructure have potential impacts on the marine environment caused by seabed perturbation. Using the MOHID hydrodynamic software, this study simulated resuspension, similar to those caused by pipelines recovery operations, and estimated the deposited particle layer onto rhodoliths and deep-water coral in continental shelf and slope in different sediment grain-size typologies. According to the proposed scenarios, simulation of resuspension indicated that particle deposition exceeded the burial thresholds (5.0 mm to rhodoliths and 6.3 mm for deep-water corals), while only in the continental shelf with fine sand seabed, the subsea pipeline removing didn't represent burial risk for considered benthic organisms.

Keywords: MOHID, Sediment, Campos Basin, Rhodoliths, Deep-water Coral.

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1. INTRODUCTION

When offshore oil and gas installations reach the end of their production life, operators and regulators must decide the best decommissioning option available, for example, to reduce the environmental impacts (Bond *et al.*, 2018; Sommer *et al.*, 2019). Large subsea infrastructure is installed onto the seabed where oil and gas exploration occur, including platforms, wellheads, and pipelines (umbilical, riser, flowline and trunk line structures) (Rouse *et al.*, 2018). In Brazil, offshore oil and gas exploration initiated in the Campos Basin at 1970's, and more than 92 and 73%, respectively, of Brazilian oil and gas production comes from offshore fields in the continental margin from 200 to more than 2,000 m, nowadays at the Pre-Salt basin (Almada and Bernardino, 2017). Similarly to other oil fields in the world such as the Gulf of Mexico and North Sea, at this time, many offshore oil and gas fields in the Campos Basin are reaching the end of their economically productive lives, and many platforms and subsea structures are reaching (or have already reached) the end of their project life, which has significantly increased the demand for decommissioning (Mimmi *et al.*, 2017; Nicolosi *et al.*, 2018). Estimates indicated that about 1,000 km of pipelines are considered a decommissioning liability, from a total of ten thousand kilometers of seabed structures across the Campos Basin.

However, decommissioning efforts present financial, law, safety, technical, environmental and socio-economic challenges, and recently the oil industry and the government come to deal with decisions like the full or partial removing of topside and subsea installations, or the abandonment of such structures in seabed (Fowler *et al.*, 2014). As example, decommissioning has to consider the interactions between pipelines and local ecosystems, including the potential impact and disturbances on biodiversity. Marine organisms might be affect through physical impacts by resuspension and deposition onto organisms after removing pipelines (Burdon *et al.*, 2018; Fowler *et al.*, 2018; Rouse *et al.*, 2019) with decommissioning now becoming a global challenge. The compatibility of decommissioning operations to marine protected areas (MPAs). Estimates show that the dredging volume varies from 0.8 to 2.3 m³ per meter of buried pipeline, and that 12% of this volume is resuspended to the water column, *i.e.* the resuspension of sediments during operations is estimated between 0.10 to 0.28 m³ per meter of pipeline (John *et al.*, 2000 *apud* Di Michele *et al.*, 2017).

Among possible threating organisms in the Campos Basin by decommissioning, the 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; PETROBRAS, 2014) 150 m depth. Rhodoliths are structures formed by free-living red calcareous algae (*Rhodophyta, Corallinales, Sporolithales* and *Peyssonneliales*) (Curbelo-Fernandez *et al.*, 2017). The calcified structure of the rhodoliths provides three dimensional habitats to benthic environment, which increase biodiversity in mobile-substrate bottoms and represent a refuge for several organisms (Figueiredo *et al.*, 2012) algae responses were measured in light levels over their depth range. Qualitative samples were obtained by dredging at 90–100 m depth 80 km offshore of Cabo Frio Island, southeastern Brazil. Histological sections indicate that Mesophyllum engelhartii (Foslie). Information about growth, sensitivity to environmental impacts and ecological importance of rhodolith communities is very scarce (Henriques *et al.*, 2014). Deep-water corals can be also found in the Campos Basin and they have no symbiotic association with algae and feed mainly on zooplankton, phytodetrite and organic matter suspended in the water column (Cavalcanti *et al.*, 2017). Deep-water corals are particularly vulnerable to any impact because of their slow growth compared to species from other marine ecosystems (Ramirez-Llodra *et al.*, 2011). In the Campos Basin, deep-water corals were found in the middle slope, within the bathymetric of 500 and 1,200 m (Cavalcanti *et al.*, 2017). Thus, the objective of the present study was to simulate the physical impacts by resuspension and deposition onto benthic organisms after removing pipelines. By using the hydrodynamic model, particle layer thickness deposited onto rhodoliths and deep-water coral were estimated in continental shelf and slope of the Campos Basin with different sediment grain-size seabed conditions. This raised preliminary questions about sediment burial and benthic organism damage by decommissioning.

