Scientific and technological research article

Study of the sedimentation and erosion rates of the La Barra sector of the San Andrés de Tumaco navigable channel, Nariño

Estudio de la tasa de sedimentación y erosión en el sector La Barra del canal navegable en San Andrés de Tumaco, Nariño

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Abstract

Monitoring the evolution of the seafloor in navigable channels ensures safe navigation. In this research, sedimentation and erosion rates were estimated using multibeam bathymetric data in the navigable channel of San Andrés de Tumaco, Nariño, Colombia, specifically in the sector known as "La Barra," for different periods between 2019 and 2021. Additionally, the coastline was traced for the years 2019, 2020, and 2021 to identify coastal dynamics at the estuary mouths closest to the study area and their relationship as sediment sources. Lastly, precipitation data were analyzed to establish its correlation as a forcing variable for sediment transport and continental sediment input into Tumaco Bay. As a result of these analyses, the highest accumulated sedimentation volume in the La Barra sector was 188 881 m^3 and the highest erosion volume was 150 245 m^3, both of which were observed in the longest observed period. Additionally, the average sedimentation rate was calculated as 24 409 m^3/month, excluding the longest period. The spatiotemporal analysis of the coastline revealed sectors with accretion, retreat, or which are stable or constant, with accretion processes predominating due to continental sediment accumulation. Furthermore, the relationship between precipitation and the accumulated sedimentation volume in La Barra sector is represented by the equation $S = 56.591P + 15\,529$, and for the accumulated erosion volume, $E = 48.749P - 5\,263.6$. Based on the estimation of sedimentation/erosion rates, coastal dynamics, and their correlation with precipitation as an influential variable in sediment transport, which generates morphological changes in the seafloor, decision-making authorities can propose adjustments in sediment removal processes in the La Barra sector to ensure safe navigation in the access channel to Colombia's second most important Pacific port.

Keywords: Bathymetry, erosion, sedimentation, navigation channel, TIN, morphological changes, sediment transport, Tumaco.

Resumen

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El seguimiento de la evolución del fondo marino en canales navegables permite garantizar la navegación segura. En esta investigación se estimó la tasa de sedimentación y erosión a partir de datos batimétricos multihaz en el canal navegable de San Andrés de Tumaco (Nariño), específicamente en el sector denominado La Barra, para diferentes períodos entre 2019 y 2021. Además, se realizó el trazado de las líneas de costa para los años 2019, 2020 y 2021 con el objetivo de identificar la dinámica costera en la desembocadura de los esteros más cercanos al área de estudio y su relación como fuente de aportes de sedimentos. Por último, se analizaron datos de precipitación con el fin de relacionarlos como una variable forzante de transporte y aporte de sedimentos continentales en la bahía de Tumaco. Producto de estos análisis, en el sector La Barra se obtuvo el mayor volumen acumulado de sedimentación, con 188 881 m^3 y de erosión con 150 245 m^3, debido a que es el período más amplio observado. Adicionalmente, se calculó la tasa promedio de sedimentación de 24409 m^3/mes, sin considerar el período más amplio. En el análisis espacio temporal de la línea de costa se evidenciaron sectores con cambios de acreción, retroceso y nulos o constantes; sin embargo, predominaron los procesos de acreción, asociados a acumulación de sedimentos continentales. Por otra parte, la relación entre la precipitación y el volumen cumulado de sedimentación en el sector La Barra se representó con la ecuación $S = 56.591p + 15529$, y con el volumen acumulado de erosión $E = 48.749p - 5263.6$. Basados en la estimación de la tasa de sedimentación/erosión, la dinámica costera y su correlación con la precipitación, como variable influyente en el transporte de sedimentos generadora de cambios morfológicos del fondo marino, las autoridades tomadoras de decisiones pueden proponer un ajuste en los procesos de remoción sobre el sector La Barra, que contribuya a una navegación segura en el canal de acceso al segundo puerto más importante del Pacífico colombiano.

Palabras clave: *batimetría, erosión, sedimentación, canal navegable, TIN, cambios morfológicos, transporte de sedimentos, Tumaco.*

Introduction

Oceans and seas are economic instruments oriented towards navigation, where maritime safety aims to prevent accidents, protect human life, and the environment (Rojas *et al*., 2018). The Colombian Pacific region has the potential to project itself into the global economy, which involves improving the design of navigation routes and ensuring their safety. This requires strategies and research to mitigate anthropogenic and natural risks in maritime activities.

Understanding the geographical, geological, and geophysical characteristics of the seafloor and the coastline allows us to describe the dynamics in navigable channels and adjacent areas, determining factors that accelerate or slow down sedimentation and/or erosion processes. The main sources of marine sediments originate from the continent, transported as river runoff into the sea. The ocean itself causes sedimentation due to remains of organisms living in it, submarine volcanoes, currents, and disintegration due to chemical action and gasses from the atmosphere (Cifuentes, Torres, & Frías, 1997).

The economic system based on maritime activities has seen significant growth, represented by the increase in commercial and port activities, which boost maritime traffic. Thinking about an event that could delay or halt these activities raises interest in processes that can affect navigability (Cifuentes & Mejía, 2015). Nowadays, with technological development, more resources are dedicated to maritime activities to ensure safe navigation. Hydrographic surveys are increasingly conducted to higher precision standards, giving priority to information on navigable channels, which are part of the national economic axis. Hence, when accelerated sedimentation processes are identified, monitoring is carried out to determine the need for their removal.

The municipality of Tumaco is home to the second most important port on the Colombian Pacific coast, where a change in morphology has been identified due to accelerated sediment accumulation in the area called La Barra, which is part of its navigable channel (Tejada *et al*., 2003). As a preventive measure to ensure navigability, the responsible entities designed a sediment trap to mitigate the impact of sediment accumulation in the channel (Barajas & García, 2014). Additionally, the Center for Oceanographic and Hydrographic Research of the Pacific (CCCP) conducts periodic hydrographic surveys, and the National Roads Institute (Invias) carries out dredging to remove sediment in the area.

The data provided by hydrographic survey campaigns serve to update the cartography of the entire Colombian maritime and river territory (General Maritime Directorate [Dimar], 2021). Navigators use the information provided in nautical charts to define their routes according to their needs and the requirements of the vessel. To provide safety for navigators, the periodicity in updating the information considers factors that accelerate the sedimentation process. Due to its geographical location, the morphological dynamics of Tumaco Bay are influenced by the number of rivers and their catchments that discharge there (Niño & Oviedo, 2018), and to their atmospheric variables such as precipitation (Gómez & Peñaranda, 2012). The semi-diurnal tides, currents, and swell entering the bay from the southwest (SW) and south-southwest (SSW), which affect sediment transport (Restrepo, Otero, & López, 2009), are responsible for transporting sediments brought by the Mira River (with an average annual flow of 868 m^3/s and the largest watercourse close to the study area) during the rainy season, when it reaches its highest flow rate (MADS-Invemar, 2012. In Barajas & García, 2014).

Based on the available information, it was possible to analyze and monitor to determine an approximate sedimentation rate in the La Barra area between 2019 and 2021, inspect changes in the coastline of estuaries near the study area using satellite images, and identify the impact of precipitation on sedimentation and erosion processes, determining a correlation factor between the variables.

Study Area

The Colombian Pacific currently has two seaports, Buenaventura and Tumaco, with the latter being the second most important for maritime activities (Gómez & Peñaranda, 2012). It is geographically located in Tumaco Bay (Nariño), surrounded by the mouths of the Chagüí, Colorado, Curay, Imbilpí, Llanaje, Rosario, and Tablones rivers (Niño & Oviedo, 2018). The study area is situated on the access channel to the port of Tumaco, which has an approximate length of 8 500 meters (BAGGERWERKEN DECLOEDT & ZN|Colombia, 2020). Specifically, it is located in the La Barra sector, covering an area of 619 611 square meters and a length of 1 750 meters. In the La Barra sector, periodic dredging of the seabed is carried out to maintain the required navigation depth for the port. The dredging area can be divided into three parts: the longitudinal sediment bar, the sediment trap, and the navigable channel (Fig. 1).

The Colombian Pacific is geologically a part of the North Andean Block, which is dominated by an active or convergent boundary resulting from the interaction between the Nazca and South American plates, composed of the continental shelf, the continental slope, and the Colombo-Ecuadorian trench (Collot, Sallares, & Pazmiño, 2009). Regionally, Tumaco Bay is conditioned by tectonic and geological processes that influence its geomorphological dynamics. For example, the bay has two continuous anticlines and a syncline in the NE direction. Additionally, towards the SW of the bay, there is the presence of the Tumaco Fault in a N45W direction, while in the northern part of the bay, the Remolino-El Charco Fault ends at Punta de Cascajal (Correa & González, 1989).

Furthermore, Tumaco Bay is associated with deltas developed on a rocky substrate consisting of Neogene sedimentary rocks, which outcrop in the cliffed coast sector and influence the transport of sediments along the coastline. It also serves as a separation between two deltaic systems, with the Patía River delta system to the north and the Mira River delta system to the south (Nivia, Pérez, & Sepúlveda, 2003). Locally, geomorphic features like islands, spits, and pillars are formed, with a higher prevalence of coastal plains, which are further comprised of non-vegetated intertidal platforms, floodplains, and plains with halophytic vegetation (Bermúdez, Álvarez, & Niño, 2014).

