

# Remote sensing as a tool for assessing landslide impacts on coastal waters at Porchat Island (SE Brazil)

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## Research Article

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# Abstract

On April 29, 2025, a water pipeline rupture on Porchat Island (São Vicente, southeastern Brazil) triggered a mass movement that released sediment into adjacent coastal waters. Effects of urban infrastructure failures on coastal water quality are rarely documented with imagery of adequate spatial and temporal resolution. We used Sentinel-2 and PlanetScope imagery, processed in ACOLITE, to estimate turbidity, suspended matter concentration (SMC), chlorophyll-a, and Secchi disk depth before and after the rupture, and related the sediment plume to meteoceanographic conditions. In Sentinel-2 images, mean SMC in the waters adjacent to the island increased from 11.15 to 21.09 g/m<sup>3</sup> and mean Secchi depth decreased from 2.01 to 1.12 m, with smaller changes in Santos and São Vicente bays. PlanetScope images showed a similar pattern near the island, with values of similar magnitude. Chlorophyll-a varied among dates without a clear response. As no in situ data were available, results are interpreted as relative changes. PlanetScope's daily revisit showed the sediment plume shrinking from 7.50 km<sup>2</sup> on April 30 to 2.02 km<sup>2</sup> on May 2 and dispersing toward central Santos Bay under waves from the southeast and south quadrants and weak winds. This case shows that an infrastructure failure can cause marked but apparently temporary changes in the optical properties of coastal waters, and indicates that high-frequency, high-resolution remote sensing is useful for rapid impact assessment and for supporting coastal monitoring and management.

## 1 Introduction

Coastal zones play a fundamental role in maintaining ecosystem services, including biodiversity conservation, carbon sequestration, and natural protection against extreme events such as storms and coastal flooding (Barbier et al. 2011; Hopkinson et al. 2019; Windham-Myers, Crooks, Troxler 2018). The maintenance of these environments depends directly on several factors, such as the continuous input of sediments from rivers, coastal erosion, and slope instability processes, considering that sediment deficits can compromise the integrity of coastal morphology and reduce the capacity of these systems to respond to environmental pressures (Coleman et al. 2022; Fagherazzi et al. 2013; Kirwan, Megonigal 2013; Ladd et al. 2019).

Among the sediment sources that influence coastal environments, mass movement processes stand out, playing an important role in landscape evolution, weathering processes, and sediment dynamics (Dadson et al. 2003; Neil et al. 2002; Rabalais et al. 2007). These events can release large volumes of terrigenous material over short periods of time, significantly altering sediment fluxes between continental and coastal environments. Studies show that episodic events, such as floods, intense storms, and landslides, can promote significant changes in aquatic ecosystems by increasing sediment and organic matter input to the coastal zone (Fong, Gaynus, Carpenter 2020; Smith et al. 2021). As a result, fast changes may occur in the physical, chemical, and biological characteristics of the water column, including changes in turbidity, transparency, light availability, and suspended matter concentration (SMC), parameters directly related to water quality and ecosystem functioning (Kobiyama et al. 2011; Simão et al. 2025).

The changes are largely governed by the optically active components of coastal waters, namely dissolved and particulate substances of organic and inorganic origin that interact with solar radiation through absorption and scattering (Barbosa et al. 2019; Mobley 1994). Among these constituents, total particulate matter (or total suspended matter), composed of phytoplankton and non-algal inorganic and organic particles, strongly influences the optical behavior of water, controlling light penetration through the water column, reducing the availability of photosynthetically active radiation, limiting primary production, and influencing the functioning of aquatic ecosystems (Mobley 1994, Li et al. 2022; Wang et al. 2022).

Another important optically active component is chlorophyll-a, the main photosynthetic pigment of phytoplankton, widely used as an indicator of phytoplankton biomass, primary productivity, and the eutrophication status of aquatic environments (Boyce, Lewis, Worm 2010; Gohin et al. 2019). In coastal and estuarine areas, its distribution shows high spatial and temporal variability due to the mixing of continental and marine waters, nutrient inputs, and local hydro-sedimentary dynamics (Arabi et al. 2020; Gitelson et al. 2007). Thus, the variables are useful indicators for coastal water quality assessment and management.

Monitoring these parameters is essential for understanding water dynamics and quality. However, conventional methods based on field sampling campaigns and laboratory analyses require substantial financial investment, human resources, and execution time, in addition to presenting limitations regarding the spatial and temporal coverage of observations (Bende-Michl et al. 2011; Brivio, Giardino, Zilioli 2001; Schaeffer et al. 2013; Volk, Liersch, Schmidt 2009).

In this context, remote sensing has become established as an important tool for the environmental monitoring of water bodies. Technological advances in orbital sensors have improved the spatial and temporal resolution of imagery, providing spatially explicit information that can support rapid impact assessment, emergency response, and coastal management (Barbosa et al. 2019; Jensen 2014).