2. MATERIALS AND METHODS

The study site is the continental shelf and slope of the Campos Basin, located at the southern Brazilian coast (Figure 1), near the State of Rio de Janeiro and Espírito Santo and limited to the north by the Vitória High (20,5° S), and to the south by the Cabo Frio High (23° S), with an area of approximately 100,000 km² (de Castro and Picolini, 2015). The Campos Basin has two distinctive domains: (1) sediments from the terrigenous inner shelf varying in size from mud to gravel; (2) carbonate sediments in the outer shelf more homogeneous with mud and, rarely sand, composed typically by bioclastic and biolitoclastic material (de Rezende *et al.*, 2017).

The study region is located on the western edge of the South Atlantic Gyre, which is limited by the South

Equatorial Current, to the north, and the South Atlantic Current, to the south. The South Equatorial Current reaches the Brazilian coast, meets the continental margin, and is divided into three main water bodies: Tropical Water; South Atlantic Central Water; and Antarctic Intermediate Water. The seabed currents of the continental shelf are strongly influenced by the South Atlantic Central Water (de Castro Filho *et al.*, 2015), and is characterized by seasonal cooling and Ekman transport (de Almeida and Kowsmann, 2015). In the region near the seabed of the continental slope, in turn, the influence of the Antarctic Intermediate Water is greater, with relatively cold water, rich in oxygen and lower salinity (de Almeida and Kowsmann, 2015). Despite the great variation in the vertical velocity profile of ocean currents along the coast, in regions near the seabed, typically low values are observed for the current velocities, both on the continental shelf and on the slope, rarely exceeding 30 cm/s (de Almeida and Kowsmann, 2015; de Castro Filho *et al.*, 2015).

In order to estimate the deposited sediment layer onto benthic organisms, simulations were performed for two sites located at the continental shelf (47 and 49 m of water depth) covered with rhodoliths and two sites at the continental slope (586 and 650 m of water depth) colonized with deep-water corals (Figure 1). Both areas were tested in conditions which seabed is composed by sand and fine sand particles.

The particle resuspension and deposition was estimated using the MOHID hydrodynamic model (Leitão *et al.*, 2008). The hydrodynamic module is responsible for calculating variables such as water elevation and current velocity, in a three-dimensional baroclinic model, from input data such as bathymetry, tide levels and wind speed. MOHID hydrodynamic module allows the model mesh to be refined both horizontally and vertically, in order to allow a better understanding of the current dynamic in the seabed, and is already being used for studies of coralline areas (Navas *et al.*, 2014). In addition, MOHID has been used for oil ocean drift (Juliano *et al.*, 2012),