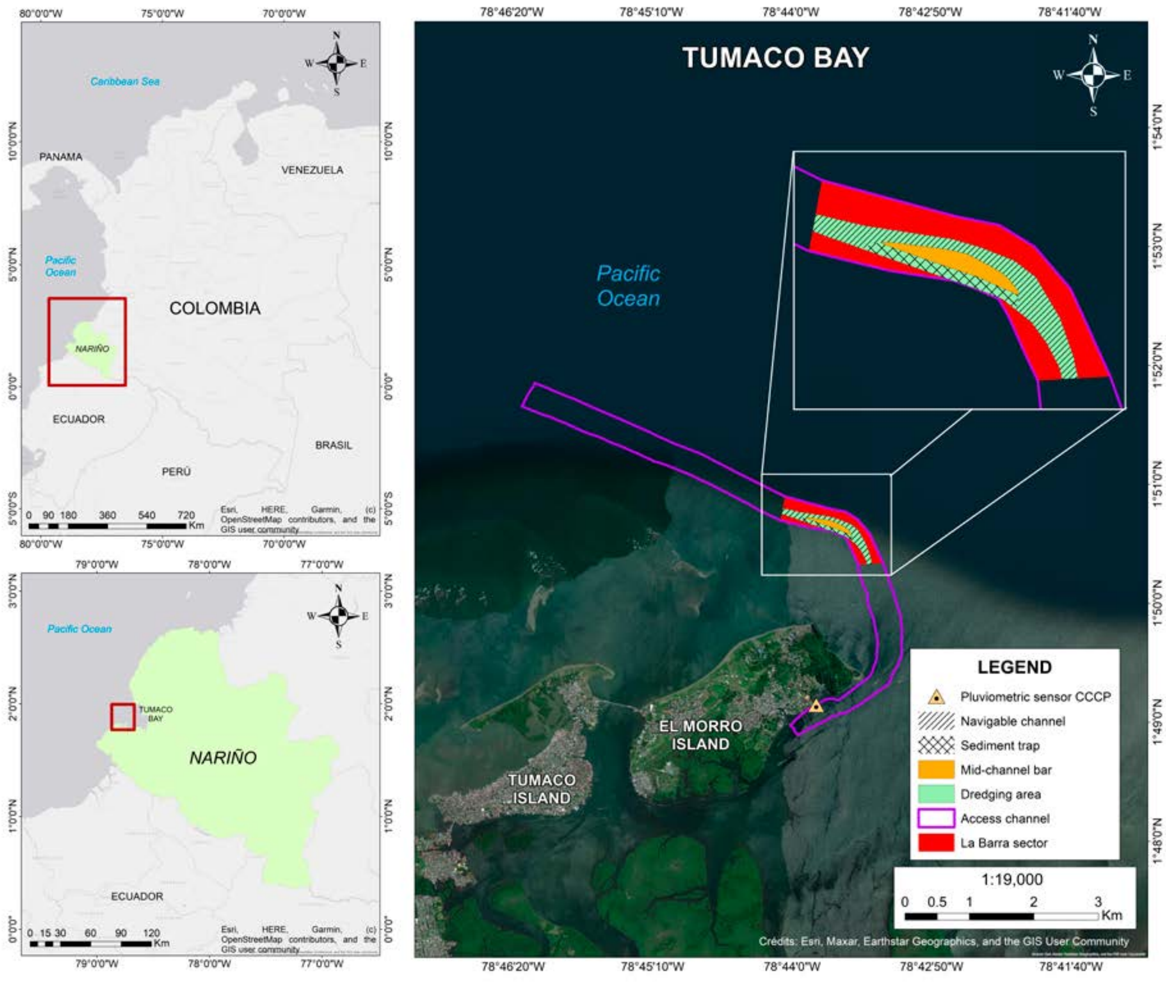


Figure 1. Geographic location of the study area

Methodology

Morphological Changes in the Seafloor

The available bathymetric data for the years 2019 to 2021 were accessed from the hydrographic survey office of the CCCP. The bathymetric information within the maritime and river spaces under the jurisdiction of the Dimar complies with technical specifications during acquisition, processing, and cartography, in accordance with Dimar Resolution No. 157 of 2011. This resolution adheres to the minimum standards established in the norms of the International Hydrographic Organization (IHO) for hydrographic surveys, 5th Edition of February 2008 (Dimar, 2011).

The surveys were conducted aboard the ARC Isla Cascajal using a RESON SEABAT 7125 multibeam echosounder and a TRIMBLE R10 Global Navigation Satellite System (GNSS), configured in differential mode (utilizing two devices simultaneously; a reference station and a mobile one) and Real-Time Kinematic positioning (RTK) (real-time corrections transmitted by networks of permanent stations). All data are referenced to the vertical datum of the mean low water of spring tides (MLWS), as determined by researchers from Dimar's research centers (Álvarez *et al*., 2018; Pulido *et al*., 2013).

The analyzed bathymetric files are not spatially homogeneous, so a boundary was defined to extract a common area for all surveys and have the same bathymetric information for spatial-temporal comparison. A TIN (Triangulated Irregular Network) comparative analysis was performed using the bathymetry, representing the landform through irregular networks of triangles (ESRI, 2016). This type of model is used for high-precision modeling of small areas, making it applicable in engineering where it proves useful for planimetric area calculations, surface area calculations, and volume calculations.

A TIN to TIN difference operation was carried out using Hypack software to determine an approximate value of accumulated erosion and/or sedimentation between consecutive bathymetric surveys. To aid in understanding, the information is presented in units of monthly accumulated volume. However, it should not be considered a fixed monthly value of accumulated erosion and/or sedimentation, as it can vary from month to month due to oceanographic and meteorological factors specific to the area. Transverse lines were also defined in order to monitor changes.

Coastline Dynamics

To identify the relationship between the morphodynamic changes of the coastline in the estuaries near the area of interest and the morphological changes in the seafloor of the La Barra sector, as well as their possible influence on continental sediment input, the coastline was identified and digitized using photo interpretation of satellite images (Castañeda, 2017). The selected estuaries were Guandarajo, Natal, Aguaclara, Trapiche, and Resurrección (Fig. 2), which, on a regional scale, belong to the Mira-Mataje rivers hydrographic zone, the Mira river sub-zone, and on a local scale, to the estuary system of the Mira river basin (Corponariño, 2007).

To determine erosion and sedimentation processes in the estuary areas, we used coastline

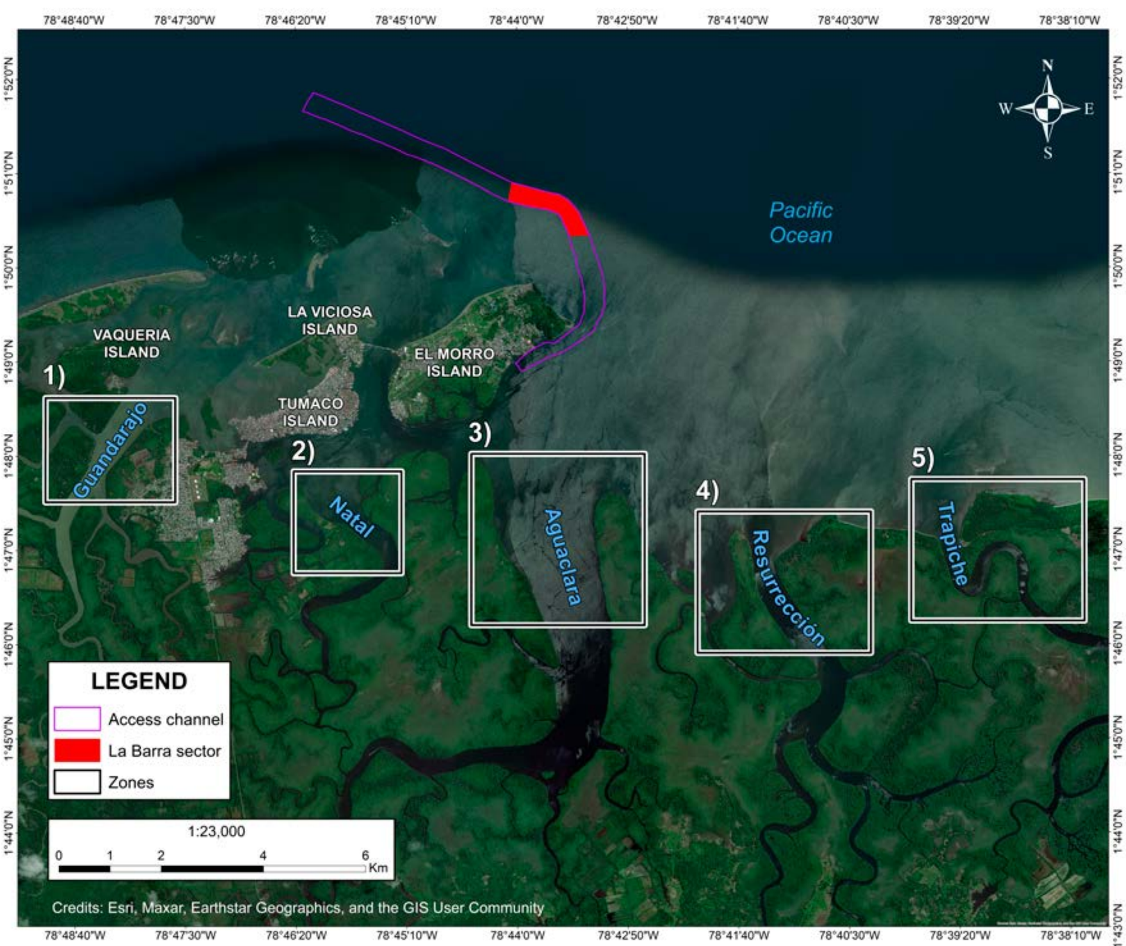


Figure 2. Geographic location of the study area and areas for coastline dynamics analysis in the estuaries of the Mira River estuary system

