A modelling approach to assess the impact of land mining on marine biodiversity: assessment in coastal catchments experiencing catastrophic events (SW Brazil)

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Abstract

Analysis that link hydrological processes with oceanographic dispersion offer a promising approach for assessing impacts of land-based activities on marine ecosystems. However, such an analysis has not yet been customised to quantify specific pressures from mining activities on marine biodiversity including those from spillages resulting from tailing dam failure. Here, using a Brazilian catchment in which a tailing dam collapsed (Doce river) as a case study, we provide a modelling approach to assess the impacts on key ecosystems and marine protected areas subjected to two exposure regimes: (i) a pulse disturbance event for the period 2015-2016, following the immediate release of sediments after dam burst, which witnessed an average increase of 88% in sediment exports; and (ii) a press disturbance phase for the period 2017-2029, when impacts are sustained over time by sediments along the river's

course. We integrated four components into impact assessments: hydrological modelling, coastal-circulation modelling, ecosystem mapping, and biological sensitivities. The results showed that pulse disturbance causes sharp increases in the amount of sediments entering the coastal area, exposing key sensitive ecosystems to pollution (e.g. rhodolith beds), highlighting an urgent need for developing restoration strategies for these areas. The intensity of impacts will diminish over time but the total area of sensitive ecosystems at risk are predicted to be enlarged. We determined monitoring and restoration priorities by evaluating and comparing the extent to which sensitive ecosystems within marine protected areas were exposed to disturbances. The information obtained in this study will allow the optimization of recovery efforts in the marine area affected, and valuation of ecosystem services lost.

1. Introduction

Mining has generated environmental damage worldwide (Fernández-Caliani et al., 2009; Johnson and Hallberg, 2005; Li et al., 2014). The activity has boomed over the second half of the 20th century (Schaffartzik et al., 2016) and there is compelling evidence that the magnitude of associated threats are increasing globally (Rosenau-Tornow et al., 2009). In emerging economies such as Brazil (Meira-Neto and Neri, 2017), China (Li et al., 2014), and India (Muduli et al., 2013), for example, the push for economic development can undermine both industry regulations and management interventions. Besides directly affecting local terrestrial ecosystems (Sonter et al., 2014), mining also affects downstream systems with contaminated water from waste deposits (Leppänen et al., 2017; Rodriguez-Iruretagoiena et

al., 2016), and spillages resulting from tailing dam failures (Kossoff et al., 2014; Segura et al., 2016). This last factor can be especially environmentally relevant for downstream marine environments. Sudden collapse of tailing dams can transport large quantities of trace elements and sediment particles over long distances and short time, which then disperse and accumulate in coastal waters. Furthermore, remobilization of sediments after strong storms or wind-driven resuspension could result in an intermittent increase of the total concentration of pollutants even if spill pollution stopped (Hatje et al., 2017). The focus of this paper is on catastrophic events associated with substantial increases in the extent and volume of sediments entering the coastal zone, which can cause ecosystem degradation throughout a region.

Understanding the effects of mining dam collapse on downstream marine systems requires modelling the flow of particles from land to the sea. To date, a substantial number of approaches to modelling runoff and sediment transport has focused on the ongoing pollutant loads resulting from long-term land use changes and non-point pollution sources, such as agricultural runoff and forestry (Álvarez-Romero et al., 2014; Haynes et al., 2007; Jiang et al., 2015; Kroon et al., 2012). Only a few approaches have accounted for extreme disturbances associated with the release of large quantities of pollutants from mining (e.g. Galván et al., 2016). Even less attention has been paid to combining hydrological and oceanographic modelling techniques for predicting the distribution of contaminants in the sea (e.g. Chérubin et al., 2008; Paris and Chérubin, 2008). Oceanographic models are advantageous over remote sensing techniques because of their ability to detect the dispersal patterns of pollutants (e.g. Marta-Almeida et al., 2016), disentangling the extent to which sediment plumes are associated with river discharge (Osadchiov and Zavialov, 2013).

Despite the occurrence of these large-scale incidents over a period of several decades (Kossoff et al., 2014), accidental release of contaminants often occur in places where we have

no baseline or pre-disturbance data on ecosystem conditions (e.g. Gomes et al., 2017). The paucity of ecological knowledge of the pre-disturbed state means that we are unable to competently assess the extent of impacts. Furthermore, most studies to date focus on single ecosystems to quantify the impact of land-based disturbances on biodiversity (e.g. Magris et al., 2018; Makino et al., 2013; Saunders et al., 2017), when in reality multiple ecosystems exist in close proximity (e.g., coral reefs, seagrass beds, algal beds, rocky reefs). Existing efforts using a suite of marine ecosystems assumed they respond equally to sediment pollutants (i.e. uniform sensitivity) (e.g. Álvarez-Romero et al., 2013) or predicted only aggregated patterns of exposure to multiple land-based drivers at a relatively coarse scale (Halpern et al., 2015).

Our study proposes a modeling approach to assess the long-term impact of land-based mining catastrophes (i.e. tailing dam failure) on marine ecosystems. We applied a hydrological model that estimates sediment transport following a tailing dam spill event, and used those results as inputs for a coastal-circulation model to simulate the dispersal of pollutants in the sea. We focused on tracking sediments because they have severe environmental impact in their own right (Brodie et al., 2012), and are closely associated with other stressors such as contaminants (e.g. iron, aluminium) (Restrepo et al., 2016). Given the data-limited context associated with catastrophes, we estimated sensitivities of key marine ecosystems (coral reefs, rocky reefs, seagrass meadows, and rhodolith beds) through a meta-analysis. This approach allows us to identify regions most impacted by land-based mining, and at particular risk of ongoing impact. Finally, to illustrate the utility of our modeling approach for conservation, we assessed the extent of impacts on areas of special interest to conservation, such as those under protection (e.g. marine protected areas - MPAs). MPAs intend to eliminate, minimise, or reduce human pressures on protected ecosystems, making them vulnerable to anthropogenic disasters such as tailing dam failure.