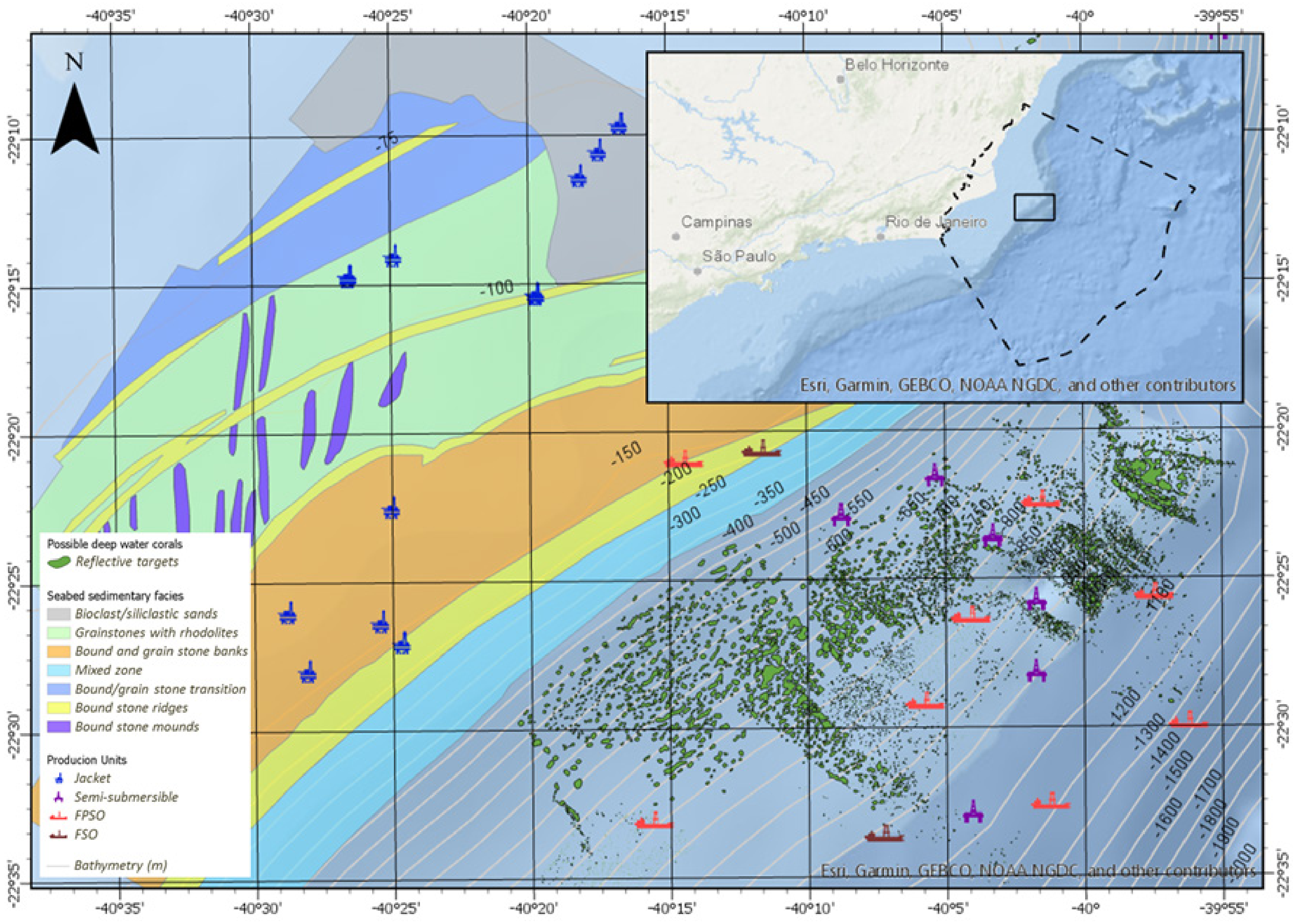

Figure 1. Map of the study area, indicating the boundaries of the Campos Basin (dashed line) (PETROBRAS, 2014).

and oil well blowout plume trajectories studies (Otero-Diaz *et al.*, 2014; Paiva *et al.*, 2017). The present study was applied to the northern Campos Basin region, due to the availability of hydrodynamic data at a depth close to the seabed, provided by the MAPEM project (Pivel *et al.*, 2009).

The results of the hydrodynamic model were obtained using downscaling techniques (Franz *et al.*, 2016). To achieve the desired resolution for the proposed study, four domains were aligned to model the hydrodynamics of the region, using the following global forcers: daily salinity values, temperature and water level values obtained from the Glorys2V4 model, available on global scale at the Copernicus project website (www.copernicus.eu); 3-hour weather data obtained from the NCEP model through the NOAA website (www.ncep.noaa.gov); and information on tidal harmonic components obtained from the FES2012 model (www.aviso.altimetry.fr). The bathymetry used for the hydrodynamic model were generated by GEBCO One Minute Grid, version 2.0 (www.gebco.net). The vertical resolution of the model was maintained exactly as adopted by the 75-layers Glorys2V4 model, being implemented with: seven sigma near-surface layers, which can model approximately 10 m of the shallowest water depth; and 68 cartesian layers, reaching a depth of 6,000 m. In the region of interest, at depths close to 1,000 m, each layer is responsible for modeling a water column segment with a thickness ranging from 80 to 100 m.