data from the years of the bathymetric surveys analyzed in this research. Three LANDSAT 8 OLI/TIRS C1 LEVEL satellite images from 2019 to 2021 were selected through the Earth Explorer data portal of the United States Geological Survey (USGS), aiming to choose those with the least cloud cover for a visual assessment of the coastline boundary (Guido *et al*., 2009) (Table 1).

Table 1. Satellite images used for coastline tracing

No.	Date	Name of the file with the images	Resolution
1	2019/03/02	LC08_L1TP_010059_20190302_20190309_01_T1	30 m
2	2020/03/04	LC08_L1TP_010059_20200304_20200314_01_T1	30 m
3	2021/03/23	LC08_L1TP_010059_20210323_20210402_02_T1	30 m

The satellite images were processed using ArcMap software, with the RGB bands 6, 5, and 4, at a working scale of 1:60 000 during digitization. Once the coastlines were digitized, the areas of accretion or retreat between the periods 2019-2020 and 2020-2021 were calculated to quantitatively understand coastal behavior.

Precipitation behavior

For the analysis of precipitation in the study area, we consulted data from nearby stations belonging to the Colombian meteorological institute IDEAM. However, due to the discontinuity in the monthly data from these stations, the decision was made to use the data measured at the nearest pluviometric station belonging to Dimar (Fig. 1). This choice was based on its geographical location within the CCCP facilities, ensuring data continuity over the period from 2019 to 2021, thanks to constant monitoring and periodic calibration of the station.

Accumulated precipitation was evaluated during the same periods when the bathymetric surveys were conducted. The aim was to identify if there is any relationship between the morphological changes of sedimentation and erosion in the seabed of La Barra and the potential contribution of continental sediments transported by the tributaries that flow into the area.

Results and Discussion

According to the available data, the extreme values of each campaign were considered to define the ranges of variation (Table 2). The morphological variation of the seabed was observed through differences in depths, with corresponding tracking for each of the dates (Fig. 3).

Table 2. General information on hydrographic survey campaigns.

Survey Campaign	Min. Depth (m)	Max. Depth. (m)
February 2019	3.23	8.67
September 2019	3.42	8.51
April 2020	1.71	8.87
July 2020	3.62	9.35
December 2020	3.36	8.57
March 2021	4.08	8.74
June 2021	3.94	8.58
August 2021	3.90	10.05

As seen in Figure 3, the channel was well defined in February 2019. Over time, the morphology changes, initially affecting the sediment trap in September 2019. This accretion process continues in the following months, as observed in April 2020, where the minimum depth value has decreased by 1.52 m in 14 months. In June 2020, Invias conducted a dredging operation in the area where the access channel changes direction, mainly in the navigable channel and the sediment trap (BAGGERWERKEN DECLOEDT & ZN|Colombia, 2020). The channel design was restored to depths of 7.6 m, according to the dredging report (BAGGERWERKEN DECLOEDT & ZN|Colombia, 2020). After that date, the images show the accumulation of sediments in the same sector.

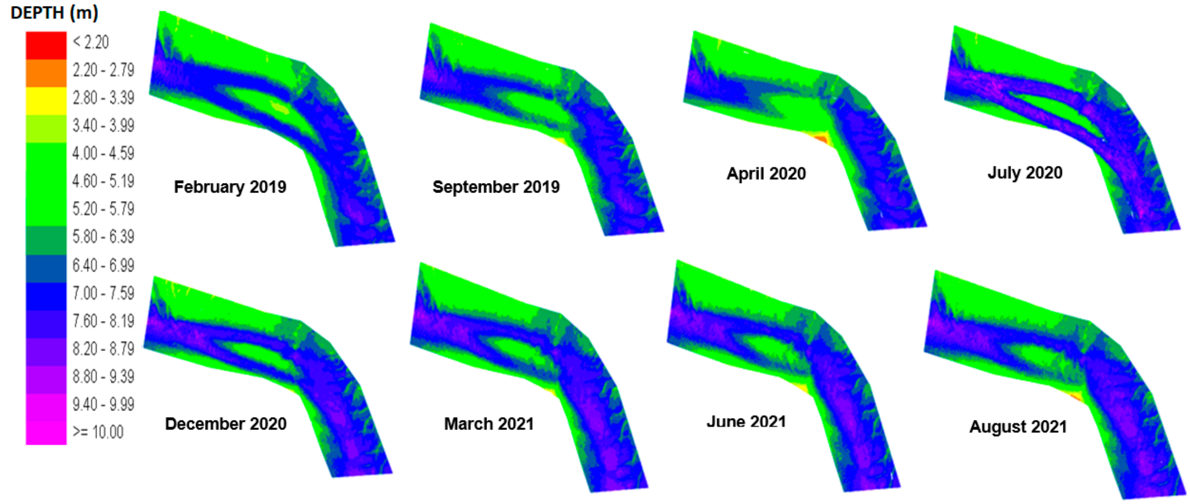


Figure 3. Bathymetry from 2019 to 2021

After comparing the available bathymetric data and the results obtained in the TIN to TIN difference operation, we established that positive values represent a sedimentation process, while negative values represent erosion (Fig. 4a).

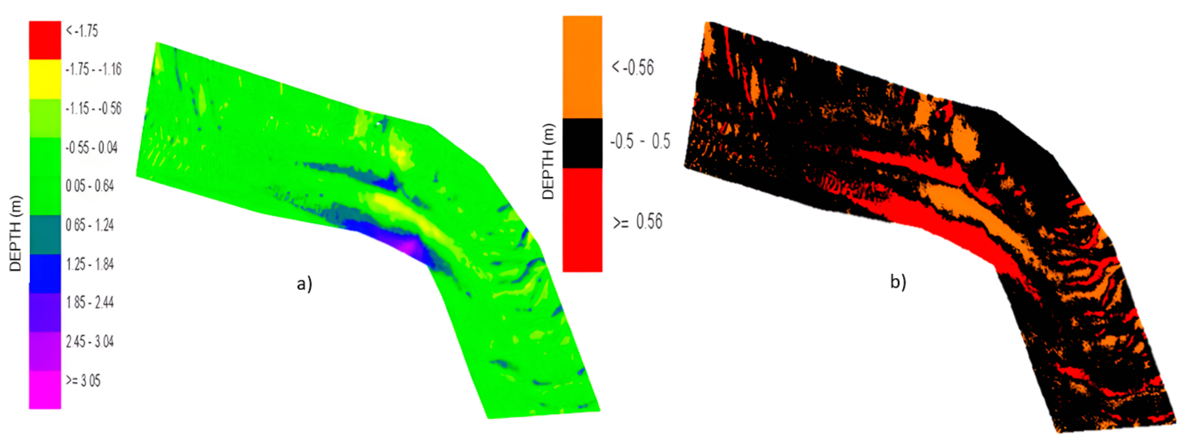


Figure 4. TIN to TIN Difference February 2019 - September 2019, La Barra sector

To identify the areas most affected by either of the two processes, three colors were assigned; black represents areas with no significant variation in the seafloor morphology, with values between -0.5 m and 0.5 m, sedimentation or accretion is represented in red, and erosion in orange (Fig. 4b). Based on these considerations, it can be seen that sedimentation primarily occurs in the concave sector of the channel. Between February and September 2019, the maximum depth of erosion and sedimentation was -1.73 m and 3.32 m, respectively, with an erosion rate of 14 310 m^3/month and a sedimentation rate of 17 699 m^3/month.

Regarding the behavior between September 2019 and April 2020 (Fig. 5), the maximum values of erosion and sedimentation were -1.80 m and 2.68 m, with an erosion rate of 8 715 m^3/month and a sedimentation rate of 20 191 m^3/month. According to the observed maps, sedimentation significantly affects the sediment trap, and these values have an impact on navigational safety. Consequently, the external entity responsible for performing maintenance dredging proceeded to remove the material in this sector in June (BAGGERWERKEN DECLOEDT & ZN|Colombia, 2020).