2. Material and Methods

2.1 Case study

We applied our approach to study the catastrophic tailing dam collapse of the Doce river (Southeastern Brazil, Fig. 1). In November 2015 about 39 million of cubic meters of metal-contaminated slurry polluted riverine and coastal waters when the tailing dam collapsed (Hatje et al., 2017). Instrumental sediment-quality records at the estuary showed that over a week after the arrival of the contaminated plume, the concentrations of some heavy metals (e.g. Cu and Zn) were >200 times higher than before (Queiroz et al., 2018). Furthermore, geochemical processes in estuarine wetland soils will cause potential ongoing mobilization of contaminants (Queiroz et al., 2018). The catchment is adjacent to the highest reef-associated biodiversity in the South Atlantic Ocean (Francini-Filho et al., 2013), an area of high conservation significance, where several MPAs have been established (Magris et al., 2013). The catchment is also a global priority for addressing land-based sources of stress as it has been subjected to iron mining industry for over 70 years (ECOPLAN-LUME, 2010), and holds a large number of tailing dams (N=138) (see Fig. S1, AppendixA1).

Figure 1. The study area: location of the Doce river catchment (83,400km²) in Southeastern Brazil (inset map A) and sub-catchments containing tailing dams (1-22, $N=138$). Inset map B indicates the location of marine protected areas along the coastal zone potentially affected by dispersion of pollutants.

2.2 Modelling procedure

2.2.1 Hydrological model set up and parameterisation

To simulate hydrologic processes and sediment exports, we used the Soil and Water Assessment Tool (SWAT), commonly used for water quality assessment and planning (Arnold et al., 2011; Neitsch et al., 2011). We chose SWAT because it is an open source software that integrates both point and non-point pollution sources. This capability is of particular relevance to our case study as we aimed to disentangle the contributions of diffusive sources of pollution such as agricultural fields, to the tailing dam collapse event. We also chose SWAT because it has been continuously improved to handle metals within

catchments (e.g. Meng et al. 2018), offering the potential for future applications. SWAT has higher model efficiency and a lower uncertainty compared with other models (Parajuli et al., 2009; Talebizadeh et al., 2010). A comprehensive description can be found in the SWAT user's manual and documentation (Arnold et al., 2011; Neitsch et al., 2011).

We set up the Doce river catchment model using the interface ArcSWAT2012, with spatial datasets that described the topography, soil type and land cover (Table 1). We divided the Doce river catchment into 258 sub-catchments (Fig. S2, Appendix A1) based on Digital Elevation Model (DEM), which we further subdivided into 384 Hydrological Response Units (HRUs), based on a 20% threshold for land use, soil type, and slope. Each HRU corresponded to a unique combination of land use, soil type and average slope (Fig. S3, Appendix A1) and the 20% threshold was chosen as recommended by Winchell et al. (2013) to remove below-threshold land use, soil and slope types so that a simplified HRU definition could be accomplished. We determined the number of HRUs based on the resolution of the best available land use and soil data. A larger number of HRUs would have provided better resolution in the outputs, but the data did not allow it, and it would have increased processing time. Furthermore, we consider that this scale of HRU delineation was satisfactory to accomplish our goal of understanding the whole-catchment sediment export in the Doce river.

Evapotranspiration is an important component of hydrological models. We used the Hargreaves method to calculate potential evapotranspiration because it requires only maximum and minimum temperature and precipitation (Hargreaves et al., 1985), and gives similar results to other more complex methods (e.g. the Penman-Monteith method) (Galván et al., 2016). We included the two largest in-stream reservoirs in the model, but were unable to include tailing ponds they are separated from the river, and because operational information and flow data were lacking. As this information becomes available, further modelling would

158 need to be done to reflect the impacts of drainage waters coming directly from ponds as well
 159 as their infiltration and percolation into the groundwater.

160 Table 1. Description of each data layer used to parameterise SWAT model for the
 161 Doce river catchment.

Type of data	Source of dataset	Description	Data resolution
Stream network	HydroSHEDS database -Hydrological data and maps based on Shuttle Elevation Derivatives at multiple Scales (www.hydrosheds.org)	The stream network dataset was superimposed onto the DEM (below) to define the location of the stream network	Global river network at 15 arc second spatial resolution (approximately 500 m pixel resolution at the equator)
Land use	Hoskins et al., (2016)	Raster dataset containing five land-use classes: vegetation, cropland, pasture, water, and urban.	Data for the year 2005 at 1km ² resolution
Soil	FAO-UNESCO (http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/faounesco-soil-map-of-the-world/en/)	Dataset containing 11 types of soil within the catchment and their textural and physico-chemical properties	Data with 9-km resolution

Elevation	INPE (National Institute for Space Research); (http://www.dsr.inpe.br/topodata/)	Digital elevation model (DEM) converted into 3 slope classes: 0-5%, 5-20%, >20%.	Shuttle Radar Topography Mission (SRTM) 90-m digital elevation data
Weather	Xavier et al., (2016)	Precipitation, and temperature (maximum and minimum).	Daily gridded data of each variable at approximately 28 km spatial resolution for period of 2000-2013; data were interpolated according to methods described in Xavier et al., (2016) from observations made in rain gauges and weather stations
Reservoirs	Aimorés hydroelectric powerplant (available in http://www.cbdb.org.br/); Coelho (2007); National Agency of	Surface area, principal spillway volume, monthly outflow data for two reservoirs associated with two hydroelectric powerplant: Mascarenhas and Aimorés.	-