MOHID simulates particle transport in the water column using a Lagrangian approach (Leitão *et al.*, 2008). Particle velocities at any point in space are calculated by linear interpolation between grid points of the hydrodynamic model. Turbulent transport is responsible for the dispersion. Random motion is governed by the turbulence parameters of the hydrodynamic model. In the Lagrangian module, it is possible to implement the processes of fine sediment dynamics related to sedimentation velocity, deposition and erosion. In this case, the transport of the particles is governed by the three-dimensional advection-diffusion equation, in which the vertical advection takes into account the particle sedimentation rate. The sedimentation velocity was estimated using the Stokes equation, due to the sediment grain-size range, characterized by a non-cohesive behavior: sand with 0.17 mm of diameter, and velocity sedimentation of 2.5 cm s^{1}; and fine sand with 0.10 mm of diameter, and sedimentation velocity of 0.9

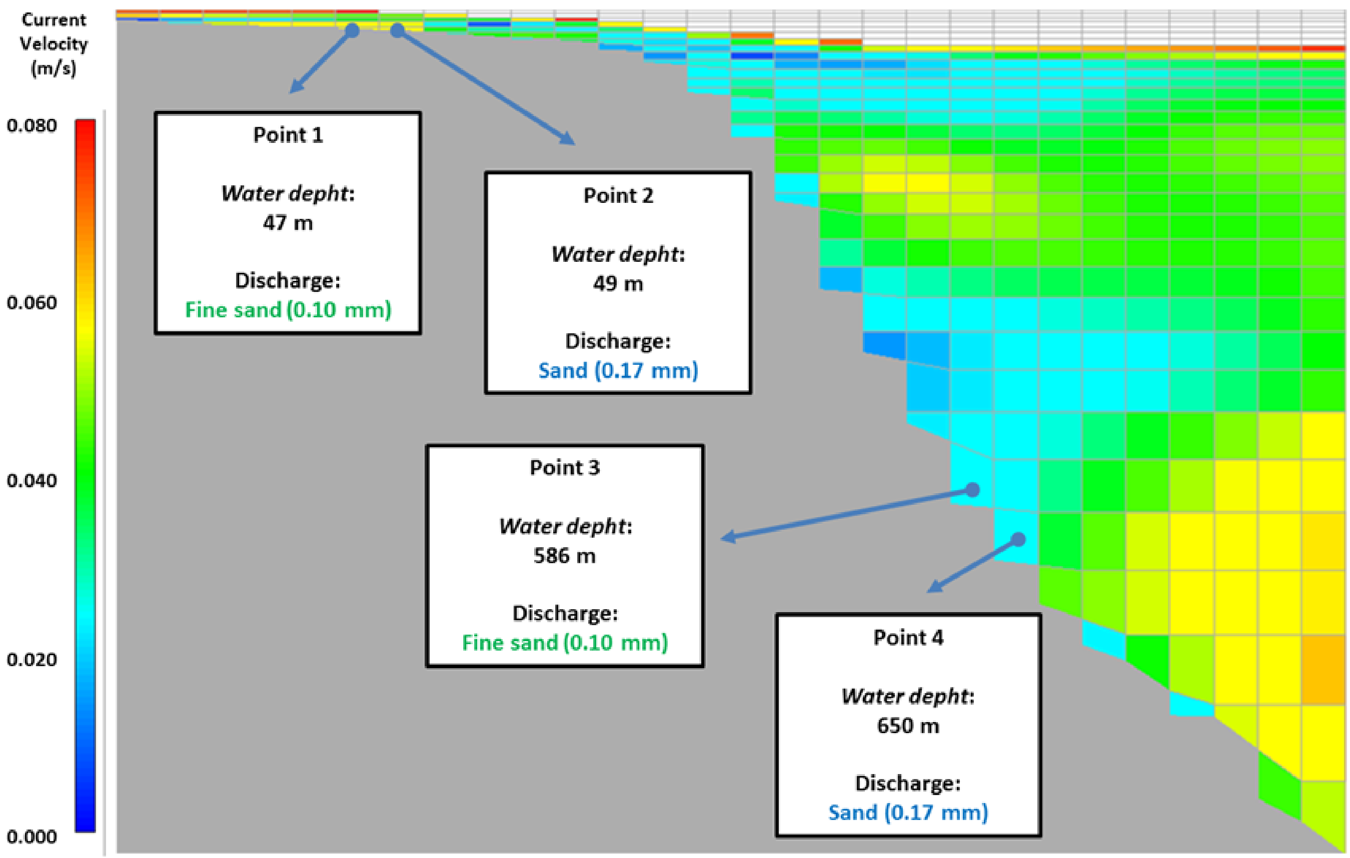

Figure 2. Representation of the vertical sections in the hydrodynamic model, with current velocities along the water column, and sediment discharge points.

cm s^{-1}. Particle diameter values were adopted based on the particle size range found in Campos Basin (Viana *et al.*, 1998).