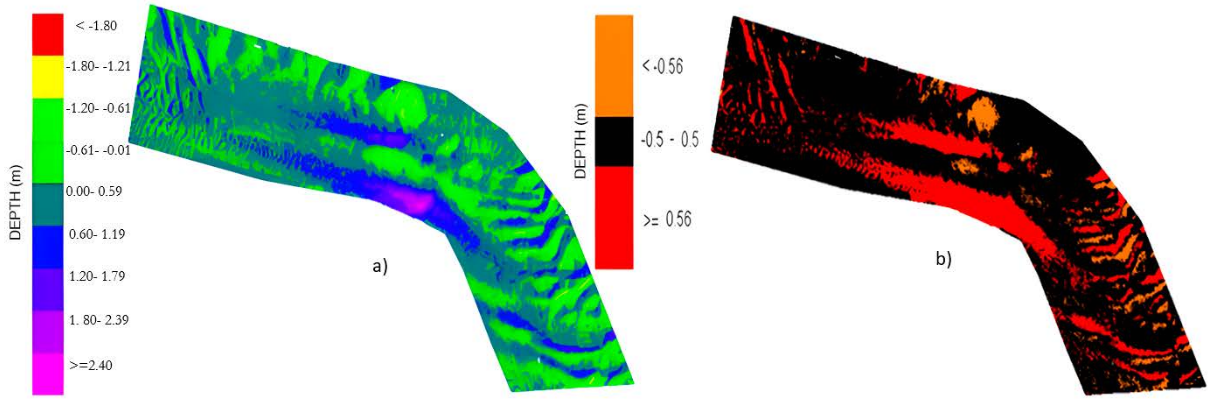


Figure 5. TIN to TIN Difference September 2019 - April 2020, La Barra sector

After the maintenance dredging of the La Barra sector, a comparison was made between the bathymetry data collected after the dredging and the data immediately before the dredging in April 2020. In this comparison, the well-defined channel design can be observed (Fig. 6).

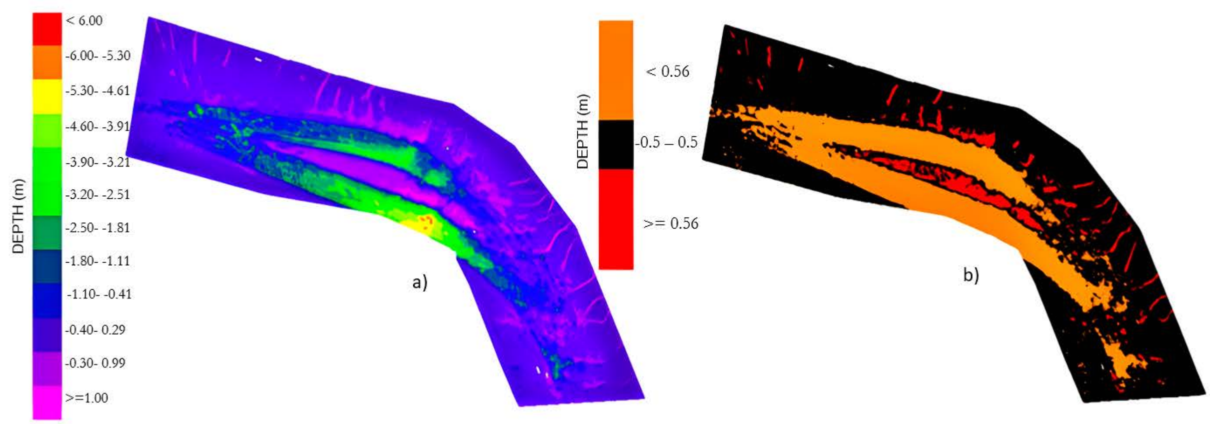


Figure 6. TIN to TIN Difference July 2020 - April 2020, La Barra sector

The maximum values between April and July 2020 were -6.04 m and 1.65 m, which could be interpreted as erosion and sedimentation processes, respectively. However, such an interpretation is not appropriate given the anthropogenic intervention that affected the seafloor morphology. Therefore, it's not advisable to express erosion and sedimentation rate values either.

During the time between July and December 2020 (Figure 7), the maximum erosion value was -2.10 m, and the maximum sedimentation value was 3.92 m. The corresponding rates of change were 17 795 m^3/month and 29 208 m^3/month, which is consistent with the rates observed between September 2019 and April 2020. Starting from December 2020, more regular bathymetric surveys were conducted to monitor the rate of change in these processes.

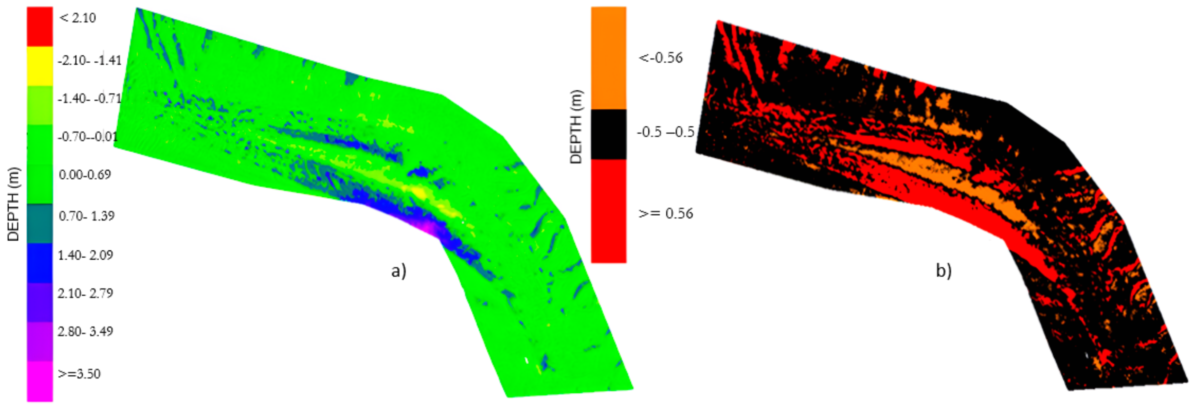


Figure 7. TIN to TIN Difference July 2020 - December 2020, La Barra sector

Three months later (Fig. 8), the erosion rate was 16266 m^3/month, with a maximum deepening of -1.11 m. However, the sedimentation rate continued to be higher than that of erosion, with a value of 28045 m^3/month and a maximum value of 1.75 m. However, these data are lower than those recorded earlier due to the reduced time period.

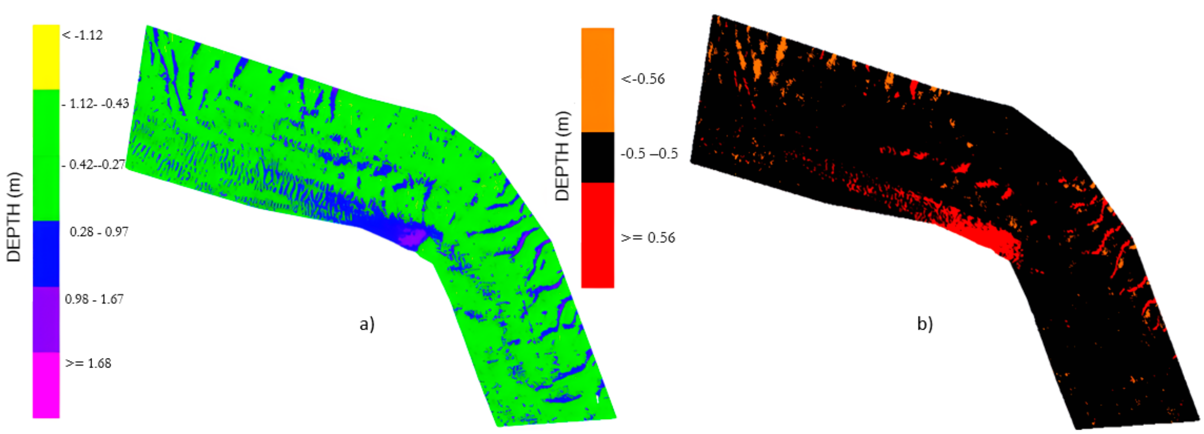


Figure 8. TIN to TIN Difference December 2020 - March 2021, La Barra sector

Maintaining the three-month interval, a comparison was made between the bathymetry data from March and June 2021 (Fig. 9), from which maximum values of -1.08 m and 1.81 m were obtained. Additionally, erosion and sedimentation rates were calculated, with values of 16 789 m^3/month and 23 718 m^3/month respectively. According to these results, the values of changes in three-month periods are proportional.