	Electric Energy (www.aneel.gov.br)		
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2.2.2 Sensitivity analysis of parameters, calibration, and validation of hydrological model

We used the stand-alone software SWAT-CUP (Calibration and Uncertainty Procedures) with the Sequential Uncertainty Fitting Procedure (SUFI-2; Abbaspour et al., 2007) to calibrate, validate and assess the prediction uncertainty in the input parameters of the model. We selected Nash-Sutcliffe efficiency - NSE (Nash and Sutcliffe, 1970) as the objective function to assess the performance of individual simulations with respect to observations. We relied on the literature to select the parameters that strongly affect hydrology and sediment transport, and corroborated our selection by sensitivity analysis in SWAT-CUP (Table S1, Appendix A2). The first two years of the simulations (2000-2001) were used to warm-up the model and were discarded in subsequent analyses, and the rest was divided between calibration (2002-2008) and validation (2009-2013) periods, with roughly the same number of wet years in each (Oliveira and Quaresma, 2017). We validated the model with the same sampled parameters selected for calibration. Appendix A2 contains details on parameters adjusted during this process and has a full description of the methods involved in the calibration and validation analysis.

To calibrate the SWAT model, we used river discharge data from four river gauges located as close as possible to the outlet of major tributaries of the Doce river, and total suspended sediment (TSS) concentration data from one (the closest to the whole catchment outlet; see their locations in Fig. 1 and Fig. S4). We compiled this information from the web-based hydrologic database developed by the national water agency (Hidroweb platform, www.snirh.gov.br/hidroweb). Our selection of river gauging stations relied mainly on the

quality and consistency of measurements; there is a paucity of measured data on discharges and sediments with sufficient quality. Because suspended sediment data is collected at the gauge four times per year, we had to convert them to monthly sediment loads. We used the package *rloadest* (Lorenz et al., 2013) that integrates the equations of the software Loadest (Runkel et al., 2004) in R to generate daily series of sediment concentration based on daily discharge, which was subsequently converted into monthly sediment load following Monteiro et al. (2016) (see Fig. S5, Appendix A2).

2.2.3 Estimation of sediment exports with SWAT

We used the calibrated SWAT model to simulate sediment export at the main outlet for (i) pulse disturbances, and (ii) press disturbances. The pulse disturbance occurred following the dam collapse in November 2015 and covered the short-term period in which the input of wastes into the river system was substantially increased, generating a river plume of increased magnitude and extent (i.e. within about a year after the collapse (Fundação RENOVA, 2017)). For the pulse disturbance, the model ran with historical precipitation and temperature data from the Hidroweb platform, which accounts for 72 monitoring stations within the catchment from Jan 2015 to Dec 2016. To model the pulse disturbance, we introduced a point source of pollution into the SWAT model to represent the tailing dam collapse, and evaluated the increase in sediment exported to the ocean. We also simulated sediment export by the river without the dam collapse to quantify the amount of sediments that would be released by the river mouth if the accident had not occurred. The sediment release rates (on a monthly basis) were determined by reviewing all available reports on monitoring the aftermath of the dam collapse (Appendix A3). Our estimates of sediment released from dam's collapse over time are indicative and will need to be refined as more accurate measures become available. To assess the model accuracy in predicting the increase

of export after the accident, we compared simulations of suspended-sediment concentrations against observed data for the first six months after the dam collapse.

We modelled press disturbances for the period after the dam collapse, covering the near-future period (2017-2029) in which rain episodes will likely result in remobilisation of contaminants from floodplains and stream sediments, and create events of increased turbidity in the coastal zone. Because monitoring agencies reported that the release of contaminants from the location of the accident stopped a few months after the accident, we assumed that only non-point pollution sources were operating within the catchment when assessing press disturbances. We used downscaled, bias corrected daily weather data (temperature, precipitation) by GFDL-ESM2M outputs, a general circulation model (GCM) developed by NOAA Geophysical Fluid Dynamics Laboratory for the Coupled Model Intercomparison Project CMIP5. We acquired the data from the Climate Change Toolkit (made available at <http://www.2w2e.com> and described by Ashraf Vaghefi et al. (2017)), a platform allowing the user to extract and prepare data for application in hydrological studies. We focused on the near future as climate change is thought to play a major role in hydrological processes after the mid-21st century (Abbaspour et al., 2009; Krysanova et al., 2015) and we wanted to isolate the effects of sediment disturbance from the climate change-related impacts in the distant future. In this analysis, we chose future climate projections under representative concentration pathway 2.6 Watts/m² (RCP2.6), an optimistic scenario of anthropogenic greenhouse gas (GHG) emissions (Moss et al., 2010). We tested for potential variability among climate projections and found that all climate variables were generally well correlated ($p < 0.05$) between scenarios across our study area (Table S4 in Appendix A4).