For the Lagrangian module, the estimates of the resuspended material took into consideration parameters used in sediment resuspension modeling during subsea dredging operations (Di Michele *et al.*, 2017). The authors estimate that the dredging volume varies from 0.8 to 2.3 m^3 per meter of buried pipeline, and that 12% of this volume is resuspended to the water column (John *et al.*, 2000 *apud* Di Michele *et al.*, 2017), *i.e.* the resuspension of sediment during operation is estimated between 0.10 to 0.28 m^3 per meter of pipeline. Therefore, each sediment source (or discharge point) represents a 5 m stretch of an 8" diameter pipeline, which has the corresponding mass resuspended during its recovery operation represented by 300 particles. Considering the proposed value of 0.2 m^3 of resuspended material for each pipeline meter, it was estimated the volume of 1.0 m^3 of resuspended material for each discharge point. Therefore, each particle of the Lagrangian module represents a volume of 1/300 m^3 of sediment.

The distance to the seabed adopted for the discharge points also took into account the results of Di Michele *et al.* (2017), where the dispersion plume reached heights of about 10 m. In the present work, we adopted a height of 15 m from the seabed for discharges positions, considering a possible sediment carry-over by the pipeline during the pipelines recovery operation. Figure 2 shows discharges from the continental shelf exposed to higher current velocities, close to 6.0 cm s^{-1}, compared to discharges on the continental slope with currents of 3.0 cm s^{-1}. In both cases, it is observed that the current velocities of the hydrodynamic model are compatible with low energy environments near the seabed, as described by de Castro Filho *et al.* (2015) on the continental shelf, and by de Almeida and Kowsmann (2015) on the continental slope.

3. RESULTS AND DISCUSSION

To evaluate the thickness of the sediment layers deposited on the seabed, a grid of 5 m x 5 m was used. Each particle represents 0.13 mm of burial, corresponding to the volume of 1/300 m^3 of sediments, deposited on an area of 25 m^2 of the seabed. The number of deposited particles (black dots) was counted for each cell in the grid and represented by the color scale from white (null) to red (120 particles) (Figure 3).

Discharge origin	Point 1	Point 2	Point 3	Point 4
Continental shelf/slope	Continental shelf	Continental shelf	Continental slope	Continental slope
Sedimentology	Fine sand	Sand	Fine sand	Sand
Burial threshold	Rhodoliths (5.0 mm)	Rhodoliths (5.0 mm)	Deepwater Coral (6.3 mm)	Deepwater Coral (6.3 mm)
Highest count particles per cell:	9 particles/25 m^2 (1.2 mm burial depht)	74 particles/25 m^2 (9.9 mm burial depht)	52 particles/25 m^2 (6.9 mm burial depht)	117 particles/25 m^2 (15.6 mm burial depht)