Despite the progress observed in the remote estimation of parameters such as turbidity, SMC, and chlorophyll-a, studies evaluating the response of coastal waters to episodic sediment input events resulting from mass movements remain scarce (e.g., Irie, Nakagawa, Higashi 2023; Kobiyama et al. 2011; Lin et al. 2011), and even fewer have done so with spatial resolutions compatible with management needs, such as delimiting the affected area and tracking its persistence. This gap becomes particularly relevant in urbanized coastal regions, where anthropogenic interventions can trigger abrupt changes in hydro-sedimentary processes and where information on such events is needed to guide response, impact assessment, and slope and drainage management.

One such event occurred on April 29, 2025, when the rupture of a water pipeline belonging to the Companhia de Saneamento Básico do Estado de São Paulo (Sabesp - Basic Sanitation Company of the State of São Paulo), located on Porchat Island, in the municipality of São Vicente (São Paulo, Brazil), triggered a mass movement on an adjacent slope. The large volume of water released caused the displacement of sediment and vegetation (Santa Portal 2025), estimated at approximately 860,000 m<sup>3</sup>

(Mário Bueno, personal communication, June 23, 2025), resulting in the transport of this material to the coastal waters near the island (G1 Santos 2025). Porchat Island is an urbanized area on steep slopes, classified as a Permanent Preservation Area and subject to civil defense monitoring for geological risk, which makes the event a representative case of the interaction between urban infrastructure, slope stability, and coastal water quality (Marques 2015). The event caused a marked visual change in water color, suggesting substantial changes in SMC and other water quality-related parameters.

Given this context, the present study aimed to quantify turbidity, water transparency, SMC, and chlorophyll-a concentrations before and after the pipeline rupture that occurred in April 2025, using high spatial resolution optical imagery, and to delineate the extent and persistence of the sediment plume in relation to the prevailing meteoceanographic conditions. By doing so, we evaluate the potential of high-resolution remote sensing as a tool for rapid impact assessment, providing support for environmental monitoring, coastal planning and management, and the assessment of the effects of urban infrastructure failures on coastal marine environments.

## 2 Materials and methods

### 2.1 Study area

Porchat Island is located in the municipality of São Vicente (Fig. 1), on the central coast of the state of São Paulo, forming part of the Santos Estuarine System (SES), a hydrological network that discharges into the Santos and São Vicente channels. The waters adjacent to the island connect Santos Bay (SB) and São Vicente Bay (SVB). The oceanographic dynamics of the bays are marked by high hydrodynamic complexity, governed mainly by a mixed microtidal regime (Seiler 2019).

From a geomorphological standpoint, the area is part of the Residual Hills compartment, situated at the base of the Serra do Mar, with elevations reaching approximately 200 meters. The local geology is predominantly composed of Precambrian rocks, such as migmatites, gneisses, and granites, resulting from the tilting of the Serra do Mar toward the ocean. The topography is markedly rugged, with steep slopes averaging 50° in inclination, and due to the abrupt contact between the hills and the sea, the island is characterized by rocky shores and cliffs, which prevent the natural formation of beaches along its immediate perimeter (Marques 2015).

Anthropogenic interference on Porchat Island intensified from the 1950s onward, evolving into consolidated urbanization with multi-story buildings and disorderly occupation, often on shallow residual soils, increasing susceptibility to mass movements. Soil sealing caused by paving and construction, combined with drainage systems that frequently become insufficient or obstructed by debris, overloads the slopes and favors erosive processes and landslides (Marques 2015).

Environmentally, Porchat Island is classified as a Permanent Preservation Area (APP), protected under the Forest Code and federal and state legislation to mitigate erosion and preserve Atlantic Forest biodiversity. However, urban pressure and historical deforestation have generated a state of physical

fragility, making the area subject to constant monitoring by civil defense preventive plans due to the risk of geological accidents triggered by intense rainfall events (Marques 2015).

## 2.2 Meteoceanographic data

The in situ wave data used in this study, significant wave height ( $H_s$ ) and period ( $T$ ), were provided by the Santos Port Authority (APS) (Mooring station in Fig. 1). Additionally, due to the lack of in situ wave direction ( $Dir$ ) data, complementary data were obtained from the Global Ocean Waves Reanalysis product through the Copernicus Marine Data Store platform (Copernicus Marine Service, n.d.), for the period between April 14 and May 3, 2025, with a temporal resolution of 3 hours and a spatial resolution of  $0.083^\circ$ , extracted from a point near the coast (location shown in Fig. 1).

Wind data for the period between April 14 and May 3, 2025, used in this study were obtained from the Sistema de Informações da Qualidade do Ar (Qualar - Air Quality Information System; location in Fig. 1), maintained by the Companhia Ambiental do Estado de São Paulo (CETESB - São Paulo State Environmental Company).

Current direction and intensity were also provided by the APS (Mooring station in Fig. 1), with values for four water column depths (4, 6, 8, and 10 m). Precipitation data for the analysis period were obtained from the Paranapuã rain gauge station (location in Fig. 1), in the municipality of São Vicente, from the Centro Nacional de Monitoramento e Alertas de Desastres Naturais (Cemaden - National Center for Monitoring and Early Warning of Natural Disasters), with data collected between April 14 and May 3, 2025. Cumulative rainfall data, in millimeters, are recorded every 10 minutes during rainfall and every 60 minutes in the absence of precipitation. From these data, daily cumulative precipitation values were calculated.