2.2.4 Connecting hydrological model to a coastal-transport model

To investigate the spatial dispersion pattern of the river plume in the ocean over time, we linked the outputs of the SWAT model to a three-dimensional, free surface, topography-

following-coordinate oceanic model: Region Ocean Modeling System (ROMS) (Shchepetkin and McWilliams, 2005). The coastal circulation model ROMS has been previously implemented to delineate river plumes during a period of few weeks after the accident, showing good agreement with ocean colour obtained from MODIS sensor (Marta-Almeida et al., 2016). We extracted monthly time series of river discharge ($\text{m}^3 \text{s}^{-1}$) and sediment concentration (i.e. total suspended sediment – TSS; mg/L) at river mouth from the hydrological modeling as inputs for the ROMS. Because the two models run separately, we manually exchanged the data between them. While this offline coupling does not require any integration of the two modelling components into a single model, it still allowed us to link human activities on land to effects on ecosystems in the sea. The same type of coupling has been carried out by Cugier et al. (2005) with a chain of models covering the river-coastal domains to investigate the effect of nutrient loading on resulting phytoplankton blooms.

To align with the sediment exports using hydrological modeling, we divided the model simulations using ROMS in two parts: (i) pulse disturbances (Nov-2015 through Dec-2016); and (ii) press disturbances (Jan-2017 through Dec 2029). We used an additional experiment (i.e. a spin up) prior to main simulations for the first ten months of 2015 (before the accident) to find the equilibrium of ROMS numerical solutions. Given the lack of reliable downscaled projections of physical variables that force the ROMS model in the future, our oceanographic modelling does not match temporally with SWAT for the press-disturbance phase. In this phase, we obtained the surface and lateral forcing by averaging 10 years of meteorological and current time series, between 2008 and 2017.

2.2.5 Identification of expected areas of sedimentation with coastal circulation model

We ran ROMS simulations using the same domain as in Marta-Almeida et al. (2016), with a grid domain extending from 15°S to 26°S and from 35°W to 45°W, configured at a variable horizontal resolution of 1.5 – 2.5 km latitude $\times$ 2 – 3 km longitude and vertical

discretization of 30 sigma levels. We forced the model with atmospheric data acquired from Climate Forecast System Reanalysis dataset (Saha et al., 2010). We forced open ocean boundaries and initial conditions with current velocities obtained from HYCOM (Wallcraft et al., 2009) and barotropic tides from the Atlantic Ocean-ATLAS solution of the TPXO dataset (Egbert and Erofeeva, 2002). Lastly, we also forced ROMS with monthly simulated flows and concentrations at the Doce river boundary.

We incorporated a sediment transport sub-model embedded in ROMS in the modelling system for computing the effects of physical factors, such as vertical advection (vertical settling), and erosion, on sediment dynamics (Warner et al., 2008). This sub-model was forced with ROMS outputs of ocean current velocities (as above) to identify potential areas of sedimentation more realistically than using a tracer (Marta-Almeida et al., 2016). The ROMS sediment transport sub-model represents sediment using separate cohesive and non-cohesive categories, each represented with fixed attributes of grain diameter, density, settling velocity, critical shear stress for erosion, and erodibility constant (see Warner et al. (2008) for a more extensive description and technical details of the sediment transport sub-model that is part of the ROMS).

Because we were interested in modelling the maximum extent over which sediment would deposit into the ocean from the river mouth as a function of time, we focused on modeling the dispersion of the finest sediment category, i.e. cohesive ones, such as silt and clay (=mud particles). The sand fraction of sediments settles out of the water column faster than silt and clay particles, limiting the impact to the adjacent areas of the river mouth. Fine-grained sediment is also more environmentally significant than sandy ones with regards of the severity of impact (Bell et al., 2015; Storlazzi et al., 2015).

The characteristics of sediment particles in the Doce river were only collected after the dam collapse, and thus we relied on these monitoring data. Ninety percent of the

sediments discharged by the river after the accident was cohesive with an average diameter of 15 μm (DNPM, 2015; DNPM, 2016). Iron ore tailings from this region typically contain heterogeneous mixtures of hematite (about 60%; density of 5250 kg/m^3) and silicates (e.g. quartz; about 40%; density of 2640 kg/m^3) and, according to Hill et al. (2000), the average settling velocity for clay-sized sediment particles is 0.0001 m s^{-1} . We ran the sub-model to determine the amount of sediment loading per unit of area of the seafloor for each month of the pulse disturbance event. We integrated the amount of sediment in the water column over the upper 200 m and expressed as kg.m^{-2} . This was the final output for our exposure component for the pulse disturbance event. For the press-disturbance phase, we used the passive tracer (i.e. without the sediment transport sub-model) as a proxy for sediment plume extent.

2.3 Effects of sediment disturbances on ecosystems

2.3.1 Ecosystem delineation

We collated and refined existing distribution maps for four ecosystems: coral reefs, rocky reefs, seagrass meadows, and rhodolith beds. We collated spatial data regarding ecosystem occurrence and extent from existing planning exercises, previous studies, and government reports (Appendix A5). We converted the extent of occurrence of each ecosystem into raster format within GIS environment, with a spatial resolution of 1 km^2 .

2.3.2 Sensitivity to sediment disturbances

We collected data through searches in the Web of Science (All Databases; Thomson Reuters 2017) database through August 2017 (see Magris and Ban, *in review*, and supplementary methods for search terms and other details on study selection – Appendix A5). The combinations of search terms covered publications studying effects of sediments in all types of tropical marine ecosystems. The meta-analysis collated empirical observations (981 single and independent measurements of a biological response made by sixty-nine studies) to

document and compare the effects of an increase in sediment concentrations relative to control levels on marine biota. Studies accounted for a variety of mechanisms causing both direct (e.g. smothering or clogging of feeding systems, burial of organisms) and indirect (light reduction) impacts from sediments. Biological responses ranged from short-term ones (e.g. physiological and behavioural alterations that occur within a lifetime) to longer term effects such as changes at the community level (e.g. species composition and diversity).