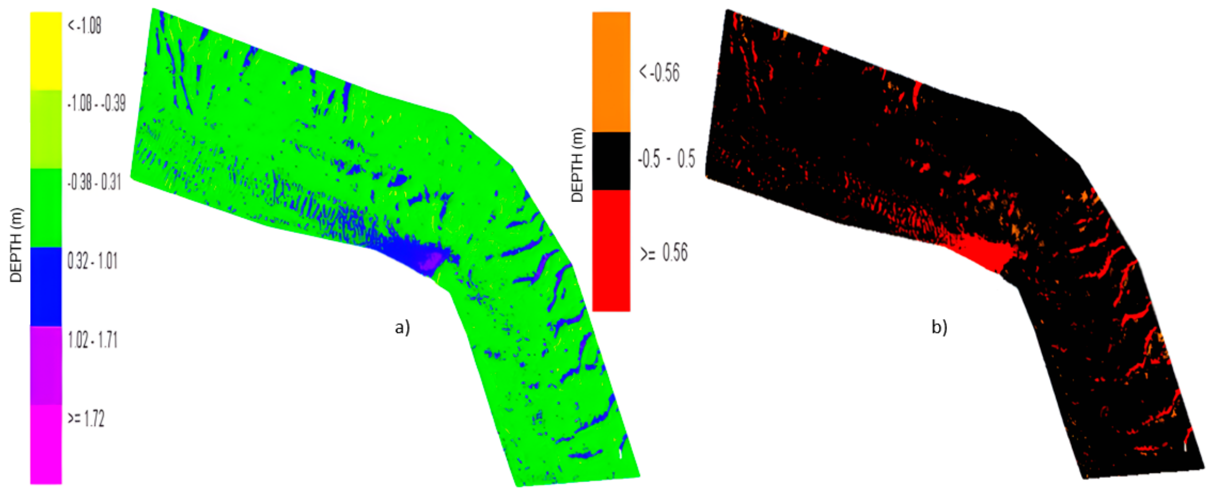


Figure 9. TIN to TIN Difference March - June 2021, La Barra sector

Reducing the time interval to two months (Fig. 10), maximum values of -0.93 m and 1.37 m were obtained, with an erosion rate of 21 586 m^3/month and a sedimentation rate of 27 593 m^3/month.

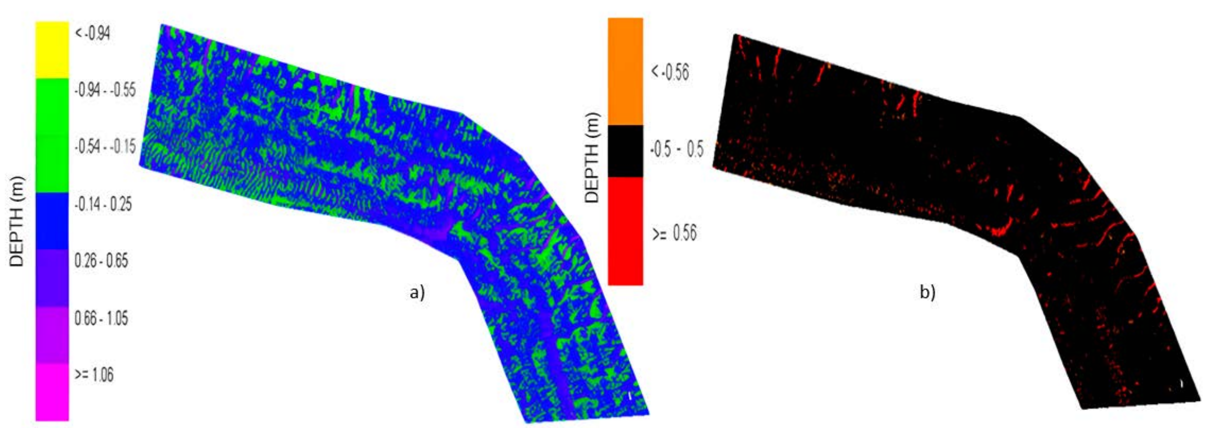


Figure 10. TIN to TIN Difference June - August 2021, La Barra sector

Based on the morphological changes in the seabed over the analyzed time period, the La Barra sector exhibits a greater tendency toward sedimentation than erosion. Considering a broader time frame from July 2020 to August 2021 (Fig. 11), the sedimentation rate is 16 694 m^3/ month, and the erosion rate is 20 098 m^3/month. Sedimentation zones had a maximum change of 4.97 m over an area of 257 093 m^2, while erosion reached -2.37 m over 362 369 m^2. This pattern shows a greater volumetric difference associated with sedimentation over a smaller area, resulting in greater shallowings that reduce navigational depth.

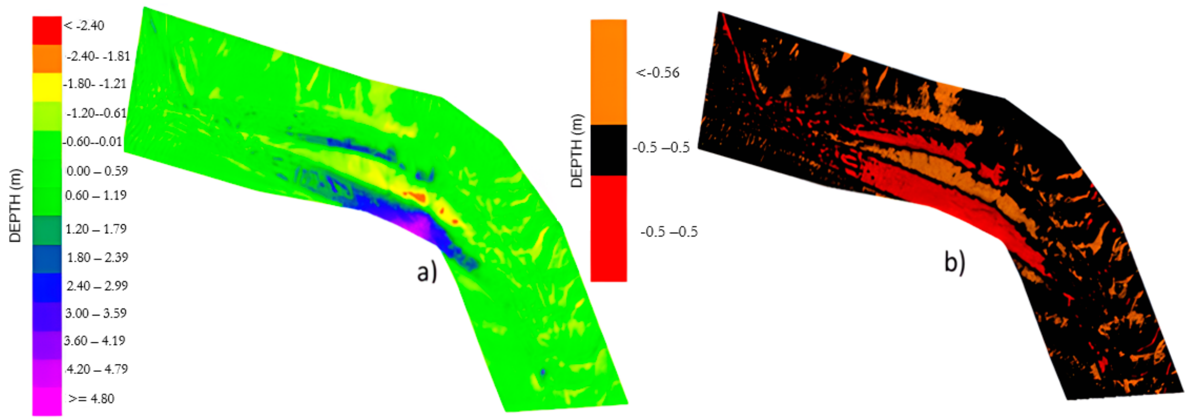
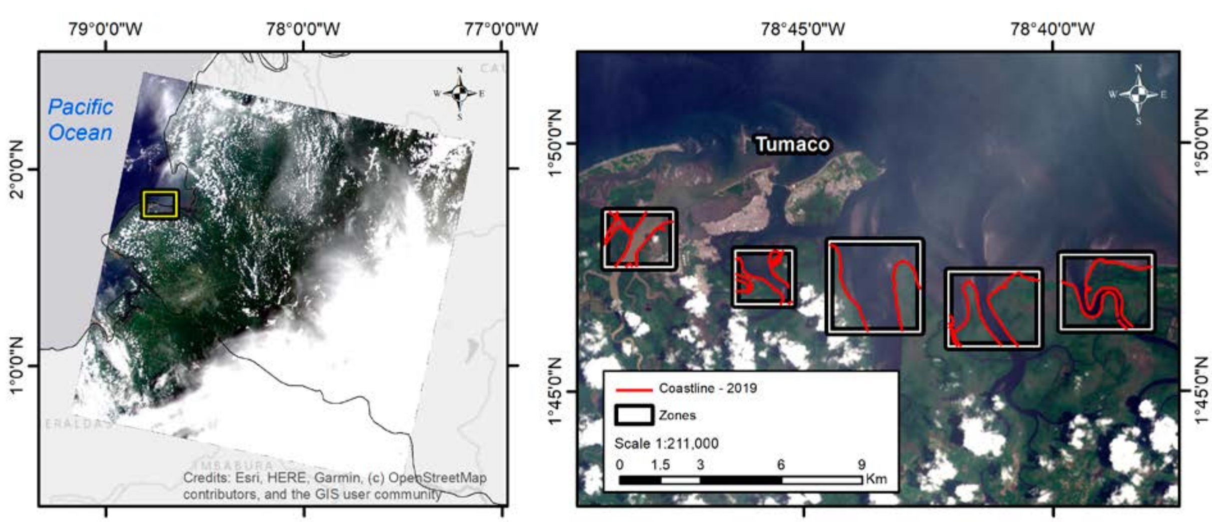


Figure 11. TIN to TIN Difference July 2020 - August 2021, La Barra sector

According to the sedimentation rates, excluding those related to dredging, there is a confirmation of sediment accumulation with a linear trend of 17 562 m^3/month. In contrast, the erosion rate shows a trend of 12 453 m^3/month, further corroborating the predominance of the sedimentation process in the sector.

The design of the navigable channel in the La Barra sector is comparable to a meander, where the dynamics manifest through simultaneous erosion and sedimentation processes. The flow velocity on the outer curve is significantly higher, implying erosion, while sedimentation occurs in the inner curve (Ceballos, 2011). This is evident in the accumulation of sediments in the inner zone or sediment trap, which progressively increases, filling it and extending beyond the longitudinal bar, ultimately affecting the navigable channel.

To relate the variables influencing the sedimentation and erosion phenomena in the La Barra sector, the continental basin near it was identified. Considering that the contributions of continental sediments are conditioned by factors such as the drainage basin area, the hydrological balance between precipitation and evaporation, geology, topography, and hydrology (Restrepo, 2005), the mouths of the Mira River estuaries were traced (Fig. 12), the recession or accretion processes were analyzed, and these were related to erosion or sedimentation, respectively.