Tidal variation was estimated using the UTide package for Python (Codiga 2011). In situ sea level data collected between August 2024 and November 2025 at Ilha das Palmas ( $24^\circ00'31.0''S$ ,  $46^\circ19'28.6''W$ , Mooring station in Fig. 1) were used to determine the harmonic constants through UTide, which were subsequently applied to generate predictions and interpret tidal phases for each of the analyzed dates (Table 1).

Table 1  
Acquisition times (UTC) of the images used and tidal information

| Date         | Sensor      | Image acquisition | Tide        |
|--------------|-------------|-------------------|-------------|
| Apr 15, 2025 | Sentinel-2  | 13:12             | Ebb, Neap   |
| Apr 27, 2025 | PlanetScope | 13:37 and 13:38   | Flood, Neap |
| Apr 30, 2025 | PlanetScope | 13:37             | Ebb, Neap   |
| May 2, 2025  | Sentinel-2  | 13:12             | Ebb, Neap   |
| May 2, 2025  | PlanetScope | 13:44             | Ebb, Neap   |

## 2.3 Satellite image acquisition and processing

Satellite image selection and acquisition were based on the Sentinel-2 and PlanetScope sensors. For the Sentinel-2 images, acquisition was carried out using the Copernicus Browser, a tool developed by the European Union's space program that allows visualization and access to data from all Copernicus missions. Sentinel-2 Level-1C Collection 1 was selected, which provides orthorectified top-of-atmosphere (TOA) reflectance. The Sentinel-2 satellite carries a multispectral sensor (MultiSpectral Instrument; MSI), with 13 spectral bands (with spatial resolution of 10, 20, and 60 meters), a 5-day revisit time, and systematic global coverage over land masses and coastal areas up to 20 km from the coast (European Space Agency, n.d). Two dates were selected: April 15, 2025 (pre-event) and May 2, 2025 (post-event).

PlanetScope TOA reflectance images were obtained from the Web imagery platform of the Programa Brasil M.A.I.S (Accession Agreement No. 23/2025/SE/MJSP). This sensor stands out for its high temporal (daily revisit) and spatial (3 m) resolution compared to other satellites. Three analysis dates were selected: one pre-event (April 27, 2025) and two post-event (April 30 and May 2, 2025), to track the extent of the sediment plume resulting from the mass movement. An additional PlanetScope image from May 4 was used only to verify whether the plume was still detectable (not shown here).

To improve data quality and eliminate atmospheric effects, atmospheric correction of the images was performed using the ACOLITE tool (version 20250402.0). The default configuration was used, based on the "Dark Spectrum Fitting" approach, which performs particularly well in turbid, productive waters (ACOLITE 2025). Cloud pixels were masked by ACOLITE using its default settings.

## 2.4 Estimation of turbidity, SMC, chlorophyll-a, and transparency

Retrieval of the bio-optical descriptors of water quality was performed using the ACOLITE processor, which, following atmospheric correction, generates Level 2R (L2R) surface reflectance products and, from these, Level 2W (L2W) products corresponding to reflectance-derived parameters. The retrieval algorithms were applied following the guidelines of the processor manual, developed for applications in coastal and inland aquatic environments, including optically complex waters (Vanhellemont, 2023).

Chlorophyll-a concentration (chl, in  $\text{mg}/\text{m}^3$ ) was calculated using an algorithm based on the reflectance ratio between the blue and green bands (Table 2), using calibration values from Franz et al. (2015) built into the software. This methodology was adopted based on a study previously conducted in the area by Fernandes et al. (2026, *in press*). The manual notes that this product should be interpreted with caution in coastal waters due to interference from sediments and colored dissolved organic matter (CDOM).

Suspended matter concentration (SMC, in  $\text{g}/\text{m}^3$ ) was estimated using the algorithm of Nechad et al. (2010; Table 2), using the red band (ACOLITE default). Turbidity (TUR, in FNU) was calculated using the algorithm of Nechad et al. (2009). Secchi disk transparency depth (Zsd, in meters) was derived using the

QAA-RGB method of Pitarch & Vanhellemont (2021). This parameter allows quantification of the reduction in water clarity caused by sediment input following the event.

To characterize the spectral response of the water, remote sensing reflectance ( $R_{rs}$ ) spectra were extracted from the ACOLITE products at three points, one in each study region (waters adjacent to Porchat Island, Santos Bay, and São Vicente Bay – Fig. 1), for all image dates. The points were selected arbitrarily within each region, without a formal sampling design, and were used only for a qualitative comparison of spectral shape and magnitude among dates, sensors, and regions.