For each selected study, we considered an observation as every single and independent measurement of a biological response obtained at a treatment and a control level. After extracting means, standard errors or standard deviations and sample sizes directly from each article, we performed mixed effects analyses to investigate the relationship between marine biodiversity and sediment disturbances for each of the four ecosystems. To assign each observation to its ecosystem, we recorded the type of habitat assessed or origin of species used in laboratory experiments. To estimate the overall mean effect of sediment disturbances on each ecosystem type, we calculated the Hedges' d (and 95% confidence interval) as an estimate of the unbiased standardised mean difference (i.e. the effect size). We conducted this analysis in R with the metafor package (Viechtbauer, 2010) and DerSimonian–Laird estimator (DerSimonian and Laird, 1986). We normalized the mean effect size for each ecosystem to the reference range of zero to one (areas beyond the extent of mapped ecosystems had a value of 0 and the highest effect size a value of 1, representing the most sensitivity ecosystem across all ecosystems considered here).

2.4 Impact assessments and conservation application

After we modelled the sediment plumes in the coastal zone over time and calculated the sensitivity of each ecosystem to sediment disturbances, the next step was to calculate the impact of pulse and press disturbances on each square grid cell (1km²) containing our focal coastal marine ecosystems. We mapped impact as a function of these two components

following the framework proposed by Mumby et al. (2014). We multiplied the rescaled effect size estimates for each ecosystem by the corresponding exposure value to sediment plumes to obtain an overall measure of impact (I_c in Eqn 1). Exposure was determined by three methods for each type of disturbance (pulse and press): (i) using the highest monthly exposure recorded; (ii) summing individual exposures across the whole period of simulation (i.e. 14 months for pulse disturbance and 156 months for press disturbance); and (iii) using the maximum value experienced for each cell across the whole period of simulation. We then calculated the cumulative impact (CI) for each grid cell by adding the I_c values derived for each type of disturbance.

$$I_c = \sum_{j=1 \text{ to } 4} E_i * D_j * S_{i,j} \quad (1)$$

Where E_i is the exposure intensity i recorded for a given pixel containing an ecosystem and calculated in line with each of the three methods described above, D_j is the presence of ecosystem j at the same location and S_j is the sensitivity of an ecosystem j to sediment disturbances.

We quantified the total impact on each of the MPAs affected by both types of disturbances. Using the maps of maximum impact across the time series, we calculated the area of each ecosystem within each MPA affected by three types of plumes: “primary plume”, characterised by extremely high values (those in the top 5th percentile); “secondary plume”, characterised by high values (between the top 15th and 5th percentile); and “tertiary plume” (belonging to the top tercile but not falling within the previous two types). This classification of sediment plumes characterised by using only the top-tercile values was because the TSS concentrations or amount of sediments were heavily skewed towards low values. We bounded the total impact score by the maximum area of selected ecosystems protected by each MPA. By doing so, we aimed to understand which MPAs should be

prioritised for ecosystem restoration, impact mitigation, or targeted for long-term monitoring of impacts.

3. Results

3.1 Prediction performance of the SWAT model

Comparisons for observed and simulated monthly discharges across all gauges (Figs. S6-S9) showed that SWAT model achieved “very good” or “good” performance for the calibration time period, whereas it achieved “satisfactory” performance for the validation time period, according to criteria suggested by Moriasi et al. (2007, 2015). Following the same criteria, the model’s performance could be considered “satisfactory” in simulating monthly sediment load for both time periods (see Fig. S10 and Table S2 in Appendix A2 for full results). A comparison with observations of TSS data at the river mouth averaged over the first six months after the accident (i.e. 2,567 mgL⁻¹) and mean prediction by SWAT model (i.e. 2,641 mgL⁻¹) showed similar results (Appendix A3).

3.2 Sediment exports with hydrological modeling

SWAT simulations showed a substantial increase in sediment exports following the collapse of the tailing dam (pulse disturbance) (Fig. 2). In 2015, prior to the accident (Jan through October), we estimated the Doce river monthly exports of sediment to the coastal zone summed 283,891 tons, following a dry year. In contrast, about 74 million of tons of sediment were discharged into the ocean during the 14 months following the dam collapse (Nov 2015 through Dec 2016). Compared with the scenario in which the accident did not occur, the amount of sediment exported by Doce river would be just over 2.5 millions of tons of sediment for the same period (2016 was much wetter than 2015). The greatest difference, of about 180-fold, in the amount of sediment exported with and without the accident was

observed in February 2016. On average, dam collapse accounted for an increase in catchment sediment export of more than 88% over the first six months from November 2015.

Figure 2. Simulated average monthly sediment export by Doce river to the ocean prior and during the pulse disturbance event (Nov 2015-Dec 2016). Error bars show the upper and lower limit of the 95% prediction uncertainty interval. Red line depicts sediment exported in the aftermath of the dam-collapse event (from November 2015 onwards). Blue line indicates sediment exports prior to disturbance and what would be exported without the dam-collapse event.

The sediment export pattern generated by the GCM model is presented in Fig. 3. Simulation results indicated that there would be an overall increasing trend in the maximum sediment exported by the river over the near future (2017-2029). Although there were a few instances of reduced amounts of sediment discharged in the ocean following the rainy seasons of 2021, 2026, and 2028, sediment export exceeded maxima of the 2-year period

(2015-2016) several times in the scenario with no dam collapse (i.e about 10^6 t). Sediment export peaked around 10^7 t during the rainy season of years 2017, 2018, 2020, 2024, and 2025 and around 10^8 t in the years 2027 and 2029.