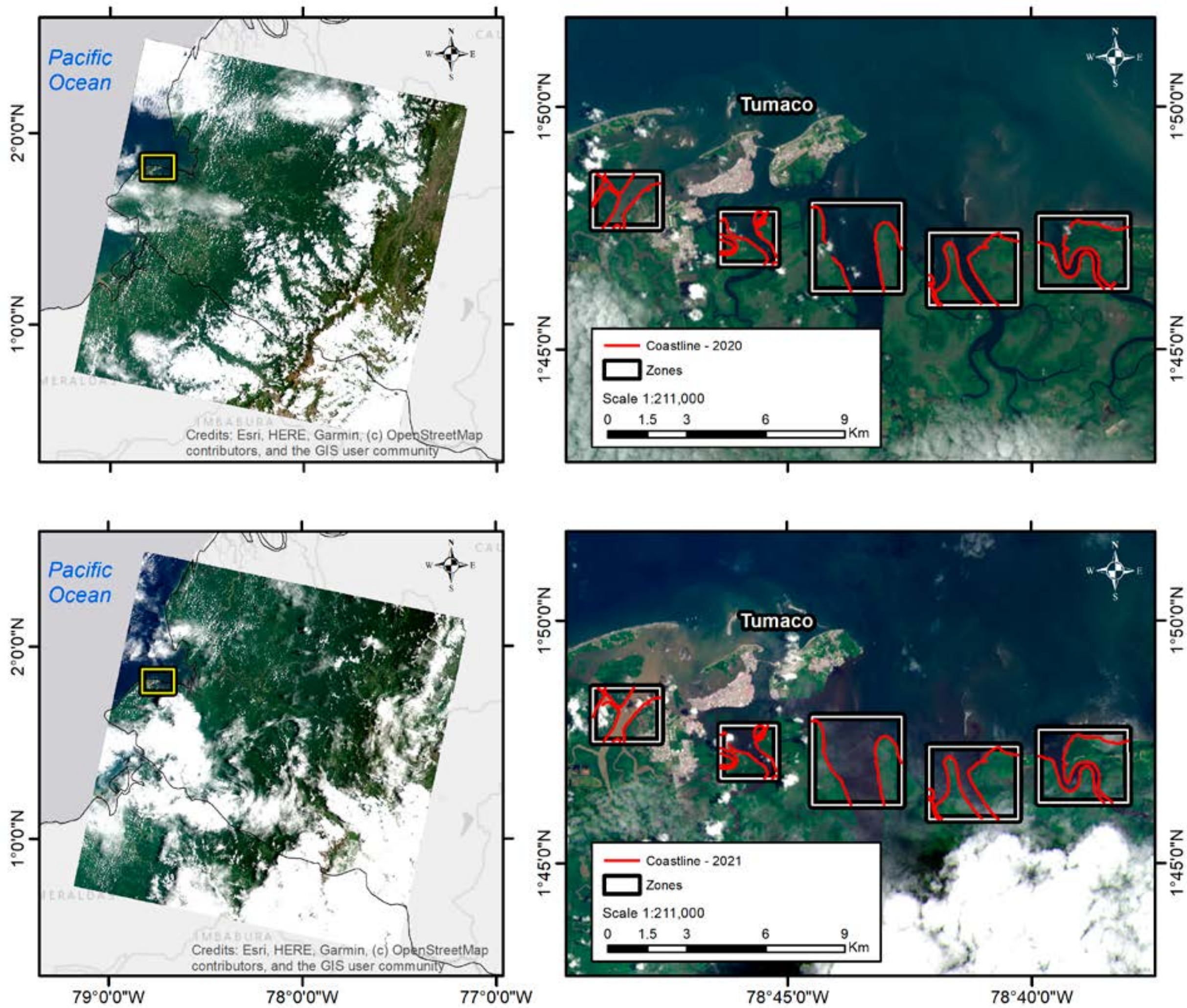


Figure 12. (Left) Visualization of the satellite images used. (Right) Coastline tracing for each satellite image

Zone 1, located in the Guandarajo estuary, shows areas of accretion and retreat along the coastline; however, the sedimentation process predominates during the two analyzed periods, with a total of 44 850 m^2 of accretion compared to 28 578 m^2 of retreat. In general, it is a dynamic area that can switch from erosion to sedimentation, or vice versa (Fig. 13A and 13B). In Figure 13C, sedimentary processes were evident during the 2019-2020 period, and in the 2020-2021 period, this pattern changed to erosive. The opposite occurs in Figure 13D, where there is an alternation along the coastline between sedimentation and erosion processes during the 2019-2020 period, changing entirely to sedimentation in the 2020-2021 period.

Zone 2 is located in the Natal estuary, and similar to the previous zone, it is evident that the predominant process is sedimentation (Fig. 14A and 14B). In general terms, it showed 27 765 m^2 of accretion and 23 602 m^2 of retreat during the two periods analyzed. In Figure 14C, it can be observed that, during the 2019-2020 period, there was a higher incidence of sedimentation compared to the 2020-2021 period, as new erosion areas were generated in the latter. Another example of this dynamic is shown in the meander curve in the area (Fig. 14D), where sediments accumulated on the convex side and eroded on the concave side during the second period.

Zone 3, located in the Aguaclara estuary, is characterized by having the highest ratio of sedimentation to erosion compared to the other four zones, as it showed a total of 41 015 m^2 of accretion and 15 948 m^2 of retreat during the two periods analyzed, with sedimentation being the most important process (Fig. 15A and 15B). Along the coastline, there is an area with sedimentation during the 2019-2020 period, and the dynamics shifted to erosion in the following year (Fig. 15C); however, Figure 15D shows the opposite, with areas of both erosion and sedimentation during the 2019-2020 period, and a change to sedimentation only in the 2020-2021 period.

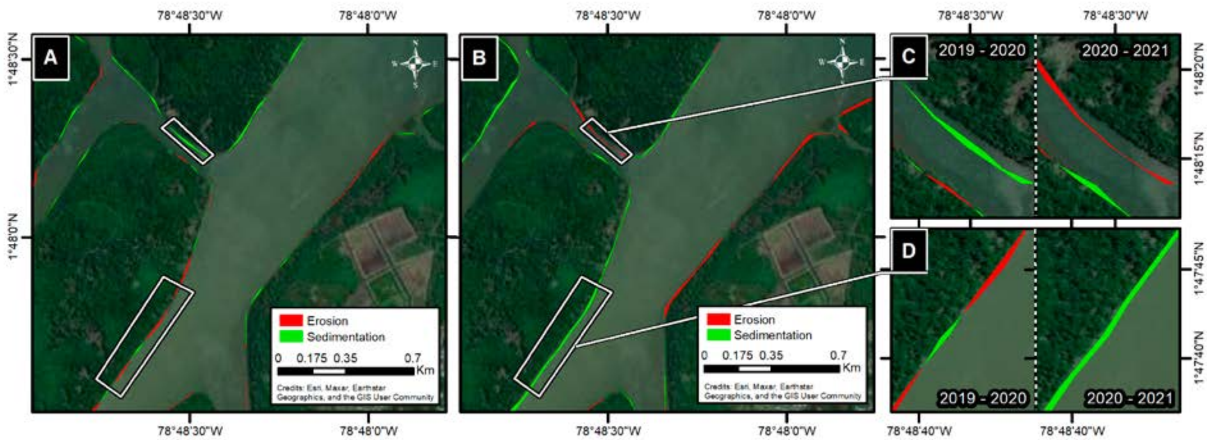


Figure 13. Areas of erosion and sedimentation in Zone 1. **A)** 2019-2020. **B)** 2020-2021. **C)** and **D)** Enlargement of specific areas for better visualization

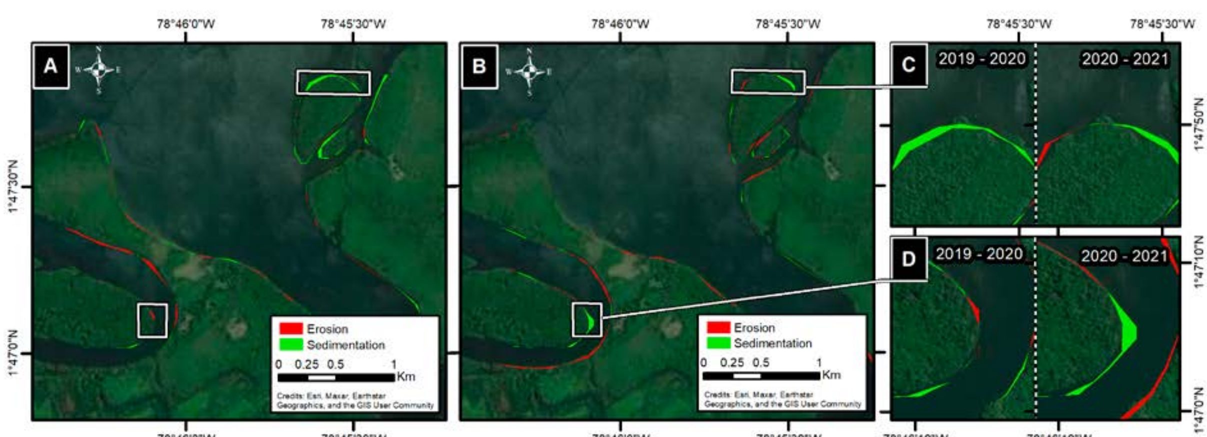


Figure 14. Erosion and sedimentation areas in Zone 2. **A)** 2019 - 2020. **B)** 2020 - 2021. **C)** and **D)** Enlargement of specific areas for better visualization