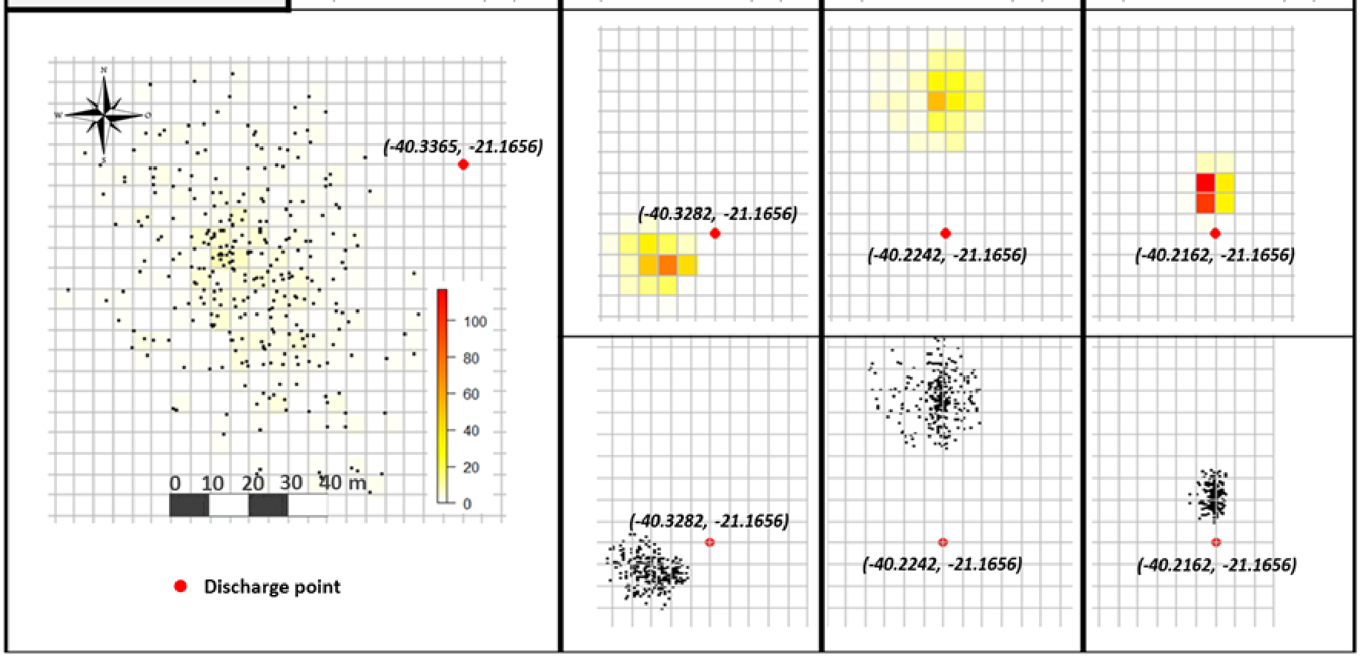

Figure 3. Particle dispersion and deposition results from the Lagrangian model. Discharges points with the respective geographical coordinates.

In general, it was possible to observe a larger dispersion of particles in the continental shelf when compared to continental slope, due to the strongest currents in shallow water. On the other hand, it was observed that there is also a tendency of greater dispersion for discharges of thinner sediments, which can be understood as a result of longer residence time in the water column, due to the lower rate of descent (Figure 3).

For continental shelf with the presence of rhodoliths, the resuspension of sand simulated a 1.2 mm (nine particles representing 0.13 mm each) layer deposition that was higher than the burial threshold for rhodoliths measured at 5.0 mm (Kjeilen-Eilertsen *et al.*, 2004) (Figure 3). The discharge of fine sand in the continental shelf presented the widespread dispersion of particles. For fine sand the simulated results were lower than the threshold values and do not imposed risk for rhodoliths. In the continental slope, the simulation of pipeline removing and particles resuspension indicated that for both grain-size simulations, results exceeded the burial threshold for such organisms indicating threatening of corals during the decommissioning activities (Figure 3).

Sediment burial may reduce the photosynthetic activity of these organisms (Figueiredo *et al.*, 2015; Harrington *et al.*, 2005; Wilson *et al.*, 2004) / PSIImax. According to Kjeilen-Eilertsen *et al.* (2004), the most conservative burial depth by drilling particulate matter is 5.0 mm, and when the thickness of the layer of settled particles exceeds this value, there is a risk of a negative effect. As noted by Baussant *et al.* (2018) peak concentrations: 2–50 mg/L, mean concentrations: 1–25 mg/L, this value corresponds approximately to the tolerance threshold reported for dredging particles in shallow-water corals (Browne *et al.*, 2015).

For continental shelf simulations, the results for both sand and fine sand indicated higher particle burial onto deep-water corals than the threshold values suggesting damage of such organisms. Several studies in laboratory have evaluated the resilience of the deep-water coral species such as *Lophelia pertusa* (Linnaeus, 1758) to high loads of sediment deposition and drill cuttings under different exposure scenarios including total burial (Allers *et al.*, 2013; Brooke *et al.*, 2009; Larsson *et al.*, 2013; Larsson and Purser, 2011). These results confirmed that a threshold level of 6.3 mm may result in damage to *L. pertusa* (Larsson *et al.*, 2013).

4. CONCLUSIONS

According to the proposed scenarios, simulation of sediments resuspension by removal of subsea pipelines and consequent layer deposition exceeded the burial thresholds for rhodoliths from the sandy continental shelf and for deep-water coral from the continental slope of the Campos Basin. Only for the continental shelf with fine sand seabed, the simulation didn't represent a burial risk for considered benthic organisms. The preliminary results suggest that removal of subsea structures may burial benthic organisms with potential damage to rhodoliths and deep-water corals. However, more studies have accuracy estimates of sediment resuspension and layer deposition onto benthic organisms to support regulatory decision making for decommissioning.

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