Figure 3. Simulated average monthly sediment exports by Doce river to the ocean over the period of press-disturbance assessment (2017-2029). Projections are based on precipitation and temperature data from CMIP5, RCP 2.6 scenario. Ribbon shows the upper and lower limit of 95% prediction uncertainty.

3.3 Coastal-circulation model

River discharge perturbation following the dam collapse (pulse-disturbance event) formed extensive sediment plumes in the coastal zone (Fig. 4). However, the sediment plume extent was spatially restricted to the coastal zone adjacent to the river mouth in February 2016, when the highest difference in terms of sediment loading was documented (i.e. 11.9 kg

m²; Fig. 4A). The southerly direction of this sediment plume from the river mouth exposed southern coastal areas (including the shoreline close to the city of Vitória) to the constituents within the plume. When summing the areal extents of the plume through the time series (Fig. 4B), it was much more prolonged and covered not only a large nearshore area towards the southern part of the river mouth but also a very large area in the north off the Doce river marine area, spreading offshore from the river mouth. Overall, over the 14-month study period, the plume shifted toward the northern coastal zone, most likely influenced by southerly winds. When assessing maximum sediment load across the time series (Fig. 4C), the spatial extent of the plume was similar to that observed through the summing-up method.

Figure 4. Plume sediment loading in the ocean and their trajectory as they move away from river mouth and sank following the dam-collapse event. Modelled sediment intensities represent the difference of monthly sediment loading per unit area (Sed) in kg m⁻² with and without the collapse. (A) Monthly average load map for February 2016 when the difference reached the largest value. (B) Summed monthly average load map across the time series (i.e.

426 *14 months: Nov 2015 through Dec 2016). (C) Maximum sediment load in each pixel over the*
427 *14 months.*

428 A substantial decrease in the TSS concentrations associated with a protracted press
429 disturbance event was evident; the highest TSS value observed was 557.4 mg L⁻¹ in
430 December 2028 (Fig. 5A). Similarly to the pulse-disturbance assessment, considering only
431 the month with the largest TSS concentration formed a more spatially constrained pollution
432 plume when compared to the estimated extents through the other two methods (Figs. 5A-C).
433 The distribution of the plume also varied considerably from the short-term assessment. For
434 example, we detected a high-turbidity plume extending much further offshore in some
435 locations (e.g. between the river mouth and capital city of Vitoria). In December 2028, the
436 plume moved southwards and bifurcated owing to the prevailing southward shelf flow along
437 the Brazilian Margin. When assessing the areal extent of plume across the whole time series,
438 we noted a more well-spread distribution, with areas situated further north off the Doce river
439 mouth being also exposed to the pollution. Furthermore, the spatial extent of the plume
440 through the summing-up and the maximum value across time showed a very similar pattern
441 in terms of maximum area influenced.

442

Figure 5. Oceanic dispersion of the sediment plumes projected for the period 2017-2029. Modelled suspended sediment (TSS) values represent TSS concentrations following precipitation and temperature for the Doce river catchment. (A) Monthly average TSS map for December 2028 when TSS reached the largest value. (B) Summed monthly average TSS map across the time series (i.e. 156 months: Jan 2017 through Dec 2029). (C) Maximum TSS concentration in each pixel over the 156 months.

3.4. The relative sensitivity of ecosystems

We found that primary producers were particularly sensitive to sediment concentration increases (e.g. crustose coralline algae forming rhodolith beds and seagrasses). Their overall effect size were both significant, and 3- and 2-fold greater than impacts on coral reefs, respectively (Figure 6). We identified a smaller negative effect for rocky reef species responses to sediment concentration increases, which was also non-

456 significant. The spatial distribution of coral reefs, rocky reefs, rhodolite beds and seagrasses
 457 are shown in the Figure 7A.

458

459

460 *Figure 6. The effects of sediment increase on different categories of response for each*
 461 *of our ecosystems. The mean effect sizes $\pm$ 95% CI were derived from random-effects meta-*
 462 *analyses. The vertical solid line indicates no effect.*

463

464 *Figure 7. Impact assessment of the mine spill event of Fundao on marine biodiversity during*465 *the pulse-disturbance event. (A) Ecosystem distributions for coral reefs, rocky reefs,*

rhodolith beds, and seagrass meadows. Maps were derived using spatial data available from existing planning exercises, previous studies, and satellite imagery. (B) Impact assessed through combining ecosystem sensitivity and exposure occurred in February 2016 (Impact 1). (C) Impact assessed through combining ecosystem sensitivity and summed exposure across months (Impact 2). (D) Impact assessed through combining ecosystem sensitivity and maximum exposure across months (Impact 3). For all assessments, impact values were normalised to range between zero and one, where one reflected the maximum impact across all pixels throughout each assessment.

3.4 Impact assessment

The marine impact of the tailing dam collapse (pulse disturbance) was prevalent on rhodolith beds that form large expanses of hard bottom habitat on the southern continental shelf off the Doce river estuary (Figs. 7B-D). However, the recorded maximum level of impact also extended to small nearshore coral reefs and rhodolith beds over the southern parts of the Abrolhos Bank (northward from the river mouth) when considering the 14 months that followed the accident (i.e. pulse disturbance). We also identified nearshore seagrasses southwards from the river mouth within the impact zone. Over the 13 years in the near future (press disturbance), large tracts of ecosystems on the Abrolhos Bank including coral reefs, seagrasses and rhodolith beds might experience higher levels of impact from the tailing dam collapse, even though they would be exposed to much lower concentrations of sediments (Fig. 8). Nevertheless, rhodolith beds in the southern parts are projected to remain highly threatened by the dam-collapse event. Given the offshore movement of the sediment plume, even rhodolith beds laying on the top of seamounts could be potentially threatened.