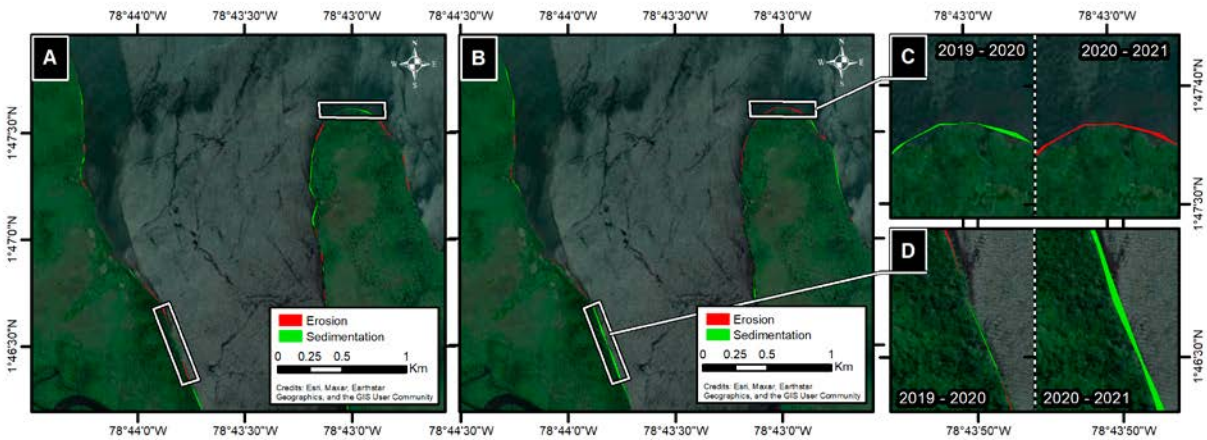


Figure 15. Areas of erosion and sedimentation in Zone 3. **A)** 2019-2020. **B)** 2020-2021. **C)** and **D)** Enlargement of specific areas for better visualization

Zone 4, located in the Resurrección estuary, differs from the other zones because it mainly exhibited erosional processes during the 2019-2020 period, with 31 828 m² of retreat and 10 880 m² of accretion, while during the 2020-2021 period, sedimentation increased and erosion decreased, with 35 440 m² of accretion and 23 572 m² of retreat (Fig. 16A and 16B). These dynamics are observed in greater detail in Figures 16A and 16B, where the green polygons associated with sedimentation increase in size and length compared to the red polygons associated with erosion from the 2019-2020 period to the 2020-2021 period.

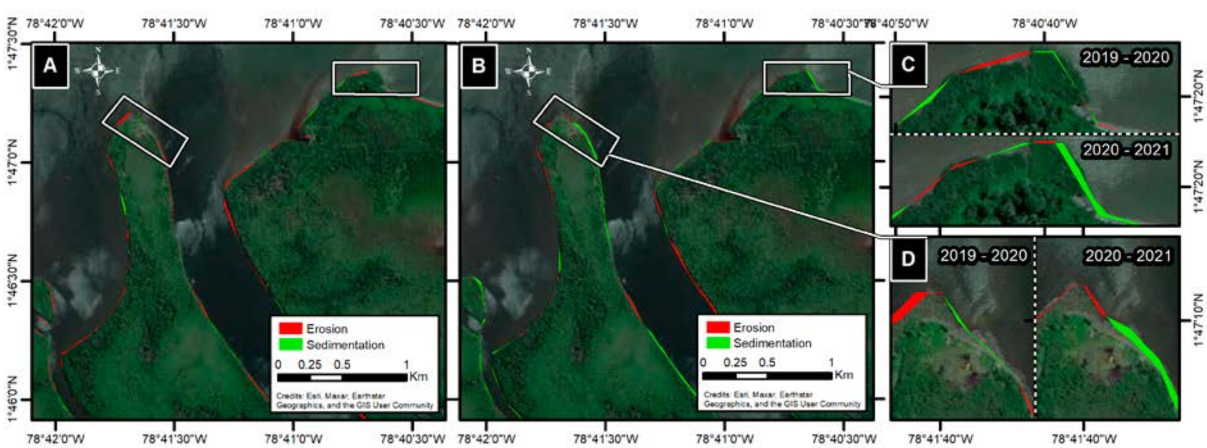


Figure 16. Areas of erosion and sedimentation in Zone 4. **A)** 2019-2020. **B)** 2020-2021. **C)** and **D)** Enlargement of specific areas for better visualization

Zone 5 corresponds to the mouth of the Trapiche estuary, in which areas of accretion and retreat were found along the coastline; however, the process of sedimentation predominated during the two analyzed periods, with a total of 48 457 m² of accretion and 28 519 m² of retreat (Fig. 17A and 17B). In Figures 17C and 17D, a change in processes between the two analyzed periods is observed on the convex edge of the curves of two meanders, which were initially erosive but then experienced sedimentation processes for the 2020-2021 period.

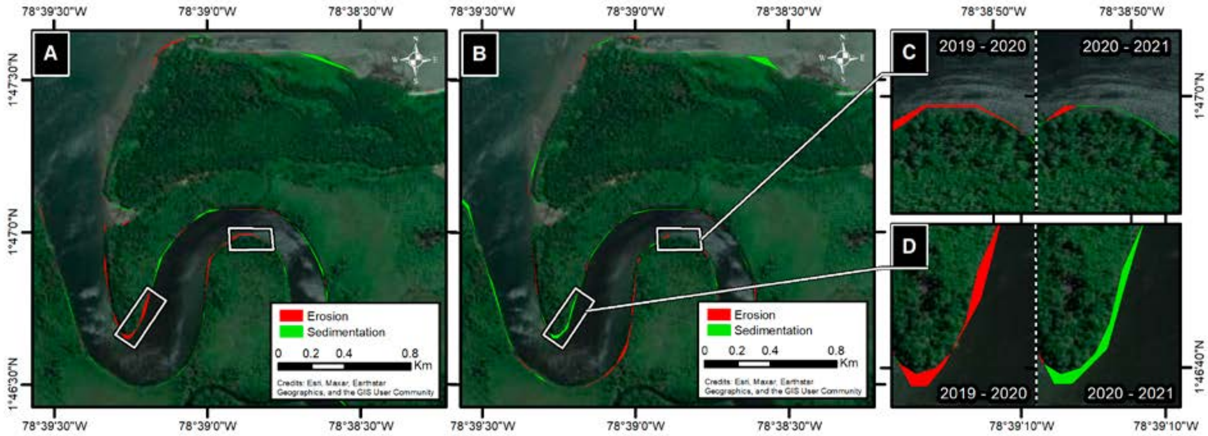


Figure 17. Areas of erosion and sedimentation in Zone 5. **A)** 2019-2020. **B)** 2020-2021. C and **D)** Enlargement of specific areas for better visualization

Due to the interaction between the sea and the estuary system of the Mira River, Tumaco Bay can be described as having typical deltaic zone behavior, in which sectors with accretion, retreat, and no changes were observed, but with accretion processes related to sediment accumulation predominating (Niño & Oviedo, 2018). In general, in the five study zones, the sedimentation process predominated, with a total of 80 051 m² for the first period and 128 356 m² for the second, except for Zone 4, where erosive processes gained strength during the 2019-2020 period while sedimentation decreased (Table 3).

The behavior of the estuaries was similar to that observed in La Barra, as over time, the amount of sediments deposited increased, likely due to transport from the mainland, as this is one of the contributing sources in this sector.

Table 3. Erosion and sedimentation data in the five study areas

Zone	2019 - 2020		2020 - 2021	
	Sedimentation (m²)	Erosion (m²)	Sedimentation (m²)	Erosion (m²)
1	15 816	13 003	29 034	15 575
2	16 446	10 002	11 319	13 600
3	16 170	10 027	24 845	5 921
4	10 880	31 828	35 440	23 572
5	20 739	17 595	27 718	10 560

Finally, precipitation data from the CCCP station were analyzed, taking into account that the effective radius of a pluviometric station is approximately 10 km, which covers the study area located at a distance of 2 856 m and the mouths of the various estuaries that converge in the area. According to the analysis presented in Tejada *et al*. (2003), the bottom of Tumaco Bay is mainly composed of fine sediments ranging from sands to silts, of lithoclastic origin (continental origin). The marine dynamics propose sediment transport in an eastward direction, from the mouth of the Mira River to the Tumaco islands, highlighting the contributions made by the river as the main source of sediments for the bay.

The sediment transport from the mouth of the Mira River continues to impact the Tumaco islands, modifying their morphology and, in turn, the current patterns in their vicinity, making it a very active system (Tejada, 2003). It is also evident that, both at high and low tides, there is a tendency to deposit sediments in the area where Guano Island was previously located (Tejada *et al*., 2003).