Statistical processing of the spatial data was performed in QGIS (version 3.42.3), from which mean values were extracted for the waters adjacent to Porchat Island and for Santos and São Vicente bays. The extent of the sediment plume was delineated from the PlanetScope imagery, considering the SMC products, where pixels above  $15 \text{ g/m}^3$  were selected to generate a binary raster (threshold chosen from visual inspection of the plume boundary in the true-color images), which was then converted to a polygon (shapefile) delimiting the area covered by the plume, allowing its area and dispersion dynamics to be monitored. No *in situ* measurements of turbidity, SMC, chlorophyll-a, or Secchi depth were available for this event, so the satellite-derived products could not be validated locally. Accordingly, the results are interpreted as relative changes between dates and among regions, rather than as absolute concentrations.

Table 2  
Parameters calculated from the satellite images.

| Parameter                                                                                                                                            | Equation                                                                                       | Notes                                                                                                                                                                                  |
|------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Chlorophyll-a                                                                                                                                        | $chl = 10^{(a_0 + a_1 + R + a_2 R^2 + a_3 R^3 + a_4 R^4)}$                                     | R: logarithm of the ratio between the maximum blue band reflectance and the green band reflectance; $a_0$ : 0.2412; $a_1$ : -2.0546; $a_2$ : 1.1776; $a_3$ : -0.5538; $a_4$ : -0.4570. |
| Suspended matter concentration                                                                                                                       | $SMC = \frac{A_T^\rho \rho_w B^\rho C^\rho}{1 + \rho_w}$                                       | $A^\rho$ : first calibration parameter; $B^\rho$ : second calibration parameter; $C^\rho$ : third calibration parameter ; $\rho_w$ : red or near-infrared band..                       |
| Turbidity                                                                                                                                            | $TUR = \frac{A_T^\rho B^\rho C^\rho}{1 + \rho_w}$                                              | $A_T$ : first calibration parameter; $B_T$ : second calibration parameter; $C$ : third calibration parameter; $\rho_w$ : red or near-infrared band.                                    |
| Secchi disk depth                                                                                                                                    | $Z_{SD} = \frac{\log\left(\frac{0.015}{0.015 - R_{rs}(\lambda_m)}\right)}{2.5 K_d(\lambda_m)}$ | $R_{rs}$ : remote sensing reflectance; $\lambda_m$ : band at which the spectral minimum of $K_d$ is located; $K_d$ : vertical attenuation coefficient.                                 |
| Note: Based on $Z_{SD}$ , in order to eliminate potentially remaining biases, the polynomial $S(Z_{SD,b})$ was used to obtain the unbiased estimate. |                                                                                                |                                                                                                                                                                                        |

## 3 Results

### 3.1 Water quality changes and plume extent

In the Sentinel-2 images, SMC, turbidity, and Zsd indicated a stronger response in the waters adjacent to Porchat Island than in the bays between the pre-event (April 15) and post-event (May 2) dates (Table 3, Fig. 2). Mean SMC and turbidity in these waters nearly doubled (from 11.15 to 21.09 g/m<sup>3</sup> and from 11.40 to 21.14 FNU, respectively), and mean Zsd decreased from 2.01 to 1.12 m, whereas changes in SVB and SB were smaller, indicating that the strongest response was concentrated near the island. Chlorophyll-a increased in all areas, but not more strongly near the landslide site.

Table 3

Mean values of water quality variables in the adjacent waters (AW) to Porchat Island, São Vicente Bay (SVB) and Santos Bay (SB), derived from Sentinel-2 (S2, April 15 and May 2) and PlanetScope (April 27, April 30 and May 2) images.

| Variable                           | Region | S2 Apr 15 | Planet Apr 27 | Planet Apr 30 | S2 May 2 | Planet May 2 |
|------------------------------------|--------|-----------|---------------|---------------|----------|--------------|
| SMC (g/m <sup>3</sup> )            | AW     | 11.15     | 15.42         | 26.79         | 21.09    | 21.07        |
|                                    | SVB    | 9.56      | 11.63         | 14.13         | 12.43    | 20.42        |
|                                    | SB     | 8.51      | 10.59         | 14.67         | 10.02    | 11.71        |
| Turbidity (FNU)                    | AW     | 11.4      | 12.26         | 21.3          | 21.14    | 16.75        |
|                                    | SVB    | 9.69      | 9.24          | 11.24         | 12.62    | 16.24        |
|                                    | SB     | 8.63      | 8.42          | 11.66         | 10.12    | 9.31         |
| Zsd (m)                            | AW     | 2.01      | –             | –             | 1.12     | –            |
|                                    | SVB    | 1.94      | –             | –             | 1.3      | –            |
|                                    | SB     | 2.51      | –             | –             | 2.11     | –            |
| Chlorophyll-a (mg/m <sup>3</sup> ) | AW     | 4.14      | 2             | 1.76          | 4.54     | 3.75         |
|                                    | SVB    | 3.45      | 1.86          | 1.68          | 4.77     | 4.09         |
|                                    | SB     | 3.68      | 1.93          | 1.72          | 4.33     | 3.88         |