Figure 8. Projected impact assessment of the mine spill event of Fundao on marine biodiversity. (A) Impact assessed through combining ecosystem sensitivity and exposure occurred in Dec 2028. (B) Impact assessed through combining ecosystem sensitivity and summed exposure across months. (C) Impact assessed through combining ecosystem sensitivity and maximum exposure across months. For all assessments, impact values were normalised to range between zero and one, where one reflected the maximum impact across all pixels throughout each assessment.

Finally, we summarised total impacts across six MPAs containing marine ecosystems within their boundaries in the coastal zone of our study region. We showed that two MPAs (i.e. Santa Cruz Wildlife Refuge and Environmental Protection Area Costa das Algas) had the highest level of impact on the totality of mapped ecosystems within their limits. These two MPAs were also the only ones impacted during the pulse disturbance event, both contain high-sensitivity ecosystems (e.g. rhodolith beds) and are located in the close proximity of the river mouth. The overall impact was lower for two other MPAs but showed that secondary

504 and tertiary plumes reached protected coral reefs and seagrasses in the coastal zone of the
 505 Abrolhos Bank, indicating impact in the coastal portion of the Abrolhos National Park.

507
 508 *Figure 9. Total impact of the mine spill event of Fundao on marine protected areas (MPAs).*
 509 *Upper panel depicts six MPAs potentially affected by the dam collapse (A). Solid polygons*

are no-take MPAs while hatched polygons are sustainable-use MPAs (e.g. artisanal fishing is allowed within their limits). Map on the left (A) also indicates the extents of the three types of plume from coastal-transport modelling during the pulse-disturbance event. Map on the right (B) shows the extent of three types of plume during the press-disturbance event. Bottom figure (C) displays the level of impact reported for each MPA according to the spatial extent of each ecosystem within their limits, type of disturbance (i.e. pulse and press disturbances), and exposure to different types of plume (i.e. primary, secondary, or tertiary).

4. Discussion

The ongoing increase of sediment delivered to the ocean (Milliman and Farnsworth, 2013) have several detrimental consequences for a range of ecological processes that might affect whole marine ecosystems. Impacts are especially severe when human activities deliver high sediment loads over short timescales such as the case of intensive and extensive sediment resulting from land-based mining operations. For the Doce river off the southeastern Brazil, our results demonstrate a tractable modelling approach to estimate the impact of a tailing dam collapse in different disturbance regimes, thereby tackling some of the practical challenges involved in this environmental impact assessment. Our simulations revealed that the amount of sediment exported by the river due to accidental disruption of a tailing dam was up to 180-fold greater than without the failure. Ecosystems such as rhodolith beds could be strongly affected by the sediment plume formed in the aftermath of the dam's collapse. We also identified locations on the Abrolhos Bank (northern parts of our study region), where nearshore coral reefs, seagrasses and rhodolith beds were potentially impacted in the following months after the accident. Moreover, scenarios of projections of weather conditions in the near future showed that sediment exports might remain elevated and,

depending on the how far sediment could travel in the future, areas of conservation concern and MPAs with high biological integrity can become vulnerable to sediment-induced disturbances. These results underscore the need to account for a range of key marine ecosystems, as well as considering current and future climate conditions, when managing and mitigating the impact of this threat.

We applied our approach to the case study of the tailing dam failure disaster that occurred in a headwater of the Doce river catchment on November 2015, although we believe our approach is flexible and can be applied to a diversity of land-based activities and types of ecosystems, beyond those addressed in this case study. Our research strengthens the argument for continuing to develop and link correlative potential sources of pollution within catchments with major downstream impacts on vulnerable coastal marine ecosystems. Our classification of disturbance regimes also offers insights into ecosystem management and restoration after accidents. For example, existing efforts to guide careful planning after accidental or catastrophic disturbances do not account for changing environmental regimes, or do not cover analyses that are relevant at regional or sub-regional scales at which most practical conservation decisions are made (e.g. Frazão Santos et al., 2013; Lan et al., 2015).

Despite the need for modelling the transport of contaminants due to tailing dam failure, there are very few models specifically developed to describe unsteady flow conditions in rivers that had their channel geometry modified following the mud wave displacement and subsequent flooding. An example is the HEC-RAS model (Horritt and Bates, 2002), a hydraulic model that requires not only outputs from rainfall-runoff model but also detailed cross-sectional data and channel geometry information. Employing HEC-RAS, with a hydrological component, may lead to more accurate predictions for the profile of contaminants along Doce river, particularly for the flooding conditions of November 2015 (immediately after the accident). However, as observed in this event, the flood damage was

more important over short distances (e.g. 100 km – DNPM, 2015) and close to the point of the dam’s collapse. While the hydraulic model presents capabilities for sediment transport that are not captured by SWAT, the methodology proposed here intended to assess the long-lasting impacts on biodiversity in the coastal zone, located much further from the zone of flooding (~600km from source of pollution).