Considering the dynamics of the Tumaco Bay, changes in sedimentation and/or erosion can occur in the access channel to the port of Tumaco. In this regard, monthly precipitation was grouped into the same periods in which bathymetric comparisons were made, and the relationship between monthly precipitation and accumulated sedimentation and erosion was analyzed. Table 4 presents the accumulated values for each variable analyzed in a specific period.

Table 4. Accumulated precipitation (CCCP Station), sedimentation, and erosion over assessed periods

Periods	Accumulated Precipitation (mm)	Accumulated Sedimentation (m^3)	Accumulated Erosion (m^3)
Feb. 2019-Sep. 2019	1 604.9	123 894.0	100 172.0
Sep. 2019-Apr. 2020	1 767.4	141 335.5	61 007.5
Jul. 2020-Dec. 2020	442.2	146 038.2	88 973.2
Dec. 2020-Mar. 2021	1 325.9	84 135.6	48 796.4
Mar. 2021-Jun.2021	1 473.6	71 155.1	50 368.2
Jun. 2021-Aug. 2021	728.3	55 186.5	43 172.4
Jul. 2020-Aug. 2021	3 055.8	180 881.1	150 244.8

The relationship between accumulated precipitation and sedimentation in the analyzed periods showed a positive trend in the study area (Fig. 18) and a correlation between the variables given by R^2, indicating an influence of precipitation on the increase in sediment.

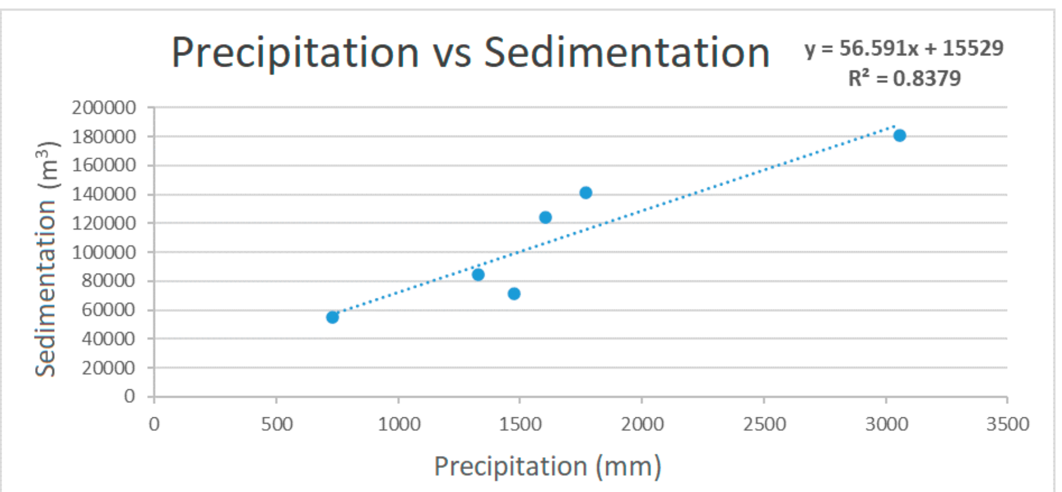


Figure 18. Accumulated precipitation (mm) vs. accumulated sedimentation (m^3)

The values of precipitation, erosion, and sedimentation corresponding to the period from July to December 2020 were excluded from the analysis due to their abnormal behavior compared to other periods. During these five months, sedimentation and erosion values were equal to or higher than longer periods. This behavior can be attributed to the increased flow velocity in the access channel, caused by human activities such as dredging. Therefore, we recommended considering hydrodynamics and current variability in the study area for future research, taking into account this anthropogenic behavior.

When relating accumulated precipitation and accumulated erosion, a positive growth is observed, and the correlation between the variables, as indicated by the R2 value, also suggests a strong correspondence between the two variables (Fig. 19). The observed correlation between precipitation and the increase in sedimentation and erosion describes an influential factor in the dynamics of Tumaco Bay. Precipitation is a significant component in the variation of sedimentation in the bay, particularly in a critical and high-interest area within the access channel to the port of Tumaco, such as the La Barra sector.

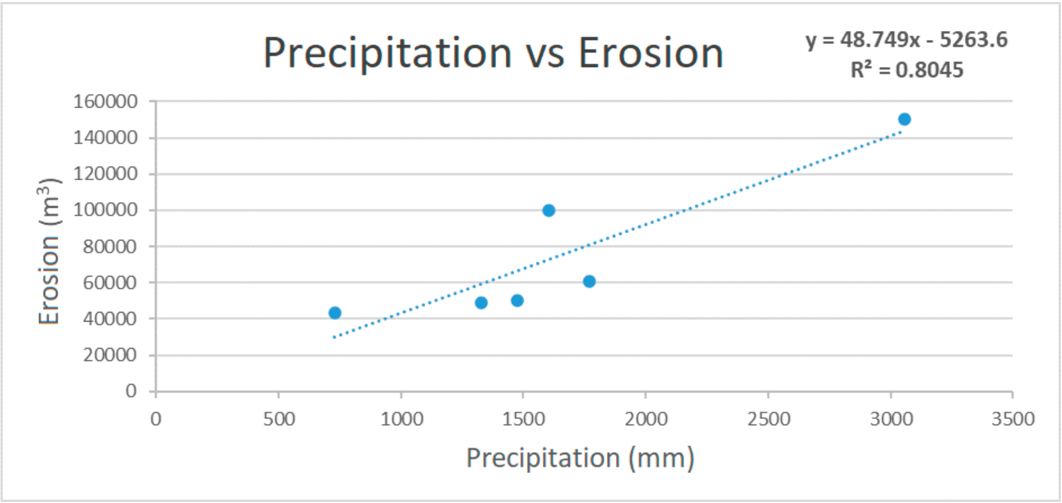


Figure 19. Accumulated precipitation (mm) vs. erosion (m^3)

Conclusions

Based on the available bathymetric data from February 2019 to August 2021, seven different analysis periods were considered, ranging from two, three, five, seven, to thirteen months, resulting in estimated values of accumulated sedimentation-erosion of 71 155 m^3 50 368 m^3, 55 187 m^3 – 43 172 m^3, 84 136 m^3 – 48 796 m^3, 146 038 m^3 – 88 973 m^3, 123 894 m^3 – 100 172 m^3, 141 336 m^3 – 61 008 m^3, and 180 881 m^3 – 150 245 m^3.

The estimated relationship between the number of months (X) and the sedimentation rate (Y) was Y = 17 562X with an R2 of 0.9262, indicating increasing sediment accumulation over time. It was also identified that in the longest period of thirteen months, there was a shallowing of 4.97 m compared to the channel's design, which poses a navigation hazard.

Regarding the erosion rate, the relationship obtained was Y = 12 453X with an R2 of 0.9542, showing a proportional increase over time but with a lower growth rate compared to the sedimentation process. The highest erosion value without anthropogenic intervention was 2.37 m for the longest period considered, and this does not affect navigation.

By quantitatively analyzing sedimentation, excluding the period from April 2020 to July 2020, when there was anthropogenic intervention in the natural behavior of the channel (dredging process), monthly sedimentation was estimated for each period. When averaging these values, a rate of 24 409.0 m^3/month was obtained, excluding the longest period.

The demarcation of coastlines at different time frames made it possible to recognize changes in erosion, sedimentation, and coastal stability at the estuary mouths near the study area. This helped identify additional sectors with an influence on sedimentation processes due to the input of continental sediments, typical of the natural dynamics of a deltaic system, which are likely to also deposit in the access channel to the port. However, it is recommended to use satellite images or aerial photographs with higher resolution and greater temporal coverage to calculate the numerical correlation between the accumulated volumes of sedimentation and erosion in the La Barra sector, precipitation, and erosion and sedimentation rates in the estuaries.

According to consulted sources, the sedimentological dynamics in Tumaco Bay depend on factors such as wave action, currents, and local morphology, among others. This analysis added precipitation to the list of variables that cause changes in sedimentation and erosion in the study area in the access channel to the port of Tumaco, showing an approximately linear relationship between sediment accumulation and precipitation, given by S = 56.591P + 15 529, and a relationship between accumulated erosion and precipitation, given by E = 48.749P – 5 263.6, both with an R^2 of 0.8. This indicates that an increase in precipitation leads to increased runoff and increased suspended sediments carried by rivers that ultimately converge near the study area.

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Authors' contributions

Conceptualization: Y. C. C., C. A. A., and A. M. M.; Methodology: Y. C. C., C. A. A., A. M. M., and P. A. Q.; Software: Y. C. C., C. A. A., A. M. M., and P. A. Q.; Validation: Y. C. C., C. A. A., A. M. M., and P. A. Q.; Analysis: Y. C. C., C. A. A., A. M. M., and P. A. Q.; Investigation: Y. C. C., C. A. A., and A. M. M.; Data Curation: Y. C. C., C. A. A., A. M. M., and P. A. Q.; Writing - Original Draft Preparation: Y. C. C., C. A. A., and A. M. M.; Proofreading and Editing: Y. C. C., C. A. A., A. M. M., and P. A. Q.; Visualization: Y. C. C., C. A. A., A. M. M., and P. A. Q. All authors have read and agreed to the published version of the manuscript.

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