In the PlanetScope images (Table 3, Fig. 3), SMC and turbidity increased in all regions on April 30, the day after the event, and the increase was largest in the adjacent waters (SMC from 15.42 to 26.79 g/m<sup>3</sup>; turbidity from 12.26 to 21.30 FNU). By May 2, the values in these waters had decreased but remained above pre-event conditions, and those in SB had returned close to them (SMC of 11.71 g/m<sup>3</sup> and turbidity of 9.31 FNU, compared with 10.59 g/m<sup>3</sup> and 8.42 FNU on April 27). In SVB, in contrast, SMC and turbidity kept increasing until May 2 (to 20.42 g/m<sup>3</sup> and 16.24 FNU), even though the plume mapped on April 30 and May 2 did not enter this bay. Chlorophyll-a decreased slightly in all regions on April 30 and increased on May 2 to values higher than those of April 27 (Table 3). The values of April 30 should be interpreted with caution, given the cloud cover in that image.

On May 2, the products of the two sensors showed the same spatial pattern and values of the same order of magnitude. Mean SMC in the adjacent waters was practically identical (21.09 g/m<sup>3</sup> in Sentinel-2 and 21.07 g/m<sup>3</sup> in PlanetScope), and the largest difference occurred in SVB, where SMC was higher in PlanetScope (20.42 g/m<sup>3</sup>) than in Sentinel-2 (12.43 g/m<sup>3</sup>). Differences in turbidity were at most 4.4 FNU, and Sentinel-2 chlorophyll-a means were slightly higher than those of PlanetScope in all regions (by 0.45 to 0.79 mg/m<sup>3</sup>).

The analysis of the PlanetScope images revealed rapid dispersion of the sediment plume generated after the landslide (Fig. 4). It initially covered a total area of 7.5 km<sup>2</sup> on April 30 and 2.02 km<sup>2</sup> on May 2. By May 4 (image not shown here, only discussed), the plume could no longer be identified in the previously affected region. The plume was concentrated near Porchat Island and advanced over the central portion of SB, without entering SVB.

## 3.2 Spectral response

The Rrs spectra obtained at the three extraction points showed, on all analyzed dates (Fig. 5), the spectral shape typical of turbid coastal waters, with a reflectance peak between 530 and 580 nm and a decline toward the near-infrared. On the dates preceding the pipeline rupture, the three sites showed relatively similar Rrs magnitudes. On April 15, peaks ranged from 0.0105 sr<sup>-1</sup> (SVB) to 0.0157 sr<sup>-1</sup> (SB), with the adjacent waters in an intermediate position (0.0127 sr<sup>-1</sup>); on April 27, the adjacent waters and SVB showed similar peaks (0.0163 and 0.0158 sr<sup>-1</sup>), while SB recorded the lowest value (0.0108 sr<sup>-1</sup>). On April 30, a marked increase in Rrs was observed at all points, most notably in SB (0.0275 sr<sup>-1</sup>), followed by the adjacent waters (0.0255 sr<sup>-1</sup>) and SVB (0.0185 sr<sup>-1</sup>); on this date, however, the PlanetScope image showed pronounced cloud cover, which should be taken into account in the analysis. On May 2, the adjacent waters showed the highest Rrs peak (0.0215 sr<sup>-1</sup> in Sentinel-2 and 0.0183 sr<sup>-1</sup> in PlanetScope), exceeding SB (0.0157 and 0.0125 sr<sup>-1</sup>) and SVB (0.0092 and 0.0075 sr<sup>-1</sup>). Good agreement was observed between Sentinel-2 and PlanetScope regarding curve shape.

## 3.3 Meteoceanographic data

Regarding the meteoceanographic data, during the analyzed period, significant wave height (Fig. 6a) ranged from 0.86 m to 2.59 m for the reanalysis data, and from 0.35 m to 2.5 m for the in situ data (R<sup>2</sup> between the datasets of 0.73). Wave periods (Fig. 6b) ranged from 4.3 to 10.39 seconds (reanalysis data) and from 4.1 to 24 seconds (in situ, with an R<sup>2</sup> of 0.57 between the datasets). Regarding propagation direction (Fig. 6c), waves predominantly came from the Southeast (SE) quadrant until April 20, followed by a shift to South (S) until April 23, returning to the SE direction between April 24 and 28, and remaining from the S thereafter.

Wind records obtained at the CETESB monitoring station (Fig. 6d), for the period from April 14 to May 3, 2025, indicated a predominance of weak to calm winds, with speeds ranging from 0 to 1.7 m/s. The highest wind speeds (up to 1.7 m/s) occurred mainly between April 17 and 19, with additional peaks recorded on April 30. Wind direction showed temporal variability, but with a predominance of winds from the southeast quadrant (SE, between approximately 120° and 170°) during the afternoons, and from the southwest/west-southwest quadrant (SW/WSW, between approximately 220° and 256°).

Regarding currents (Fig. 6e and f), the data showed a fairly similar pattern across the analyzed depths (4, 6, 8, and 10 m). Current speeds reached a maximum of 0.4 m/s. In terms of direction, a typically

bidirectional pattern was observed, with currents predominantly oriented between the N-NE and S-SW quadrants, with similar directions throughout the water column.