The sediment export at the river mouth remained high until April 2016 (five months after the onset of the pulse event) and was close to reference levels (i.e. simulations without the accident) afterwards. According to Rudorff et al. (2018), the Doce river turbidity returned to the natural expected values between the months of June and September of 2016. Part of the difficulty in explaining the mismatches between the amount of sediment exported from the catchment and peaks of turbidity is that both modeling studies relied on predictions carried out with *in situ* sediment measurements with low time resolution; for instance, sediment flow data at high temporal resolution (e.g. daily time step) became available only during the past few months, after the accident occurred. Because some areas within Doce river catchment are highly prone to rain erosion (Oliveira and Quaresma, 2017), a more technically demanding approach is needed, requiring collection of lengthy and frequent series for sediment flow, so that simulation runs with SWAT can be carried out on daily basis to increase model accuracy. While our work is intended to give an overall picture of the differences that are due to the tailing dam failure event, it provides insights that are beneficial to quantify the relative contribution of a point pollution source associated with mining operations within the catchment, in terms of sediment delivery.

Many studies using SWAT to estimate sediment transport reported good performance in limited data settings (e.g. Dutta and Sen, 2017; Monteiro et al., 2016; Vigiak et al., 2015). Our calibration and validation results also represented good fit between simulated and measured discharges at selected points of the catchment and simulated sediment

concentrations matched TSS values measured or estimated for the region (Oliveira and Quaresma, 2017), and showed a temporal correlation with seasonal variation. Therefore, the tailing dam failure event was by far the main pollutant contributor to the adjacent coastal zone after the accident (e.g. average increase of 88% in sediment exports over the pulse disturbance regime).

The transport and fate of sediments in coastal waters have been elucidated through monitoring and modelling activities as well as the analyses of remote sensing imagery (e.g. Álvarez-Romero et al., 2014; Brodie et al., 2010; Devlin et al., 2012; Rudorff et al., 2018). When these estimates are coupled with rainfall-runoff models both for baseline conditions, and for forecasting changes under future conditions, they can be used to assess the environmental variation of impacts on unprecedented spatial and temporal scales. Presently, the only study that had analysed sediment plume dispersal for a couple of months after the tailing dam collapse using sophisticated remote sensing techniques (Rudorff et al., 2018) culminated in considerable agreement with our study; they detected a high-turbidity plume movement towards the south and reported that this plume was constrained closer to the coast. Briefly, they also reported a change in the direction of the plume towards the northern part of our study area according to satellite imagery from early 2016. Our study expands knowledge of the spatial and temporal extent of sediment distribution in coastal waters and reinforces the findings of negative impacts of suspended sediments on the southern portions of the Abrolhos Bank.

Our simulations suggested that three types of marine ecosystems and four MPAs were or can be affected by the dam failure. The results can help guide the selection of specific management actions for a given ecosystem or MPA. For instance, most of the rhodolith beds located on the southern continental shelf of the study area are high priorities for restoration due to past exposure to sediments. Conversely, coral reefs and rhodoliths on the northern

portions of the Abrolhos Bank should be particularly targeted for ecological monitoring, as these ecosystems are projected to experience future exposure to sediments. An understanding of the relative conditions of the protected ecosystems is urgently required and can be used to direct resources to aid in biodiversity protection and restoration. This is particularly important because existing MPAs are costly to manage (Ban et al., 2011; Magris et al., 2017), and imply an associated higher biological integrity than the broader seascape (Sciberras et al., 2015). Integrating the empirical approach on ecosystem conditions with modelling will allow for refinements in vulnerability assessment and in the detection of trends in ecosystem integrity over time.

There are several uncertainties in the present study, which might influence the results. The majority of water quality modeling studies using SWAT, including the application described here, have used monthly inputs to drive the models. However, meteorological and hydrological inputs at finer scale could result in different simulations of pollutant transport, which needs to be further examined. Furthermore, the measure of plume dispersal in the sea adopted in the analysis for the future does not account for projections of physical variables used to force the model because the information was not currently available (e.g. characteristics of sediment particles exported from the river without the dam collapse). In general, we found that the total area potentially affected are predicted to be enlarged; this pattern is probably exacerbated as coupling particle settling rate with the horizontal particle movement due to currents will limit the maximum extent over which sediment would disperse into the ocean from river mouth and impact biodiversity. Our analyses were adequate given the information available, but we also recommend further research to explore changes in sediment plume due to future ocean circulation changes. Finally, the effects of sediments on marine species and ecosystems, which are already well-documented (Bell et al., 2015; Erftemeijer et al., 2012; Jones et al., 2015, 2016), would likely increase if other closely

related stressors such as nutrients and contaminants that interact to cumulatively impact biota are added to our modelling framework.

5. Conclusion

In conclusion, this study represents the first preliminary assessment of the hydrological consequences of the recent tailing dam collapse and future conditions on the marine area influenced by land-based mining activity within the Doce river catchment. Analyses of hydrological modelling combined with oceanographic dispersion were conducted through the quantification of exposure to pollution, sensitivity of ecosystems, and their occurrence in coastal marine area adjacent to the river mouth. Our analyses demonstrated that the cumulative effects over time of the dam collapse exported a lot of sediment to the ocean, likely affecting key sensitive ecosystems (including protected ones). This study provides a reference for understanding the amount, priority level for threat mitigation and ecological monitoring of impacts, and location of areas being affected in the sea. High priority areas for threat mitigation and restoration were identified along the outer continental shelf off southeastern Brazil and southern portions of the Abrolhos Bank, where the presence of key sensitive ecosystems fall within the zone of influence of primary and secondary pollutant plumes, triggering impact events. We also suggest routinely targeting sensitive components of key ecosystems such as rhodolith beds, coral reefs and seagrasses across the whole Abrolhos Bank into current monitoring network, given the potential for future impacts. In particular, specific assessments involving the four MPAs affected in the region will be necessary to help recover marine biodiversity threatened by this disaster, and an accurate valuation of ecosystem services lost.

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