Precipitation data recorded at the Paranapuã station (Fig. 6g), in São Vicente, indicate the occurrence of significant rainfall events during April 2025. On April 19, the highest volume was recorded, with 74.4 mm. On the dates preceding the pipeline rupture (April 24, 25, and 28) cumulative rainfall of 20.8 mm, 16.4 mm, and 24.6 mm was recorded, respectively. On the day of the rupture (April 29), only 0.4 mm was recorded, and dry conditions predominated in the following days.

## 4 Discussion

### 4.1 Drivers of the event

The integrated analysis of remote sensing data and meteoceanographic conditions indicates that the mass movement event that occurred on Porchat Island constituted a point-source sediment input event capable of altering the quality of the adjacent coastal waters, although its effects were predominantly transient. The results indicate that the observed dynamics appear to have resulted from the interaction between prior soil saturation, the sudden water input resulting from the pipeline rupture, and the hydrodynamic processes acting in SB.

Episodic sediment input events triggered by infrastructure failures or mass movements on urbanized slopes, although still poorly documented in the coastal remote sensing literature, find relevant parallels in other regions of the world. On the California coast, Warrick et al. (2025) used satellite imagery combined with hydrodynamic modeling to characterize fine sediment plumes originating from beach nourishment operations, demonstrating that wave height, wind speed and direction, and sediment settling velocity exert strong control over the direction and extent of the turbid plume, a meteoceanographic control pattern very similar to that observed in this study for the dispersion of the Porchat Island plume. In Taiwan, Zhou et al. (2026) reconstructed, through multisensor remote sensing, a cascade of hydrogeological hazards triggered by a typhoon-induced landslide that dammed a river and subsequently breached, showing how the integration of different orbital data sources allows detailed temporal documentation of slope destabilization processes and their subsequent hydrological impacts, reinforcing the potential of high-resolution remote sensing for monitoring episodic events similar to the one in São Vicente.

Although only 0.4 mm of precipitation was recorded on the date of the rupture (April 29, 2025), the rainfall data show that the terrain was already under the influence of conditions favorable to instability. In the days preceding the event, cumulative rainfall of 61.8 mm over 5 days was recorded. This precipitation history suggests that the soil may have presented a high degree of saturation, reducing its mechanical resistance and increasing susceptibility to mass movements, which is consistent with the pattern of disorderly urbanization on shallow residual soils and insufficient drainage systems already

described for Porchat Island by Marques (2015) and with the history of anthropogenic pressure on the Santos and São Vicente Estuarine System reported by Sartoretto (2014).

## 4.2 Oceanographic control and plume response

The dispersion dynamics of the sediment plume observed after the event on Porchat Island are consistent with the prevailing meteoceanographic conditions in SB, especially with the wave and wind regime recorded between April 29 and May 2, 2025. The initial propagation of the plume toward the central portion of SB was mainly associated with the change in wave incidence direction. On April 29, there was a rotation from the Southeast (SE) to the South (S) quadrant, with directions varying between  $160^\circ$  and  $175^\circ$ , favoring the transport of sediments remobilized in the Porchat Island region to adjacent areas of the bay. This mechanism, combined with the peak significant wave height recorded during this period (Fig. 6a), may help explain the extent observed on April 30, 2025, when the plume occupied its largest mapped area, 7.50 km<sup>2</sup>.

In the following days, however, the area occupied by the plume decreased rapidly, reaching 2.02 km<sup>2</sup> on May 2, 2025, and becoming undetectable in the images from May 4. This contraction is consistent with the evolution of meteoceanographic conditions over the period: significant wave height and wind speed, which reached higher values around April 29–30, showed a declining trend in the following days (Fig. 6a, d), with low to moderate wind speeds (up to 1.7 m/s) progressively reducing the energy available to keep sediment material resuspended and actively mixed in the water column. With this decrease in energy, the material in suspension tends to be progressively diluted by the continued action of local currents, which showed a typically bidirectional pattern between the N-NE and S-SW quadrants throughout the water column (Fig. 6e, f), favoring the exchange and renewal of the water mass in the region adjacent to the island even under neap tide conditions (Green and Coco 2013). This pattern of a pulse followed by rapid decay is consistent with the behavior described for other coastal plumes of episodic origin, controlled mainly by wave height and wind speed and direction (Warrick et al. 2025).

The confinement of the plume to SB, without sediments entering SVB, is consistent with the base circulation already described for the SES. Computational hydrodynamic modeling studies indicate that the trajectories of continental waters reaching Santos Bay follow distinct preferential patterns depending on their origin, for example, waters from the Cubatão River tend to reach Santos Bay preferentially through the mouth of the São Vicente Estuary, while those from the Quilombo River preferentially follow the Port Channel (Roversi et al. 2016), which helps explain why local circulation tends to compartmentalize the dispersion of material between the different water bodies of the system, even in the face of a point and abrupt input such as that from Porchat Island. This behavior is also consistent with the long-term characterization of Santos Bay as a receiving environment for significant contributions of suspended material, nutrients, and chlorophyll-a from the Santos and São Vicente estuarine channels, especially during periods of higher river discharge, which favor eutrophication processes in the bay (Moser et al. 2005).

Chlorophyll-a was higher on May 2 than on the previous PlanetScope dates and than on April 15 in Sentinel-2, reaching similar values in both sensors (about 3.8–4.8 mg/m<sup>3</sup>). However, Sentinel-2 values on April 15 were already close to those of May 2 (3.5–4.1 mg/m<sup>3</sup>), whereas PlanetScope values on April 27 and 30 were lower (about 1.7–2.0 mg/m<sup>3</sup>), so the data indicate variability among dates rather than a response clearly attributable to the landslide. Nutrient remobilization, runoff after the rainfall of April 19–28, and the biogeochemical response described for this estuarine system (Moser et al. 2005) are possible explanations, and interference of sediments and CDOM on the blue-to-green algorithm cannot be excluded; *in situ* data would be needed to separate them. Nevertheless, SMC and turbidity in SVB increased between April 27 and May 2 (Table 3), which may reflect continental runoff or estuarine discharge after the April rainfall.

## 4.3 Sensor comparison and uncertainties

The Sentinel-2 and PlanetScope products for May 2 showed a consistent spatial pattern and values of the same order of magnitude (Table 3). Mean SMC in the adjacent waters was practically identical (21.09 and 21.07 g/m<sup>3</sup>), and the largest difference occurred in SVB (12.43 and 20.42 g/m<sup>3</sup>). The PlanetScope maps showed more pronounced spatial variability, an effect consistent with its higher spatial resolution, which preserves features of heterogeneous plumes that coarser pixels smooth out (Dorji and Fearn 2017). Differences in acquisition time (about 30 minutes apart), spectral bands, and radiometric calibration may also contribute, and without *in situ* data it was not possible to determine which product is closer to the actual concentrations.

Comparisons between these sensors in other settings show that performance depends on the variable and the algorithm. Mansaray et al. (2021) compared PlanetScope, Landsat-8, and Sentinel-2 for chlorophyll-a, turbidity, and Secchi depth in agricultural reservoirs in Oklahoma (USA), and Wasehun et al. (2025) found that the performance of Sentinel-2 and PlanetScope for chlorophyll-a in a North Carolina reservoir varied with the algorithm. Regarding radiometric accuracy, Di Francesco et al. (2025) note that the PlanetScope constellation lacks onboard radiometric calibration, which hinders corrections compared to Sentinel-2, especially in scenes affected by sun glint and greater uncertainty in atmospheric correction.

The increase in suspended solids associated with the resuspension and displacement of sediment by waves and currents tends to raise turbidity and reduce water column transparency (Green and Coco 2013), as observed in the decrease of Zsd, because more suspended particles increase light scattering and absorption and limit light penetration. The consequent reduction in the light available to phytoplankton may limit primary production (Cloern 1987), but no clear chlorophyll-a response to the event was detected here.

The Rrs spectra reinforce, with some caveats, the spatial pattern of the plume mapped via PlanetScope. On May 2, under more favorable atmospheric conditions, the highest Rrs peak occurred in the adjacent waters, consistent with the still elevated SMC and turbidity recorded there. The April 30 image, however, requires greater caution. Although the generalized increase in Rrs at all points is compatible with the

sediment input immediately after the rupture, this image had pronounced cloud cover. ACOLITE masked cloud pixels, but cloud shadows over water are not removed by the processor and may have been retrieved as water, biasing the products locally, and radiance from nearby clouds may have contaminated neighboring water pixels through adjacency effects, artificially raising the reflectance (Feng and Hu 2016). Atmospheric correction is also more uncertain in scenes with high cloud cover (Pahlevan et al. 2021; Warren et al. 2019). Thus, the peak observed in SB (whose extraction point was outside the plume mapped that day) cannot be safely attributed solely to sediment advection driven by the wave rotation from SE to S on April 29. The same caution applies to the SMC, turbidity, and chlorophyll-a means of April 30 and to the plume area of 7.50 km<sup>2</sup> on that date, since masked areas may have concealed part of the plume and shadows may have affected its delineation. Even so, the increase near the island on April 30 is consistent with the pattern observed in both sensors on May 2, so the direction of the response is more reliable than its magnitude. This limitation reinforces the need to prioritize images with lower cloud cover, and to mask cloud shadows, in the rapid assessment of similar events.

In addition, the Sentinel-2 pre-event image (April 15) precedes the heavy rainfall of April 19 (74.4 mm) and April 24–28, so part of the changes observed in the bays may reflect continental runoff. The PlanetScope baseline (April 27) was acquired after these rains, and in SVB the PlanetScope values kept increasing until May 2 even though the mapped plume did not enter this bay, which suggests a contribution from other sources.

## 4.4 Implications for coastal management and monitoring

The Porchat Island event illustrates a type of disturbance that is rarely captured by conventional monitoring. The plume was detectable for only a few days, expanding to 7.50 km<sup>2</sup> by April 30 and shrinking to 2.02 km<sup>2</sup> by May 2. Its maximum mapped extent could be documented only because PlanetScope provides daily revisits at 3 m spatial resolution. The Sentinel-2 images available for the analysis spanned the period of the event but did not coincide with its peak. On its own, therefore, this sensor would have documented the change in water quality but not the extent or the rapid dissipation of the plume, also given its coarser spatial resolution. This supports the argument of Dorji and Fearn (2017) that sensor characteristics determine which features of heterogeneous plumes are resolved, and suggests that, for episodic events, temporal resolution is as decisive as spatial resolution.

The event also shows how infrastructure and slope conditions interact with coastal water quality. The rupture occurred on an urbanized slope after several rainy days, in an area classified as a Permanent Preservation Area and monitored by civil defense for geological risk (Marques 2015). In this context, the water released by the pipeline probably acted as a trigger on soil that may already have been close to its stability limit, which suggests that risk assessments based only on rainfall thresholds may not capture failures in drainage and water supply infrastructure. Studies of cascading effects triggered by landslides, such as that of Zhou et al. (2026) in Taiwan, likewise emphasize the importance of combining multisensor observations with information on triggering conditions. In the case of Porchat Island, satellite products made it possible to document the coastal consequences of this failure, an aspect that is often outside the scope of slope monitoring programs.

The temporary nature of the optical changes should be interpreted with caution. The rapid dissipation of the plume is consistent with the energetic dispersion and renewal of the water mass discussed, as well as with the behavior of episodic plumes described by Warrick et al. (2025). However, the fate of the approximately 860,000 m<sup>3</sup> of mobilized material was not assessed. Sediment that left the water column may have settled on the seafloor of Santos Bay, where its effects would not be visible in optical imagery. In addition, the biological response, particularly the variation in chlorophyll-a among dates chlorophyll-a, cannot be clarified without *in situ* data. Since Santos Bay supports uses that depend on water quality, the disappearance of the surface signal cannot be equated with the absence of impacts. Rather, the results indicate that satellite imagery is suitable for delineating the affected area and its short-term persistence, whereas assessing ecological and deposition effects requires complementary field sampling soon after similar events. Finally, the workflow used here relied on open-access Sentinel-2 data, institutional access to PlanetScope, and standard ACOLITE processing, which makes it potentially replicable by environmental agencies.

## 5 Conclusion

The mass movement triggered by the pipeline rupture on Porchat Island represented a point-source sediment input with marked, though apparently transient, impacts on the water quality of the adjacent coastal waters. Between April 15 and May 2, mean SMC in the adjacent waters increased by about 89% (11.15 to 21.09 g/m<sup>3</sup>) and mean Secchi depth decreased by about 44% (2.01 to 1.12 m) in Sentinel-2, with smaller changes in Santos and São Vicente bays. The sediment plume mapped with PlanetScope decreased from a maximum mapped extent of 7.50 km<sup>2</sup> on April 30 to 2.02 km<sup>2</sup> on May 2, and was no longer identifiable on May 4.

Plume dispersion was consistent with the combination of prior rainfall, which probably left the slope saturated, the rotation of wave incidence toward the south quadrant, which directed the material toward the central portion of Santos Bay, and the subsequent decline in wave and wind energy, which coincided with the dilution of the plume by local currents. Chlorophyll-a did not show a response clearly attributable to the event, since values varied among dates and sediment and CDOM interference on the algorithm cannot be excluded.

These conclusions should be considered in light of some limitations. No *in situ* data were available for validation. Therefore, results are interpreted as relative changes rather than absolute concentrations. The Sentinel-2 April 15 image preceded the heavy rainfall of late April, so changes in the bays may partly reflect runoff. The April 30 image was affected by cloud cover and cloud shadows; the number of post-event images was limited, and the analysis of meteoceanographic forcing was qualitative. Within these limitations, the combined use of Sentinel-2 and PlanetScope, and particularly the daily revisit of the latter, made it possible to document the extent and persistence of the plume, demonstrating the potential of high-resolution remote sensing for the rapid assessment of urban infrastructure failures and for supporting coastal monitoring and management. The workflow relied on open-access Sentinel-2 data, institutional access to PlanetScope, and ACOLITE processing, which makes it potentially replicable by

environmental agencies. Future work combining rapid field sampling, hydrodynamic modeling, and sensor-specific validation would help quantify sediment fate and biological effects.

## Declarations

## Author Contribution

T.O.A: Conceptualization; Methodology; Validation; Formal Analysis; Investigation; Data Curation; Writing – Original Draft.B.S.F: Methodology; Software; Validation; Formal Analysis; Investigation; Data Curation; Visualization; Writing – Original Draft.B.C.C: Conceptualization; Methodology; Writing – Review & Editing; Supervision; Project Administration.

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## Data Availability

Data will be made available on request.

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